Final report

Climate Change Committee
UK projections of climate risks and effectiveness of adaptation measures for water scarcity

Societal impacts and costs

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We also thank the members of the Project Steering Group and Sector Stakeholder Group for their thoughtful contributions. Their sector-specific knowledge and real-world perspectives grounded our analysis and enriched its relevance.

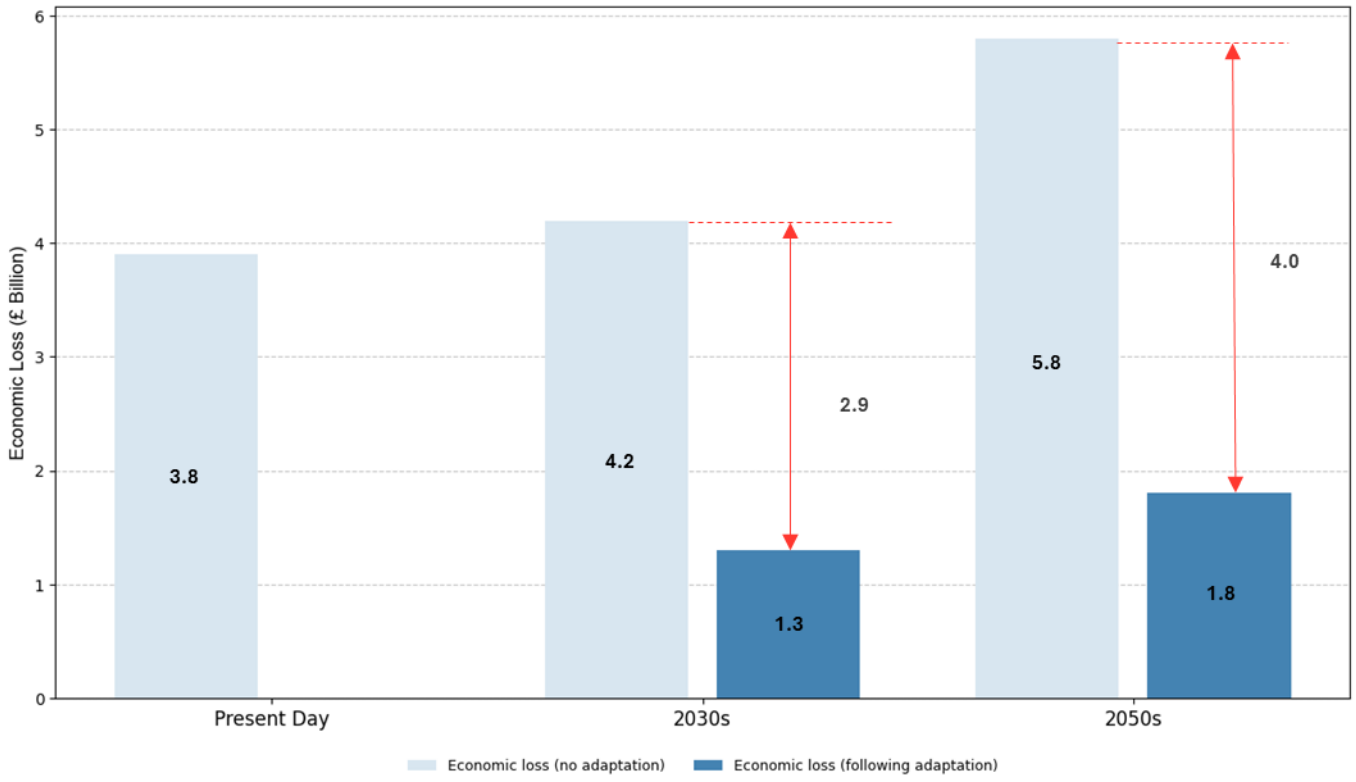
This project was delivered through the collaboration of WSP, Cambridge Econometrics, Cranfield University, and HR Wallingford.

Executive summary

Key messages

This assessment indicates that there are substantial current direct economic losses from chronic water stress to agriculture, industry, and power in the UK, in the region of £3.8 billion per year today, which present as current inefficiencies in industries that are largely built to deal with current levels of water stress. Inclusion of indirect economic losses would further increase this figure. As water stress increases in the future, these direct economic losses have been calculated to increase by a further £2 billion, reaching £5.8 billion per year by the middle of the 2050s. Adaptation actions identified for agriculture, industry, and power can meet the water demand identified in most of the current and future scenarios assessed across the UK. By implementing these measures, direct economic losses could be reduced by more than the cost of these adaptation actions: annual average avoided economic losses are in the order of £2.9 billion in the 2030s and £4.0 billion in the 2050s (see Figure 4-1, below). After accounting for the proportionately modest annual average costs of adaptation actions (about £100 million annually over the 2050s), these figures amount to a net avoided annual average loss of approximately £2.8 to £3.9 billion. This demonstrates that proactive adaptation measures offer a significant cost-benefit advantage see Figure 0-1.

Figure 0-1 Avoided climate risk from a cost-optimal adaptation package (central scenario – UK combined). Presented as the economic loss with no adaptation and economic loss with adaptation (£ billion)



In carrying out this project, various assumptions, simplifications, and estimates were necessary. It is essential to consider these factors when reviewing the results and conclusions. A summary of limitations can be found at the end of this section.

Introduction

Climate change is here now and will continue to increase weather extremes until the world meets net zero. At the time of writing this report (summer 2025), five areas of England are in drought, following the driest six months to July since 1976. The impacts of this summer's drought are beginning to be understood; for example, broad water restrictions have been in place, and some farms are reporting substantial drops in yields.

Climate change driven water scarcity is continuing to emerge as a critical systemic risk for the UK economy. The Climate Change Committee's (CCC) independent advice on the UK's Fourth Climate Change Risk Assessment (CCRA4, 2026)[1] finds that more action is needed to address risks to the water system, with drought continuing to pose a major threat.

Despite these warnings and impacts, adaptation to water scarcity risk is progressing slowly. The CCC's 2025 Adaptation progress report[2] explicitly notes that there has been insufficient to partial progress in delivering and implementing adaptation measures to ensure a resilient water supply. A key barrier is the absence of comprehensive cost–benefit evidence on adaptation interventions: companies and policymakers lack clear economic justification for investing in resilience measures such as efficiency upgrades, alternative supplies, or catchment collaboration[3]. As a result, the adaptation agenda is stalled in large part by insufficient economic evidence to support prioritisation and investment decisions.

Given the convergence of climate-driven water stress, increasing sectoral demand, and tightening regulatory expectations, this project aims to help address evidence gaps with a nation-level assessment of water scarcity risks. This project also provides economic evidence to inform cost-effective adaptation pathways across agriculture, industry and power sectors. These sectors are not only water-intensive but also tightly interdependent, meaning disruptions in one can cascade across supply chains. In this project, we focus on direct water stress impacts and adaptations outside of the public water supply system.

To facilitate this project, assumptions, simplification and estimations had to be made throughout and are important to understand alongside the outcomes and conclusions; the reader is referred to the end of this section for a summary.

This project supported the development of the Well-Adapted UK report (WAUK report), which is part of the CCC's independent advice on the Fourth UK Climate Change Risk Assessment (CCRA4). The WAUK report aims to highlight climate risks which could threaten successes of UK policy and societal outcomes, now and in the future, and identify cost-effective adaptation actions that have the greatest socio-economic impact.

This project will inform decision-making through spatial analysis of risk and adaptation (and variability across the UK) with quantification of the costs and effectiveness of adaptation by identifying, collating,

1 UK Climate Change Committee (2026) Independent Assessment of UK Climate Risk (CCRA4) Available at: [link to be created]
2 UK Climate Change Committee (2025) Progress in adapting to climate change: 2025 report to Parliament. Available at: https://www.theccc.org.uk/publication/progress-in-adapting-to-climate-change-2025/
3 National Infrastructure Commission (2018). Preparing for a Drier Future: England's Water Infrastructure Needs.

and assessing data related to the exposure, vulnerability and adaptive capacity. The assessment recognises the unique climate, geographical, social, economic and infrastructure contexts across the four nations and how climate risk and adaptive capacity has spatial and socio-economic components.

Baseline risk assessment methodology

Water stress

The assessment built upon existing water resources work undertaken across the UK; this was the National Framework for Water Resources in England, and the CCRA 3 assessment in Northern Ireland, Scotland, and Wales.

Drought can manifest as long-term shortages in water (termed here chronic water stress) or through shorter-term intensive events (termed acute water stress). For chronic water stress assessment, national surface water abstraction licence data, along with modelling was used to understand existing water demand, availability and the potential impacts of climate change. Acute water stress assessment involved analysis of modelled climate futures. Regional climate models were used to simulate the future impacts of climate change.

Economic losses

Economic losses are measured in terms of gross value added, which is the economic value-added during production processes (i.e. the difference between the value of the final output and the input costs, including taxes, profits and wage costs). Direct economic losses are calculated in real terms, in 2024 price base Great British Pounds. Rather than calculating economy-wide impacts, specific methodologies were developed that best captured the potential economic losses from key sectors. The calculation method varied by broad sector:

- For the power sector, it is the additional system cost to the UK from sourcing electricity from more expensive alternative sources when water is not available for specific generation technologies.
- For industry, we assess production that is foregone because of the unmet water demand.
- For agriculture, we separately quantified the impacts on both crop yields and quality (based on prices achieved for different grades of produce).

In all cases, assumptions and simplifications were required to aggregate from site- and day-specific impacts that would be felt to estimate effects upon a whole sector based on annualised unmet water demand.

Adaptation

A long list of adaptation measures was identified for each sub-sector through extensive literature reviews and insights from subject matter experts. Options were then short-listed based upon the availability of data to quantify their impact on water stress and cost.

Each of the short-listed measures was evaluated individually using a broad set of criteria, including water saving or augmentation potential, associated costs (capital, annual operation, and maintenance), sector applicability, uptake rates, adaptation measure lifespan, delivery timeframes, and wider benefits such as

carbon reduction and biodiversity enhancement. The assessment relied on both published literature and contributions from the project stakeholders.

The cost optimal adaptation plan was then developed using optimisation algorithms for all nations and sectors and results validated through the review by project stakeholders.

Understanding the risk

Chronic water stress

The economic results are reported as annual average damages and net present value (2024 prices) losses across the sum of the sub-sectors at a partial sector level of agriculture, industry and power. These losses result from water scarcity across the year and are measured in 'gross value added' (the difference between the value of the final output and the input costs, including taxes, profits and wage costs).

Existing water stress is calculated to lead to losses across agriculture, industry and power of around £3.8 billion per year today. As water stress increases in the future, these economic losses have been calculated to increase by a further £2 billion, reaching £5.8 billion per year by the middle of the 2050s.

Industry dominates the direct economic losses in absolute terms, followed by power and agriculture. This reflects chiefly the overall contribution of industry to the UK economy, and the fact that the industry sector is expected to continue to rely heavily on abstracted water in the future. Economic losses are largest in mineral products, extractives & other large manufacturing, followed by paper & pulp. These impacts are likely to manifest as temporary shutdowns for industry, reduced yields and quality of agriculture, and higher energy costs.

Project estimations suggest present day economic losses across all sectors. The methodology used to calculate current levels of unmet water demand, and its relationship to economic activity, is consistent with interpreting this economic loss as an inefficiency; with these sectors building their business models around the challenges that water stress already presents.

In aggregate, economic losses are substantially larger in England than the devolved nations, primarily because of the relative size of these sectors in each nation, although some differences emerge at the sub-sectoral level.

Considering relative impacts across the nations, agricultural subsector losses are largest in England but are a much lower percentage than industry losses. The economic losses by industry subsector are disproportionate across nations, with important impacts in Wales from chemicals and food & drink, Scotland with food & drink and England for paper & pulp. In Northern Ireland, the impacts observed in industry are in the minerals and large manufacturing sub-sector: these are higher than the impacts for other nations, except for Scotland in the 2050s.

Acute water stress

The acute water stress assessment focused on hydrological droughts and their impact on abstraction to indicate sector-specific vulnerabilities shaped by distinct water usage patterns. Key overall findings reveal reduced summer and autumn river flows across England. As an illustrative example, the results for power indicate that, while climate-driven changes are relatively modest compared to demand growth,

the East of England stands out as the most severely affected region by acute water stress. The frequency of severe events is estimated to increase by a factor of 2.6 from the 2030s to the 2050s, highlighting the importance of timely, targeted measures to strengthen resilience in the face of growing risks.

However, the methodology faces substantial limitations, as highlighted in the Scope and limitations chapter. Consequently, results are indicative and require further validation with stakeholders.

An effective adaptation response

The assessment indicates that there is opportunity to substantially reduce water scarcity losses by implementing adaptation to increase resilience both immediately, and into the future. The adaptation identified for each sector can meet the increased water demand identified in most of the current and future scenarios assessed across the UK. The economic losses could be reduced by more than the cost of adaptation, with avoided losses in the order of £2.9 billion in the 2030s and £4.0 billion in the 2050s, dropping to £2.8 billion and £3.9 billion after the comparatively low annual average cost of adaptation (approximately £30 million annual average totex (total expenditure) over 2030s, and. £100 million over the 2050s), i.e. net savings after the costs of adaptation are included, highlighting the high cost-benefit of taking proactive adaptation measures.

The assessment identified an immediate opportunity in both industry and agriculture for adoption of cost-effective, sector-specific adaptation measures, such as objective-based irrigation (during night-time hours for example) and increased on-site water storage. These approaches can reduce water demand and enhance water availability, which can substantially reduce associated disruption costs. The subsequent adaptation measures are generally implemented at the catchment and system levels (i.e. providing indirect benefit), and several cost beneficial options exist to meet the adaptation requirements through to the 2050s.

Several system measures with long lead in times, such as desalination plants and water transfers, are identified as adaptation options for industry in the West and South-East of England, and East and North Scotland. Due to their long lead in times, work would need to commence rapidly for them to be implemented in time to meet the demand. These measures are cost effective and can benefit multiple abstractors through a single investment. It is worth noting that system and catchment measures may need to be promoted, developed and maintained by regulators, agencies and network operators outside of the individual sectors.

In the power sector, most of the shortlisted adaptation measures involve providing additional water to meet operational demands, either through on-site storage in the near term or catchment/system-level approaches such as small-scale desalination. Due to the site-specific nature, adaptation by switching cooling methodologies to lower water use was not incorporated.

Work competed for The Energy System Catapult[98] evaluated retrofitting or modifying cooling technologies, demonstrating that there is a trade-off between water requirements, consumptiveness, and costs for thermal technology cooling methods. This work highlighted that for new power generation sites, the main adaptation action is to strategically site them to use water from coastal and estuarine sources for cooling.

The assessment of an effective adaptation response necessarily focussed on generally applicable adaptations. It should be noted that optimal adaptations for all sectors will be highly process, operational, geographic and site specific. They can require substantial process and operational changes and typically occur alongside investment lifecycles in the operational infrastructure. This means that there is an

opportunity for more cost-efficient approaches, and a lesser reliance on catchment and system adaptations.

Transition to Net Zero

The CCC's Balanced Pathway to net zero could imply a reduction in freshwater demand for power generation because fossil fuels are replaced with less water intensive renewables. The emergence of hydrogen and carbon capture and storage for thermal power introduces new, but highly localised water demands. Decarbonising UK industry through electrification, hydrogen and carbon capture and storage will shift energy and water usage patterns. While this is anticipated to lower water demand overall, it could heighten risks if hard-to-abate sectors cluster together in already water-stressed catchments.

Strategic, system-wide planning is essential to anticipate and manage these challenges along with other water intensive emerging technologies. Integrating spatial and environmental capacity assessments into infrastructure and technology investment decisions will help ensure that the UK's decarbonisation remains both sustainable and resilient to future water scarcity.

Scope and limitations

As with all studies of this nature, the scope has had to be constrained, and many limitations and simplifications incorporated. These include:

- This is a national-level assessment, which is not suitable for site specific conclusions or analysis. The sectors (agriculture, industry and power) have been split into key sub-sectors, defined based upon their abstractive nature, national importance and vulnerability. This means that estimates represent the sums of the sub-sectors, not the whole sector.
- The assessment is built upon water abstraction licence information. This licence data provides important details of abstraction volumes, but not on water management practices and temporal demands. It also does not provide insight into the proportion of their licensed volume that abstractors use and therefore does not indicate actual water usage.
- The assessment needs to incorporate many realisations of the future, such as climate, water demand and environmental policies. In all cases, the future conditions are not known and have had to be estimated. It is particularly important to note that climate change estimates have been derived based upon regional climate models, which are known to under-represent extreme conditions. Sensitivity analysis was undertaken to understand the impacts of these.
- Insufficient data was available to undertake reliable statistical analysis of acute water stress events, with only relative comparison possible, limiting the analysis and conclusions of these risks. Economic losses are considered likely to be non-linear and highly context specific, so have not been estimated. Possible changes to the seasonality and duration of acute water stress were explored for the power sector in England only, and so this assessment provides an incomplete view of the risks associate with acute water scarcity.
- Direct economic impacts only have been determined based upon simplified assumptions between water scarcity and loss. Indirect costs have not been estimated but are likely to be substantial.

- The adaptation response has been determined based upon the national water stress assessment. Optimal adaptations will be highly process, operational and site specific, particularly for industry. These results should be viewed in this context.
- Only water scarcity is considered in this analysis. The effects of other climate hazards could have greater magnitude impacts on these sectors. The impact on these sectors of all climate hazards combined is also likely to be much greater but is outside the scope of this assessment.

Stakeholders, including policy makers, regulators, sector representatives, and experts were proactively engaged throughout the project, helping to ensure that the methodology was appropriate.

Conclusions

This assessment indicates that there are substantial current direct economic losses from chronic water stress in agriculture, industry, and power, in the region of £3.8 billion per year today which present as current inefficiencies. Inclusion of indirect economic losses would further increase this figure. As water stress increases in the future, these economic losses have been calculated to increase by a further £2 billion, reaching £5.8 billion per year by the middle of the 2050s. The adaptation measures identified for each sector can meet the demand identified in most of the current and future scenarios assessed across the UK. The economic losses could be reduced by more than the cost of adaptation, with avoided costs in the order of £2.8 billion in the 2030s and £3.9 billion in the 2050s, after the costs of adaptation actions have been considered.

A multifaceted approach will be necessary to achieve these reductions in losses, including site specific assessments, and cooperation across multiple water users. System (such as grey water reuse) and catchment adaptations (such as swales) focus on providing water into the wider system (rather than site specific) and may need to be promoted, developed and maintained by regulators, agencies and network operators outside of the individual sectors. Several system measures with long lead in times are identified as adaptation options for industry. Due to their long lead in times, work would need to commence rapidly for them to be implemented in time to meet the demand.

Achieving effective adaptation across sectors will depend on aligning the roles, responsibilities, and outcomes among water users, providers, and regulators.

By integrating information about future freshwater demand from environmental capacity assessments into system, cluster and catchment-level planning, decision-makers can ensure that investments in water intensive infrastructure are water efficient by design and sited in appropriate locations and therefore are both sustainable and resilient to future water stress.

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Abbreviations and glossary

Abbreviations

£NPV	Net Present Value
AMP	Asset Management Planning
ATR	Autothermal Reforming
BECCS	Bioenergy with Carbon Capture and Storage
CAMS	Catchment Abstract Management System
CapEx	Capital Investment Costs
CB7	7th Carbon Budget
CCC	Climate Change Committee
CCGT	Combined Cycle Gas Turbine
CCRA3	Third UK Climate Change Risk Assessment (Previous)
CCRA4	Fourth UK Climate Change Risk Assessment (Current)
CCS	Carbon Capture and Storage
CGWL	Current Global Warming Level
CHP	Combined Heat and Power
CO2e	Carbon Dioxide Equivalent
DA	Devolved Administration
EAAD	Estimated annual average damage
ED	Environmental Destination
EFI	Environmental Flow Indicator
eFLaG	Enhanced Future Flows and Groundwater
ESME	Enhanced Systems Modelling Environment

EWN	Energy Water Nexus
GDP	Gross Domestic Product
GHG	Green House Gasses
GVA	Gross Value Added
GWLs	Global Warming Levels
HOF	Hands Off Flow
IPCC	Intergovernmental Panel on Climate Change
LCOE	Levelised Costs of Electricity
NESO	National Energy System Operator
NF2.0	Environment Agency's National Framework for Water Resources 2025
ONS	Office of National Statistics
OpEx	Annual Operating and Maintenance Costs
PCC	Per Capita Consumption
PV	Photovoltaic
PI	Precision Irrigation
PSG	Project Steering Group
PWS	Public Water Supply
RCM	Regional Climate Model
REA	Rapid Evidence Assessment
RO	Reverse Osmosis
SEA	Strategic Environmental Assessment
SPOT	Simple Portfolio Optimisation Tool
SSEP	Strategic Spatial Energy Plan
SSG	Sector Steering Group
SSSI	Sites of Special Scientific Interest

TotEx	Total Expenditure
UKCP18	UK Climate Projections
WAUK report	Well-Adapted UK report
WCWR	West Country Water Resources
WRE	Water Resources East
WFD	Water Framework Directive
WRGIS	Water Resources GIS
WRMP	Water Resources Management Plan
WRMP24	Water Resources Management Plan 2024
WRN	Water Resources North
WRSE	Water Resources South East

Glossary of terms

Term	Explanation
Abstraction	The process of taking water from a natural source (such as a river, lake, or aquifer) for human use, including for agriculture, industry, or power generation. Abstraction is regulated by licenses, which specify the volume and conditions under which water can be withdrawn. The report discusses abstraction in the context of water demand, licensing, and environmental sustainability.
Acute Water Stress	Short-term, extreme variations in water availability, typically driven by episodic events such as droughts. Unlike chronic water stress, which reflects long-term shifts in average conditions, acute water stress captures the intensity and frequency of extreme hydrological events that can disrupt water abstraction and supply.
Adaptation	The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects. Source: IPCC AR5[4].
Adaptation Pathway	A generic term that involves the analysis of adaptation options over time to changing risk levels. This term has been applied in a number of different ways, which include: i): Adaptation roadmaps or pathway frameworks, which consider portfolios of adaptation that change over time, to allow analysis of the timing and sequencing of adaptation and identify priorities; ii) Adaptive management, which is an iterative cycle of monitoring, research, evaluation and learning, i.e. a process, that is used to improve future management strategies (also called iterative risk management); iii) Dynamic adaptation route-maps, which focus on decision making under uncertainty and identify adaptation tipping points (or turning points), the point at which a particular action is no longer adequate for meeting the plan's objectives, that act as triggers for a change in adaptation. Source: CCRA3 Glossary[5]
Augmentation Potential	The estimated capacity of a proposed measure to increase the availability of water resources within a given system or region. It is typically assessed alongside water-saving potential and considers how much additional water supply can be generated through interventions such as infrastructure upgrades, alternative sources, or efficiency improvements.
Biodiversity	The variability among living organisms from all sources including, among other things, terrestrial, marine and other aquatic ecosystems, and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems. Source: IPCC AR6[6]
Bioenergy	Energy derived from any form of biomass or its metabolic by-products

[4] IPCC (2014) Fifth Assessment Report Available at: https://www.ipcc.ch/assessment-report/ar5/
[5] UK Climate Risk (2021) Glossary (CCRA3-IA) Available at: https://www.ukclimaterisk.org/publications/technical-report-ccra3-ia/glossary/#section-2-adaptation
[6] IPCC (2021-2023) Sixth Assessment Report Available at: https://www.ipcc.ch/assessment-report/ar6/

Term	Explanation
Capital Expenditure	Funds used by an organisation to acquire, upgrade, or maintain physical assets such as property, industrial buildings, or equipment.
Chronic Water Stress	Long-term shifts in patterns indicative of wetter or drier periods within the simulated time series
Climate	Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation and wind. Climate in a wider sense is the state, including a statistical description, of the climate system. Source: IPCC AR5[4].
Climate Change	A change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external processes such as modulations of the solar cycles, volcanic eruptions, and persistent anthropogenic changes in the composition of the atmosphere or in land use. Source: IPCC AR5[4].
Co-Benefits	The positive effects that a policy or measure aimed at one objective might have on other objectives, thereby increasing the total benefits for society. Co-benefits are often subject to uncertainty and depend on local circumstances and implementation practices, among other factors. Source: IPCC AR5[4]
Consumptiveness	The proportion of abstracted water that is not returned to the environment or water system after use.
Cost-Effectiveness Ratio (CER)	A metric used to compare the relative efficiency of adaptation measures by expressing their cost per unit of benefit delivered. In the context of water-stress planning, it represents the Equivalent Annual Cost (EAC) of a measure divided by the volume of water benefit achieved, typically expressed as £ per megalitre (£/Ml).
Cost-Optimal Adaptation Package	The combination of measures that meets water resilience targets at the lowest equivalent annual cost (EAC). It considers cost-effectiveness (£/Ml), synergies between measures, and wider benefits like carbon reduction and biodiversity.
Drought	Following the disciplinary views of drought defined by Wilhite & Glantz (1985)[7] and subsequent referencing including International Panel for Climate Change[8]. • Agricultural: insufficient rainfall or dry soil adversely affects farming and crop growth.

[7] Understanding the Drought Phenomenon: The Role of Definitions (accessed 27/11/2025)
[8] Seneviratne, S.I., X. Zhang, M. Adnan, W. Badi, C. Dereczynski, A. Di Luca, S. Ghosh, I. Iskandar, J. Kossin, S. Lewis, F. Otto, I. Pinto, M. Satoh, S.M. Vicente-Serrano, M. Wehner, and B. Zhou, (2021) Weather and Climate Extreme Events in a Changing Climate. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1513–1766, doi: 10.1017/9781009157896.013.

Term	Explanation
	• Meteorological: rainfall in a region falls below average levels, • Ecological: limited water availability impacts the local environment, • Hydrological: reductions in water bodies such as streams and reservoirs, which may result from low precipitation, inadequate snowmelt, or other factors.
Ecosystem	A functional unit consisting of living organisms, their non-living environment and the interactions within and between them. The components included in each ecosystem and its spatial boundaries depend on the purpose for which the ecosystem is defined: in some cases, they are relatively sharp, while in others they are diffuse. Ecosystem boundaries can change over time. Ecosystems are nested within other ecosystems, and their scale can range from very small to the entire biosphere. In the current era, most ecosystems either contain people as key organisms, or are influenced by the effects of human activities in their environment. Source IPCC AR6[6]
Elasticity of output	The sensitivity of economic performance, such as productivity or gross value added (GVA), to changes in water availability. In the context of water stress modelling, it quantifies how a percentage change in water supply or unmet demand affects the output of a sector or region.
Environmental Destination	A water resources policy developed for England that defines where and by how much water abstraction must change to achieve and maintain a healthy water environment, both now and in the future. It sets long-term environmental outcomes to ensure that abstraction from rivers, lakes, wetlands, and estuaries is environmentally sustainable, addressing both current unsustainable practices and future pressures.
Environmental Flow Indicators (EFI)	A benchmark used to determine the minimum proportion of natural river flow needed to sustain the ecological health of a waterbody. It helps assess whether current or future abstraction levels are environmentally sustainable. If abstraction exceeds the EFI threshold, it may trigger the need for abstraction recovery measures to restore flows and protect ecosystems. EFIs are central to water resource planning and scenario modelling, especially under water stress conditions. Source: Appendix 4: Longer term environmental water needs NFWR 2020[9]
Equivalent Annual Costs	The annualised cost of an investment or measure, considering both capital and operational expenses over its lifespan.
Estimated Annual Average Damage	The economic losses resulting from unmet water demand over the course of a year. This metric is calculated using Gross Value Added (GVA), which measures the difference between the value of final output and the input costs, including taxes, profits, and wage costs. By expressing damages in terms of GVA, this approach

[9] Environment Agency (2025) Appendix 4: Longer term environmental water needs Available at: https://assets.publishing.service.gov.uk/media/685131c82288b8d4cf98765b/Appendix_4_Longer_term_environmental_water_needs_NFWR_2020.pdf

Term	Explanation
	captures the broader economic impact of water shortages on production and sectoral performance.
Final Adaptation Package of Measures	The optimal combination of regional option packages, strategically sequenced over the planning horizon, to reduce or eliminate the projected unmet demand for a given sector. This package represents the most effective set of interventions designed to ensure water resource resilience and sectoral sustainability under current and future stress conditions.
Flow Deficit Intensity	The severity of water shortfall relative to required environmental or abstraction flows during stress periods. It is typically expressed as a ratio or percentage, comparing the deficit volume to the target flow.
Flow Duration Curve	A graphical representation of the relationship between streamflow magnitude and the percentage of time that flow is equalled or exceeded during a given period. Flow percentiles represent specific points on a Flow Duration Curve (FDC) that indicate the discharge value exceeded a given percentage of the time during the analysis period.
Future Levelised Costs of Electricity (LCOE)	The Levelised Cost of Electricity (LCOE) is the discounted lifetime cost of building and operating a generation asset, expressed as a cost per unit of electricity generated (£/MWh). It covers all relevant costs faced by the generator, including pre-development, capital, operating, fuel, and financing costs. This is sometimes called a life-cycle cost, which emphasises the "cradle to grave" aspect of the definition. Source: Electricity generation costs 2023[10]
Global warming levels (GWL)	Global warming refers to the increase in global surface temperature relative to a baseline reference period, averaging over a period sufficient to remove interannual variations (e.g., 20 or 30 years). A common choice for the baseline is 1850–1900 (the earliest period of reliable observations with sufficient geographic coverage), with more modern baselines used depending upon the application. Global warming Levels refer to 1.5ºC, 2.0ºC and 2.5ºC of warming above pre-industrial levels. Source IPCC AR6[6]
Gross Value Added (GVA)	The difference between the value of the final output and the input costs, including taxes, profits and wage costs
Hands off Flow (HOF)	Licence conditions that require abstractors to cease water abstraction when river flows fall below a specified threshold. These rules are designed to protect water-dependent ecosystems during periods of low flow. In practice, separate averages are calculated for abstractions with and without HOF conditions, and these are applied accordingly to ensure compliance and safeguard environmental integrity. Source: Water Regulation | Engage Environment Agency[11]

[10] Department for Energy Security and Net Zero (2023) Electricity generation costs 2023. Available at: https://www.gov.uk/government/publications/electricity-generation-costs-2023

[11] Environment Agency (2025) Water Regulation Available at: https://engageenvironmentagency.uk.engagementhq.com/water-regulation#:~:text=The%20EA%20check%20compliance%20against,protect%20the%20water%20dependant%20environment.

Term	Explanation
Hazard	The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources. In the IPCC, hazard refers to climate-related physical events or trends. Source: IPCC AR5[4].
Impact Pathway Models	Models that illustrate the range of impacts that assessed sectors are likely to face under current and future water stress conditions. These models trace the causal chain from water availability challenges to sector-specific consequences, providing a structured view of potential risks. These impact pathways cover both operational risks (e.g. reduced crop yield, loss of quality, higher operating costs) and market risks
Individual Measure	A single adaptation option assessed on its own for water-saving or augmentation potential, costs, feasibility, and wider benefits, before combining into packages. I.e. Installing roof rainwater collectors on farms.
Institutional Option	An institutional approach involving the introduction of a potential water permit trading scheme. This option aims to enhance the efficiency of licence allocation across sectors and businesses in different regions, ensuring that the overall water availability remains unchanged.
Intensity	The magnitude or size of a problem, in this case, volume of unmet demand measure as a volume of water.
Land use	The total of arrangements, activities and inputs undertaken across certain land cover types (a set of human actions). The term land use is also used in the sense of the social and economic purposes for which land is managed (e.g., grazing, timber extraction, conservation and city dwelling). Source: IPCC SR1.5[12]
Mitigation	A human intervention to reduce emissions or enhance the sinks of greenhouse gases. Source IPCC AR6[6]
Modified Net Impacts	The cumulative alteration to natural river or watercourse flow conditions resulting from human activities and regulatory constraints. These modifications account for all abstractions and discharges, as well as influencing factors such as: • Environmental destination requirements that reduce licensed abstraction volumes. • Consumptive nature of upstream abstractions, which permanently remove water from the system. • Hands off Flow (HOF) conditions imposed on licences, restricting abstraction during low-flow periods. Together, these adjustments represent the net change from natural flow caused by operational, regulatory, and environmental drivers.

[12] IPCC (2018) Global Warming of 1.5 ºC Available at: https://www.ipcc.ch/sr15/

Term	Explanation
Net Present Value	A generic term for the sum of a stream of any future values that have been discounted to bring them to a present value.
Net Zero	Condition in which metric-weighted anthropogenic greenhouse gas (GHG) emissions are balanced by metric-weighted anthropogenic GHG removals over a specified period. The quantification of net-zero HG emissions depends on the GHG emission metric chosen to compare emissions and removals of different gases, as well as the time horizon chosen for that metric. See also: Greenhouse gas neutrality, Land use, land-use change and forestry (LULUCF), Net zero CO2 emissions. Source IPCC AR6[6]
Operational Expenditure	The ongoing costs for running a business, asset, or system, including maintenance and utilities.
Optimisation	The process of identifying the most effective sequence and combination of decisions over a planning period, while satisfying defined constraints and objectives. It is widely used across sectors such as utilities, transport, and infrastructure to support strategic planning. Optimisation algorithm is applied to generate plans that deliver optimal whole-life value by selecting and sequencing beneficial options. The process involves three key components: 1. Measures or packages of measures to implement. 2. Profiles of unmet demand to reduce or eliminate. 3. An algorithm that determines the best combination of measures to meet those demand profiles.
Quantile-Quantile Mapping	A statistical adjustment technique used to align the distribution of one dataset with another by matching their respective quantiles. In climate modelling, this method is applied to correct biases in simulated data by referencing observed data over a defined baseline period.
Recent Actual Rates	The average daily volume of water abstracted by a licensed user over a defined recent period (typically the last six years) distributed across the days when abstraction is permitted under the licence. These rates are expressed in litres per day (l/d) or cubic meters per day (m^3/d) and reflect actual usage rather than the full licensed volume. In modelling and risk assessments, Recent Actual Rates are used as a baseline abstraction level to which multipliers or adjustment factors are applied. This helps simulate future demand scenarios, assess environmental impacts, and evaluate regulatory compliance under varying flow conditions. Source: 4. Water availability: National Framework for Water Resources 2025 - GOV.UK[13]

[13] Environment Agency (2025) 4. Water availability: National Framework for Water Resources 2025. Available at: https://www.gov.uk/government/publications/national-framework-for-water-resources-2025-water-for-growth-nature-and-a-resilient-future/4-water-availability-national-framework-for-water-resources-2025

Term	Explanation
Regional Option Package	A scenario-based intervention model applied across a defined geographic area, such as a catchment or administrative region, to estimate the collective impact of water-saving measures. It typically includes assumptions about: • The number of sites or farms where the intervention (e.g. rainwater collectors) is deployed. • The uptake rate (percentage of eligible participants adopting the measure). • The resulting total water savings for the region.
Resilience	IPCC AR5[4] defines as: the capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure while also maintaining the capacity for adaptation, learning and transformation. However, the term resilience is now used very widely, in different ways, and therefore in CCRA3 we try and avoid the term due to the lack of a commonly applied definition. The exception is where it is used in existing Government policies, or in plans or actions as stated by the private sector or other groups, noting in such cases the specific definition should be included. Source: CCRA3 Technical Team[5].
Risk	The potential for adverse consequences where something of value is at stake and where the occurrence and degree of an outcome is uncertain. In the context of the assessment of climate impacts, the term risk is often used to refer to the potential for adverse consequences of a climate related hazard, or of adaptation or mitigation responses to such a hazard, on lives, livelihoods, health and well-being, ecosystems and species, economic, social and cultural assets, services (including ecosystem services), and infrastructure. Risk results from the interaction of vulnerability (of the affected system), its exposure over time (to the hazard), as well as the (climate-related) hazard and the likelihood of its occurrence. Source: IPCC SR1.5[12]. Note that in CCRA3, the term risk is used for negative consequences (i.e. threats).
River Flow Regime	The characteristic pattern of flow variation in a river over time, including the magnitude, frequency, duration, timing, and rate of change of water discharge. It reflects both natural hydrological processes and human influences such as abstraction, land use, and climate change.
Sequestration	The net uptake of carbon from the atmosphere and long-term storage as non-volatile carbon. This can be in the wood of living trees, in soil, or in long lived wood products. Source Forest Research(Carbon Glossary - Forest Research)[14]
Severity	The magnitude of a problem combined with the duration of time that the problem occurs i.e. intensity x duration of a period of water stress.
Theories of change	Structured conceptual frameworks that map out the causal pathways through which water-related pressures (such as scarcity, abstraction limits, or drought) can lead to economic impacts across sectors. These frameworks aim to identify and connect sector-specific sensitivities, dependencies, and feedback loops, enabling analysts to

[14] Forest Research – Carbon Glossary. Available at: https://www.forestresearch.gov.uk/climate-change/carbon/carbon-glossary/

Term	Explanation
	understand how water stress might disrupt productivity, supply chains, or investment patterns.
Thresholds	Levels above which there is step-change in risks, and which may necessitate much greater levels of adaptation. These include biophysical thresholds, engineering thresholds, performance thresholds and policy thresholds. Source: CCRA3 Technical Team[5].
Total Expenditure (ToTex)	The combined value of capital expenditure (CapEx) and operational expenditure (OpEx) used by water companies to deliver services and infrastructure. It is a regulatory accounting concept used by Ofwat to assess efficiency and value in water sector investment planning. Source: OfWat KPMG Report[15]
Uncertainty	A state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of Sources, from imprecision in the data to ambiguously defined concepts or terminology, incomplete understanding of critical processes, or uncertain projections of human behaviour. Uncertainty can therefore be represented by quantitative measures (e.g., a probability density function) or by qualitative statements (e.g., reflecting the judgment of a team of experts). Source: IPCC AR5[4].
Unmet demand	The volume of water that an abstractor is licensed to take but cannot access due to flow restrictions or low river levels. It is calculated by distributing the abstractor's annual licensed volume across the permitted abstraction days (in megalitres/day or m^3/day). On days when abstraction is required but river flows fall below the Hands-Off Flow (HOF) threshold specified in the licence, or below the intake level if no HOF is defined, abstraction must stop. The water volume needed on those non-abstraction days is recorded as daily unmet demand. This is summed annually and normalized by abstractor size to estimate the total unmet demand for all abstractors within a catchment. The result is expressed in megalitres per year (Ml/year; or other period) and used to calculate the Annual Average Unmet Sector Demand as a percentage of the total water required by each subsector.
Uptake rate	The proportion achieved of a notionally achievable level, such as a maximum technically feasible level or a target level set by policymakers. Uptake rates have been expressed as a range (min, max, best) and represent additional further uptake potential of different adaptations over and above current applications (where applicable).
Vulnerability	The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt. Source: IPCC AR5[4].
Wastewater	Water that requires collection, transport, treatment, and discharge to remove contaminants before it can be safely returned to the environment or reused.

[15] OFWAT (2018) Innovation and efficiency gains from the totex and outcomes framework Available at: https://www.ofwat.gov.uk/wp-content/uploads/2019/01/Ofwat_totexoutcomes_FINAL_30012019.pdf

Term	Explanation
	Wastewater systems are designed to protect public health, meet user needs, and promote environmental sustainability. Source: ISO 24516-3: ISO 24516-3:2017 - Guidelines for the management of assets of water supply and wastewater systems — Part 3: Wastewater collection networks[16]
Water demand	The total volume of water required to meet the needs of various users (such as households, agriculture, industry, and the environment) within a specific area and time. It encompasses both actual consumption and anticipated needs, and is influenced by factors such as population size, economic activity, climate, land use, and service levels.
Water Resources Management Plan	A statutory document produced by each water company in England and Wales. It outlines a comprehensive framework for securing water supply and protecting environmental resources over a 25-year planning horizon. The plan details how the company intends to maintain a resilient and sustainable water supply for its customers while enhancing the natural environment. Source: Water resources planning guideline - GOV.UK[17]
Water scarcity	A condition where water demand exceeds available supply in each region, either permanently or seasonally. It is driven by a combination of climatic factors, population growth, land use changes, and water management practices. Scientifically, it is often quantified using metrics such as the Water Scarcity Index (WSI), the ratio of water demand to water supply; or the Falkenmark Indicator, which defines scarcity as less than 1,000 m^3 of renewable freshwater per person per year. Source: Global assessment of water challenges under uncertainty in water scarcity projections | Nature Sustainability[18]
Whole life carbon	'Whole Life Carbon' emissions are the sum total of all assets related GHG emissions and removals, both operational and embodied over the life cycle of an asset including its disposal (Modules: A0-A5; B1-B7; B8 optional; C1-C4, all including biogenic carbon, with A02 assumed to be zero for buildings). Source: Leti: Microsoft Word - 20230118.Carbon Definitions RICSPS Version.docx)[19]

[16]ISO (2017) ISO 24516-3:2017 Available at: https://www.iso.org/standard/64668.html
[17] Environment Agency, Natural Resources Wales and The Water Services Regulation Authority (2021) Water resources planning guideline. Available at: https://www.gov.uk/government/publications/water-resources-planning-guideline
[18] Greve, P., Kahil, T., Mochizuki, J. et al. (2018) Global assessment of water challenges under uncertainty in water scarcity projections. Nat Sustain 1, 486–494 Available at: https://doi.org/10.1038/s41893-018-0134-9
[19] Leti (2023) Improving Consistency in Whole Life Carbon Assessment and Reporting. Available at: https://www.leti.uk/_files/ugd/252d09_04f3e91a9a1a431b8dbaf35a0a1a81f3.pdf

1. Introduction

1.1 Background

Water scarcity is emerging as a critical systemic risk for the UK economy; the quantification of these implications at a national level are maturing, but in areas are insufficient for decision making. The CCC's independent advice on the UK's Fourth Climate Change Risk Assessment (CCRA4, 2026)[20] finds that more action is needed to address risks to the water system, with drought continuing to pose a major threat.

Despite these warnings, adaptation to water scarcity risk is progressing slowly. The 2025 adaptation progress report[21] explicitly notes that there has been insufficient to partial progress in delivering and implementing adaptation measures to ensure a resilient water supply[22]. A key barrier is the absence of comprehensive cost–benefit evidence on adaptation interventions: companies and policymakers lack clear economic justification for investing in resilience measures such as efficiency upgrades, alternative supplies, or catchment collaboration[23]. As a result, the adaptation agenda is stalled in large part by insufficient economic evidence to support prioritisation and investment decisions.

There are few national scale risk assessments of prolonged or repeated water stress events, and their economic consequences are poorly understood at this scale. Whilst certain sectors such as agriculture have received some research attention at the local and regional scales, impacts on critical sectors such as food and drink, manufacturing and energy generation are less well quantified[24]. These sectors are not only water-intensive but also tightly interdependent, meaning disruptions in one can cascade across supply chains.

Furthermore, regulatory changes such as the reform of the water abstraction licensing regime,[25] and Ofwat-driven resilience duties[26], as well as Defra's adaptation reporting powers[27], call for various organisations across key economic sectors to identify and manage water-related physical risks and plan for adaptation and resilience. However, in the absence of detailed sector-level valuations of risk exposure and adaptation benefits, compliance risks becoming procedural rather than transformative[28].

Given the convergence of climate-driven water stress, increasing sectoral demand, and tightening regulatory expectations, this project aims to help address these gaps. It provides a nation-level assessment of the spatial water scarcity risks, economic evidence to inform cost-effective adaptation pathways across agriculture, industry and power sectors. In this project, we focus on changing patterns of water demand outside of the public water supply system.

[20] UK Climate Change Committee (2026) Independent Assessment of UK Climate Risk (CCRA4) Available at: [Link to be provided]
[21] UK Climate Change Committee (2025) Progress in adapting to climate change: 2025 report to Parliament. Available at: https://www.theccc.org.uk/publication/progress-in-adapting-to-climate-change-2025/
[22] UK Climate Change Committee (2021). CCRA3 – Business and Industry Summary for Policymakers.
[23] National Infrastructure Commission (2018). Preparing for a Drier Future: England's Water Infrastructure Needs.
[24] Aldaya, M.M. & Hoekstra, A.Y. (2010). The Water Needed for Food, Energy and Industry in the UK. WWF.
[25] Resilience in the round - Ofwat https://www.ofwat.gov.uk/regulated-companies/resilience-in-the-round/
[26] Defra (2025) Water Company Drought Plan Guideline. Available at Water company drought plan guideline, 2025 - GOV.UK
[27] DEFRA (2023) Consultation on the Fourth Round of the Climate Adaptation Reporting Power Available at: https://consult.defra.gov.uk/climate-change-adaptation/fourth-round-adaptation-reporting-power/
[28] UK Climate Change Committee (2021). CCRA3 – Business Adaptation Gaps Analysis.

This project supported the development of the Well-Adapted UK report (WAUK report), which is part of the CCC's independent advice on the Fourth UK Climate Change Risk Assessment (CCRA4). The WAUK report aims to highlight climate risks which could threaten successes of UK policy and societal outcomes, now and in the future, and identify cost-effective adaptation actions that have the greatest socio-economic impact.

This project will inform decision-making through spatial analysis of risk and adaptation (and variability across the UK) with quantification of the costs and effectiveness of adaptation by identifying, collating, and assessing data related to the exposure, vulnerability and adaptive capacity. The assessment recognises the unique climate, geographical, social, economic and infrastructure contexts across the four nations and how climate risk and adaptive capacity has a spatial and socio-economic component.

1.1 Research design

1.1.1 Summary

The analysis followed the Climate Change Committee's (CCC) methodology[29] across three sequential stages to first, define the problem; second, estimate the baseline current and future risk, and finally, to identify and shortlist possible adaptation measures, and develop and test a cost-optimal adaptation package.

A mixed methods research design was adopted, facilitating comprehensive integration of both quantitative and qualitative data. This approach enabled the development of contextual and explanatory narratives alongside quantitative model outputs. The guiding principles, research challenges, and frameworks outlined in this Chapter underpin the methodological choices for the project. These considerations required an approach that balances computational efficiency with methodological rigor, emphasising transparent communication of uncertainties, systematic scenario design, and the incorporation of stakeholder expertise to ensure the validity of findings.

1.1.2 Guiding principles

A set of principles have guided the research design for this project, as follows:

- The assessment centres on quantifying and qualifying direct economic losses resulting from water stress at both the nation and UK-wide levels. This broad-scale focus ensures that the analysis captures the scale of impacts and provides insights that are relevant to strategic decision-making across all nations. Quantification is a key part of this assessment, which necessitated many assumptions and simplifications, and should be grounded upon a solid evidence base.
- The research should advance the adaptation agenda through the provision of robust evidence on the cost effectiveness of a range of adaptation measures for water stress, emphasising the importance of proactive planning and implementation.
- The risk assessment method should be designed to maintain and enhance consistency with other concurrent water resource planning studies such as the Environment Agency's National Framework

[29] Climate Change Committee (2024) Phase 2: Modelling and Analysis, Methodology document. Received as part of the Request for Proposal documents.

for Water Resources 2025 (NF2.0)[30]. By aligning methods and analytical frameworks where possible, the research contributes to a coherent evidence base that can be readily integrated with existing national and regional water management initiatives.

- Stakeholders, including policy makers, regulators, sector representatives, and experts will be proactively engaged throughout the research process. This approach not only assures the validity and credibility of findings but also helps secure stakeholder buy-in, fostering confidence in the outcomes and supporting effective implementation of recommendations.
- Align with the CCC established approaches for climate framing, risk assessment, and economic analysis. This ensures that the study's methodology is consistent with other research supporting CCRA4 and the WAUK Report.

1.1.3 Research challenges

The project relied on the best available existing data sets rather than undertaking new primary data collection. While this approach ensured efficiency and leverages established models and databases, it also presents the challenge of working within the constraints of data that had gaps and varying levels of detail across the nations.

Distinguishing the anthropogenic climate change signal from natural variability is a challenge, especially over the short to medium term (up to 2050) but is further complicated in the UK, where weather patterns are strongly influenced by the North Atlantic Oscillation, storm tracks and high-pressure blocking events[31]. This can lead to particularly large biases in some regions and may also result in the models not being able to simulate key dynamical patterns and weather regimes key to the formation of droughts[32]. Whilst some large climate model ensembles used to drive hydrological models have characterised internal atmospheric circulation variability with some skill, these modelling approaches remain in the research domain[33].

With this challenge in mind, careful consideration was given to both the strengths and limitations of the UK Climate Projections (UKCP18) Regional Climate Models (RCMs)[34] and their associated hydrological products (see Appendix E for further discussion). The UKCP18 models provide valuable insights into emerging trends for future climate scenarios, but their resolution does not capture all the relevant internal variability that leads to the natural variability seen in UK hydrology. In addition:

- The sample size of 12 RCM models is small.
- Long periods of dry or wet conditions are not simulated well.
- The bias correction method applied potentially influences future changes.

[30] Environment Agency (2025) The National Framework for Water Resources 2025. Available at: https://assets.publishing.service.gov.uk/media/685d4a2ac2633bd820a92a99/2025_EA_National_Framework_Water_Resources_-_summary_document.pdfhttps://assets.publishing.service.gov.uk/media/685d4a2ac2633bd820a92a99/2025_EA_National_Framework_Water_Resources_-_summary_document.pdf

[31] Climate change and water in the UK – past changes and future prospects

[32] Sillmann, J., Thorarinsdottir, T., Keenlyside, N., Schaller, N., Alexander, L.V., Hegerl, G., Seneviratne, S.I., Vautard, R., Zhang, X. and Zwiers, F.W., Understanding, modeling and predicting weather and climate extremes: Challenges and opportunities, Weather and climate extremes, 18, pp.65-74 (2017)

[33] Climate variability conceals emerging hydrological trends across Great Britain - ScienceDirect

[34] Met Office (2018, updated 2019) UKCP18 Science Overview Report. Available at: https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP18-Overview-report.pdf

- Spatial averaging to the UK scale may hide the magnitude of the changes at the regional or local scale.
- Time period (to 2050s rather than to 2080s) may not be sufficient to demonstrate significant climate forcing.

The development of an analytical approach that accurately reflects the natural variability of river flows, as well as the complex interactions arising from water abstraction and discharge, was a substantial challenge. Capturing these dynamics is critical for realistic risk assessment, yet modelling such processes involves intricate hydrological and operational considerations, that are only represented at a very high-level in national-scale datasets.

The risk assessment addresses both chronic and acute water stress. Chronic water stress refers to long-term shifts in patterns indicative of wetter or drier periods within the simulated time series, whereas acute water stress pertains to variations in extreme events, such as episodes of drought. Abstractors will be influenced by both the average (chronic) and extreme (acute) levels of water stress. The former will likely impact longer-term, day-to-day, business decisions and substantial long lead-time adaptation-related infrastructure development. The latter describes the short-term risks to abstractors and their businesses that may also require an emergency response.

Defining drought events (acute water stress) presents challenges. The Intergovernmental Panel on Climate Change (IPCC) typically identifies four categories[35]:

- Meteorological drought: rainfall in a region falls below average levels.
- Agricultural drought: insufficient rainfall or dry soils adversely affects farming including crop growth and yields.
- Ecological drought: limited water availability impacts the local environment.
- Hydrological drought: reductions in water bodies such as streams and reservoirs, which may result from low precipitation, inadequate snowmelt, or other factors.

While droughts are fundamentally linked to meteorological conditions, variables such as elevated temperatures, soil moisture content, land use practices, operational decisions, and seasonal demand can alter the severity and characteristics of droughts and their effects on receptors of interest. This analysis concentrates on those holding surface water abstraction licences, focusing on hydrological droughts and their influence on river flows, and ultimately, on the capacity of abstractors to obtain the required water. More than 25,000 surface water abstractors exist in the UK; data on these abstractors was based upon their licences, which does not include, for example, details on any existing adaptation measures already incorporated or operational practices. The economic impacts of acute water stress have therefore been described qualitatively.

A broad range of future possible scenarios were defined to encompass the wide array of factors influencing water stress, including climate change, policy shifts, and socio-economic trends whilst balancing computational burden.

[35] Seneviratne, S.I., X. Zhang, M. Adnan, W. Badi, C. Dereczynski, A. Di Luca, S. Ghosh, I. Iskandar, J. Kossin, S. Lewis, F. Otto, I. Pinto, M. Satoh, S.M. Vicente-Serrano, M. Wehner, and B. Zhou, (2021) Weather and Climate Extreme Events in a Changing Climate. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1513–1766, doi: 10.1017/9781009157896.013.

The formulation of theories of change to map out the pathways by which water stress could affect economic performance and lead to losses was complex. Each sector exhibits unique sensitivities and dependencies, meaning that generic models were insufficient. The challenge lay in accurately delineating causal connections, feedback loops, and critical thresholds that might trigger substantial economic impacts under different water stress scenarios.

1.1.4 Assessment frameworks and metrics

The project used a widely recognised risk assessment framework, aligned with the CCC's methodology, where risk is defined as the product of hazard, exposure, and vulnerability[36]. This method calculates risk by characterising hazards, such as the likelihood and severity of water scarcity events, assessing the exposure of abstractors and evaluating the vulnerability or resilience of those exposed elements. By combining these components, the approach provides an overview of how and where the impacts of water scarcity may occur across various sectors, sub-sectors and nations in the UK.

In this risk assessment, both the hazard and exposure are captured in a computed metric termed "unmet demand", as described in Box 1-1.

Box 1-1 - Unmet demand – what it is and how it is calculated

Unmet demand was derived for each abstractor considered in the risk assessment from the total volume of water they are licensed to abstract annually spread across the days in the year that abstraction is permitted. Each day the abstractor takes required water, until the river flow scenario is below the 'Hands Off Flow' (HOF) condition on the abstractor's licence, which is a defined low-flow level that an abstractor has agreed to cease abstraction at. When this occurs, abstraction ceases. If no HOF condition is present on the licence, then abstraction ceases when river levels are lower than abstraction intake, i.e., as the river runs dry.

The volume of water required by the abstractor on those days where abstraction is not possible is the daily unmet demand volume. The daily unmet demand is totalled for each year and assumed to represent the unmet demand of all the subsector abstractors in the same catchment (normalised by size of abstractor). A percentage of total water required by each subsector that is unavailable annually is then calculated i.e., % annual average unmet sector demand.

Unmet demand results are integrated with impact pathway models that illustrate the range of different impacts that the assessed sectors are likely to face when experiencing current and future water stress. The economic losses quantified in this analysis do not cover all the aspects of the impact pathways, but only on Gross Value Added (GVA) losses in the relevant sectors. These losses are expressed as Estimated Annual Average Damage (EAAD) (£/year), as described in Box 1-2.

Box 1-2 - Estimated annual average damage

Estimated annual average damages are the economic damage arising from the unmet water demand across the year. This is measured as 'gross value added' (the difference between the value of the final output and the input costs, including taxes, profits and wage costs).

[36] Climate Change Committee (2024) Methodology V2. Shared with WSP in January 2025.

The calculation method varies by broad sector; in the power sector, we consider the additional system cost to the UK from sourcing electricity from more expensive alternative sources when water is not available for specific generation technologies. For industry, we assess production that is foregone because of the unmet water demand. For agriculture, we quantify impacts on yields and quality (based on prices achieved for different grades of produce).

In all cases, assumptions and simplifications are required to aggregate from site-and day-specific impacts that would be felt to estimate effects upon a whole sector based on annualised unmet water demand.

1.1.5 Stakeholder engagement

Numerous stakeholder organisations in the UK use, regulate, manage, and study water resources. Their effective engagement was crucial to this research's success.

A cross-section of organisations from UK governments, regulators, and academia formed a Project Steering Group (PSG) to review and assure project results at key stages. The PSG actively sponsored the project, lending credibility by challenging findings and offering insights into current water resource management issues, regulatory impacts, and future policy development. The PSG provided the overall assurance function for the results of the research.

The Sector Steering Group (SSG) comprised representatives from various UK power, agriculture, and industry sectors, primarily selected from relevant trade associations. Their participation occurred at key decision points in the project to provide sector specific insight to refine the research scope, identify sources, and assess the resilience of current business models to present and future water stress, as well as helping to identify adaptation options.

Semi-structured interviews were conducted with sector experts to enhance our understanding of each sector's vulnerability and exposure to water stress hazards. Following a similar (but qualitative) engagement method as detailed in Chen et al (2024)[37], these interviews were based on a case study of the 2022 drought, with storylines representing alternative ways the event could have unfolded, which can be used to explore plausible worst-case scenarios, helping to develop the impact pathway models. Insights from these discussions also informed the risk assessment methodology. Furthermore, this engagement provided sector perspectives on current and anticipated adaptation measures and the effectiveness of these measures.

1.2 A review of present-day risks and adaptation measures

A Rapid Evidence Assessment (REA) was conducted during the initiation phase of the project to evaluate the impacts and associated costs of water stress, as well as the types and effectiveness of adaptation measures currently implemented to reduce related risks. In total, 77 peer-reviewed academic papers were systematically reviewed and synthesised in accordance with REA screening protocols. The REA findings indicated that the economic sectors examined in this study exhibit varying degrees of vulnerability to both chronic and acute water stress hazards, with exposure, vulnerability, and adaptation effectiveness differing across regions and sectors. Additionally, the REA identified significant data and

[37] Chen et al (2024) Added value of seasonal hindcasts to create UK hydrological drought storylines (NHESS - Added value of seasonal hindcasts to create UK hydrological drought storylines).

evidence gaps, which informed the overall research approach. A summary of key findings for each sector is provided below, with the full REA available as a supporting technical report (see: *Rapid Evidence Assessment, Sectoral Narratives*[38]).

1.2.1 Agriculture

In the UK, agriculture is an economically important sector, contributing c0.5% of Gross Domestic Product (GDP), producing half the food consumed and employing 467,400 people up to the farm-gate[39]. The downstream dependent benefits are also substantial – for example the agrifood and drinks sector in the Anglian region was previously estimated to contribute £34 billion per year to the UK's GVA, sustaining >150,000 jobs and providing 18% of national farm-gate output. UK agriculture encompasses a wide range of activities, from food and non-food crop cultivation to livestock rearing, spread across various regions each with differing agroclimatic and soil conditions.

In the agricultural sector, evidence predominantly highlights acute water stress-induced impacts, with reduced crop productivity (yields and quality) as well as England's irrigation demands projected to rise by 14–30%[40] against declining water supplies. Historical events, such as the 2011 drought, incurred substantial economic losses to UK agriculture (£400 million)[41]. Recent droughts in 2018 and 2025 have highlighted the importance of water supplies for both agricultural irrigation and for livestock, and the need to develop robust adaptations to reduce the impacts of future droughts and water scarcity on this sector.

Irrigated production is shown to be particularly vulnerable. The dry conditions in 2012 alone resulted in £72 million in losses for irrigated potato production in England[42]. As the climate warms, irrigation demand is projected to rise particularly in parts of the UK, such as East Anglia and Northwest England[43]. In areas where irrigation is well-established a changing climate will likely drive further investment in irrigation infrastructure underpinned by greater dependence on on-farm 'high flow' storage to support a transition away from rainfed cropping. However, competition for water resources is intensifying, driven by both climate change and non-climatic factors like population growth, environmental improvements and economic development. Climate change is likely to worsen this competition by creating more arid environments and increasing precipitation variability, which will force agriculture to compete with urban and industrial sectors for land, water, and economic resources[44]. The drought impacts experienced in 2025 are likely to have caused even higher economic impacts, but reported evidence is not yet available.

The REA also drew out important differences for the agriculture sector between the four nations of the UK. For example, the economic importance of barley production for the Scottish alcohol industry. Barley production is crucial to the success of Scotland's whisky and brewing industries, which generate substantial revenues for the country. Whilst the average turnover for all Scottish business was approximately £673,000 in 2018, Scottish distilleries have an approximate annual turnover of

38 WSP (2025) CCRA4: Task 1.2. Rapid Evidence Assessment, Sectoral Narratives.
39 Department for Environment Food & Rural Affairs (2022) Agriculture in the UK Evidence Pack (online). Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1106562/AUK_Evidence_Pack_2021_Sept22.pdf
40 Daccache, A., Weatherhead, E.K., Stalham, M.A., Knox, J.W (2011) Impacts of climate change on irrigated potato production in a humid climate. Agricultural and Forest Meteorology, 151(12), pp. 1641-1653.
41 University of Cambridge Programme for Sustainability Leadership, Anglian Water (2013) Water, Water Everywhere? Available at: https://www.cisl.cam.ac.uk/system/files/documents/water-water-everywhere-scroll.pdf.
42 Akande K, Hussain S, Knox J, Hess T, Hooftman D, Stratford C, Schafer S, Acreman M and Edwards F (2013) The Impacts of Drought in England. R&D Technical Report WT0987/TR. Department for Environment, Food and Rural Affairs Water Availability Division, London
43 Henriques, C., Holman, I.P., Audsley, E., Pearn, K (2008) 'An interactive multi-scale integrated assessment of future regional water availability for agricultural irrigation in East Anglia and North West England'. Climatic Change, 90(1-2), pp. 89-111.
44 Motha RP (2007) Development of an agricultural weather policy. Agricultural and Forest Meteorology, 2–4:303–13

£5.3 million[45]. Given the importance of barley to these industries, any disruptions to its production, whether from climate impacts and/or due to water scarcity, would have serious economic consequences. Maintaining stable barley yields in the future will be essential to preserving the profitability and global competitiveness of Scotland's alcohol industry[46]. Increasing temperatures and reducing rainfall in the future could also reduce cereal yields with increasing dependence on supplemental irrigation needed to buffer drought impacts[47].

1.2.2 Industry

The REA found limited published research on the industry sector. The lack of costed impact data highlights a knowledge gap that was, in part, addressed through collaboration with steering groups and review of grey literature.

The 2018 drought in northern Europe severely impacted Scotland's whisky production, particularly within the River Spey catchment, a crucial area for distilleries. Many distilleries halted operations due to low river flows and high temperatures which led to an insufficient water supply for their operations[48]. This is because whisky production relies heavily on large quantities of water for processes such as mashing and cooling. With river levels falling drastically, distilleries faced a lack of available water, forcing them to pause production to avoid over-extracting from already depleted water sources, which could harm the environment and deplete resources further.

The Environment Agency (2015)[49] estimated, for England, that under a three-year extreme drought in 2050, the food and beverage manufacturing sector would face an economic impact of £750 million. This loss would represent 1.8% of the sector's future GVA and is primarily attributable to supply chain disruption associated with reduced agricultural production. Under the same drought scenario for the chemical and pharmaceutical manufacturing sectors the economic impact was estimated to be £270 million of GVA. This economic loss stems from several factors, including water scarcity, rising energy costs, disruptions in raw material supply, supply chain delays, and the need to comply with stricter environmental regulations. These challenges reduce production efficiency, increase operational costs, and limit output, ultimately leading to substantial financial losses.

Mining and quarrying, along with paper manufacturing, are projected to face heightened water scarcity in areas where these industries are currently located due to a combination of climate change and increasing demand for water from a growing population. In some scenarios, by the 2050s, nearly 10% of water abstractions by the mining and quarrying sector could take place in areas where water supplies are insufficient to meet environmental needs during an average summer, even before accounting for the sector's demands[50].

[45] O'Connor, A., (2018) Brewing and distilling in Scotland - economic facts and figures.
[46] Cammarano, D., Hawes, C., Squire, G., Holland, J., Rivington, M., Murgia, T., Roggero, P.P., Fontana, F., Casa, R., Ronga, D. (2019) Rainfall and temperature impacts on barley (Hordeum vulgare L.) yield and malting quality in Scotland. Field Crops Research, 241(1), pp. 107559.
[47] Clarke, D, Hess, T.M, Haro-Monteagudo, D, Semenov, M.A., Knox, J.W (2021) Assessing future drought risks and wheat yield losses in England. Agricultural and Forest Meteorology https://doi.org/10.1016/j.agrformet.2020.108248.
[48] The Guardian (2019) Scotch on the rocks: distilleries fear climate crisis will endanger whisky production. Available at: https://www.theguardian.com/uk-news/2019/jun/02/scotland-whisky-climate-crisis-heatwave-distilleries-halt-production
[49] Environment Agency, 2015. Water supply and resilience and infrastructure (online). Available at: https://assets.publishing.service.gov.uk/media/5a804f89ed915d74e622db6a/ea-analysis-water-sector.pdf
[50] Climate Change Committee (CCC), 2013. Adaptation Sub-Committee, 2013. Managing the land in a changing climate: Progress Report 2013.

1.2.3 Power

In the UK water scarcity directly affects thermal power plants, which frequently rely on large volumes of water for cooling. During droughts or extreme heat events, water availability decreases, while demand for electricity can increase. Heatwaves also lead to higher water temperatures in rivers and lakes, diminishing the effectiveness of cooling systems, which thermal power plants rely on for dispersing waste heat[51].

Climate-induced changes in river flow regimes are already having substantial impacts on hydropower generation, particularly for run-of-river systems common in the UK and Ireland. As precipitation patterns shift, seasonal river flows become less predictable, modifying the energy output. Droughts and prolonged dry periods intensify this issue by further limiting water availability[52]. Assessments show that climate change induced streamflow alterations, and differences in abstraction licences by 2080 will result in a reduction in annual water resource availability for hydropower in Wales (−2.1%) and Northern Ireland (−1.9%), compared to increased availability in England (+3.0%) and Scotland (+12.9%), and no changes in Ireland[53]. However, for the UK, research indicates possible production increases of up to 2% by the end of the century under various warming scenarios, though outcomes range from negative to positive depending on rainfall variability and climate models used. A -2% change in UK hydroelectric generation, currently averaging 5,786 GWh/year, could equate to an economic impact of approximately £12 million annually, underscoring the financial implications of climate variability for the sector[54].

For renewable technologies such as wind and solar there is no evidence in the literature of direct impacts on generation associated with water stress. For the emerging hydrogen sector, both green and blue hydrogen rely on large amounts of water for production and cooling. For green hydrogen, it is estimated that by 2050, process water requirements for high hydrogen production scenarios in the UK could exceed 400 million litres per day (Ml/d), with a sharp increase from 2030. Cooling water requirements are also high, with estimates ranging from 10,000 Ml/d to 39,000 Ml/d by 2050[55]. Whilst blue hydrogen does not use water in the production process, cooling requirements are expected to rise from 880 Ml/d in 2030 to 6,858 Ml/d by 2050 in a medium production scenario[55]. With increasing drought risks, these technologies could face water shortages. Shortages could almost halve the amount of water available for these technologies, leading to projected annual costs exceeding £100 million[56].

Adaptation strategies include enhancing flexibility in water resource management through optimised reservoir storage and operational adjustments, deploying hybrid cooling systems for power stations to reduce freshwater use, and tapping into unconventional water resources such as treated wastewater and desalinated seawater. While these strategies are well-documented, quantitative evaluations of their effectiveness remain underexplored.

51 Byers, E.A., Coxon, G., Freer, J. and Hall, J.W. (2020) 'Drought and climate change impacts on cooling water shortages and electricity prices in Great Britain', Nature Communications.
52 ASC (2016) UK Climate Change Risk Assessment 2017 Evidence Report – Summary for Scotland. Adaptation Sub-Committee of the Committee on Climate Change, London.
53 Dallison, Richard & Patil, Sopan & Williams, A. Prysor. (2021). Impacts of climate change on future water availability for hydropower and public water supply in Wales, UK. Journal of Hydrology: Regional Studies. 36. 100866. 10.1016/j.ejrh.2021.100866.
54 Watkiss, P., Cimato, F., Hunt, A. (2021). Monetary Valuation of Risks and Opportunities in CCRA3. Supplementary Report for UK Climate Change Risk Assessment 3, prepared for the Climate Change Committee, London.
55 AECOM, (2024) National Framework for Water Resources – Water and Energy. Environment Agency.
56 Ward, J. and Wentworth, J. (2021). Water supply resilience and climate change. UK Parliament POST.

2. Baseline risk assessment method

The baseline risk assessment methodology has been developed to evaluate the amount of water demand that may be "unmet" as the climate reaches Global Warming Levels (GWLs) of 1.5ºC, 2.0ºC and 2.5ºC of warming above pre-industrial levels. The assessment considers other possible drivers including growth in water use due to sectoral changes in the 2050s (see Chapter 2.1.6) as well as the anticipated changes in environment policy and planned public water supply actions that will influence abstractors and river flows through to 2059.

This assessment uses the most up-to-date abstraction information to estimate whether, in the future, existing abstractors are likely to have their demand for water met. The assessment also investigates how the drivers of change could also impact more extreme acute water stress events such as droughts in terms of their severity and duration.

The following chapters outline the workflow, data, and methods used for estimating unmet demand and identifying substantial water stress events such as droughts.

2.1 Input data and preparation

2.1.1 Abstraction data sources

The data used to both select and then model the abstractions came from the most up-to-date abstraction information at a national scale. For England this is available from the Environment Agency, using their Water Resources GIS (WRGIS) tool: a spatial database of river flows, abstractions and discharges used for undertaking assessments of abstraction pressures and water availability in England for national-scale water resources planning[57]. The WRGIS provides the underpinning evidence for NF2.0 making this assessment as consistent as possible with the framework and therefore with the Environment Agency's licensing information and Environmental Destination[58] planning in England. Thus, conforming to our guiding principle to maintain and enhance consistency with other concurrent national scale water resources planning.

In CCRAs 2 and 3, similar tools were developed and used for Wales[59], Scotland and Northern Ireland. These tools have been updated and reused for this assessment and are based around a flow duration curve mass-balance.

Some abstraction licences extend back several decades. Typically, newer licence records contain greater detail and are more accurate compared to historical records. In certain instances, historic licences do not specify the precise location within a water body from which an abstractor sources water.

[57] Environment Agency (2021) Appendix 2: Longer Term Environmental Water Needs (Enhanced Scenario). Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/958640/Appendix_2_WRGIS_and_environmental_scenarios__for_water_stress.pdf

[58] Environmental Destination is the umbrella term used by the Environment Agency for returning abstractions in England to a sustainable level by reducing or removing licences from existing abstractors.

[59] A previous version of the WRGIS was available for Wales from 2015, before devolution of regulation to Natural Resources Wales.

Consequently, it is not always possible to determine whether a particular abstractor can access their desired water resources, or to assess their vulnerability to climate change.

The tools were developed for use in national scale assessments and are not a substitute for detailed simulation-based hydrological, hydrogeological or water resources modelling at a local scale.

2.1.2 Defining the sectors and sub-sectors

A sector typology has been developed to help structure the assessment. The typology at the highest level is broken down into the three principal economic sectors of: agriculture, industry and power. These sectors have been further segmented into sub-sectors, see

Table 2.1 for details, to facilitate a comprehensive analysis of the distinctive attributes within each.

The sectoral typology is structured to capture shared exposure and vulnerability to relevant hazards, as well as to identify potential adaptation strategies available to each group. This categorisation was established by considering both the sectors with the highest current water demand and those emerging industries projected to require substantial water resources as technological advancements occur.

Table 2.1 Sector and sub-sector breakdown

Industry	Power	Agriculture
Food & drink (e.g., dairies, breweries and wine)	Hydropower	Irrigated production (outdoor and protected)
Chemicals & petrochemicals	Fossil fuels & nuclear	General agriculture (Including livestock and poultry
Paper & pulp	Renewables (wind, solar)	Aquaculture
Mineral products, extractives and other large manufacturing	Biomass	
	Energy from waste	

2.1.2.1 Agriculture

The agricultural sector refers to direct water abstractions to support field-scale (outdoor) and protected (covered) irrigated crop production, general agriculture (including livestock and poultry), and aquaculture. Crop irrigation is highly water consumptive compared to general agriculture and aquaculture and therefore was the focus of this assessment.

Representative crops were selected for outdoor agricultural (potatoes, carrots, onions) and protected horticultural (strawberries) production. These crops were chosen to reflect the high importance of irrigation for both maximising crop yields but also for quality. Potatoes and field vegetables account for approximately 50% and 25% (each) of the total national irrigated area and volumes of water applied[60]. Strawberries represent a particularly high-value crop where irrigation is essential given the protected nature of production – most commercial production is under polytunnels or glass and therefore 100% dependent on irrigation.

[60] "Irrigation water strategy for UK agriculture and horticulture" by Knox, J.W., Kay, M.G., Holman, I.P., and Hess, T.M. (2020). Available at irrigation-strategy-2020.pdf.

2.1.2.2 Industry

The industrial sector refers to the manufacturing industry in the UK, covering several sub-sectors. From a water consumption perspective, major industrial sectors include chemicals, food & drink, mineral products (which includes steel and extractive sectors like mining), paper & pulp. These sub-sectors made up more than 90% of the industry abstractors[61].

Abstraction sizes range from small to large, across the various sub-sectors. For example, distilleries (within food and drink) have a larger number of small units in northern UK, whereas steel has predominantly larger units. Abstraction licenses in Industry also have a geographical variance, with Wales having a large, concentrated mining sector. Water use intensity and growth rates also vary by sub-sector. This highlights the heterogeneity within Industry which has been covered, with research covering the national picture as well as regional effects.

2.1.2.3 Power

The power sector, in the context of this research, refers to the generation of electricity for the public and industry supplied via the national grid. Private power generation has been excluded. The representative locations for modelling were selected according to the following criteria:

- Sites contributing power to the national grid are identified by filtering abstraction licence details.
- Generation technology types are included to provide comprehensive sectoral coverage: unclassified power, energy from waste, fossil fuels, biomass/fossil fuel co-fired, hydropower, and renewables (wind and solar). Not all sub-sectors are present in every country or region.
- The selection aims to represent all UK regions and a variety of climatological and hydrological locations where feasible.
- Abstraction sizes, ranging from large to small, are covered to include infrastructure of national significance as well as smaller plants of potential local relevance.

2.1.3 Defining regions

The following regional breakdowns were applied, from which a percentage of each region's sub-sectors were selected and modelled (see Figure 2-1 and Figure 2-8 to Figure 2-10):

England - divided into regional water resources groups: Water Resources South East (WRSE), West Country Water Resources (WCWR), Water Resources North (WRNorth), Water Resources East (WREast), and the English counties within Water Resources West (WRWest - England)

Wales - separated by the Welsh counties within Water Resources West and the remainder of the country: Western Wales, Eastern Wales (also termed WRWest - Wales).

Scotland - identified in accordance with the three regions for which climate summaries are provided by the UK Met Office: West Scotland, East Scotland and North Scotland.

Northern Ireland - kept as a single whole region: Northern Ireland (whole).

[61] WIREs Water (2014), 1:207–217. doi: 10.1002/wat2.1012

Figure 2-1 Defined regions of the UK

2.1.4 Selecting reference sites and abstraction licences

Assessing risks to all sector abstractors across the UK was not computationally feasible. As an alternative, a selection of representative abstractors was chosen to analyse unmet demand at specific reference locations from across the regions defined in Chapter 2.1.3. The results for these reference locations were then aggregated to catchment, national, and UK levels. These reference locations consisted of surface water abstractions specifically licensed for supplying the identified sub-sectors and were selected to represent typical sub-sector abstractors, or in some cases, substantial individual abstractions in more remote locations. As an example, three types of reference sites were:

- Typical sector locations (e.g., the heavily irrigated production area in Suffolk and Essex in South-East England – Figure 2-2).
- Locations with several substantial abstractions from different sectors within one river network (e.g., the industrial area on the River Trent near Derby – Figure 2-3).
- Substantial individual abstractions by a specific subsector in an isolated area (e.g., the large manufacturing facility near Stirling - Figure 2-4.

These different distributions of reference sites helped facilitate the extrapolation of unmet demand results to other sites with similar characteristics.

Figure 2-2 Heavy irrigated production hotspot in the South-East Suffolk and Essex areas

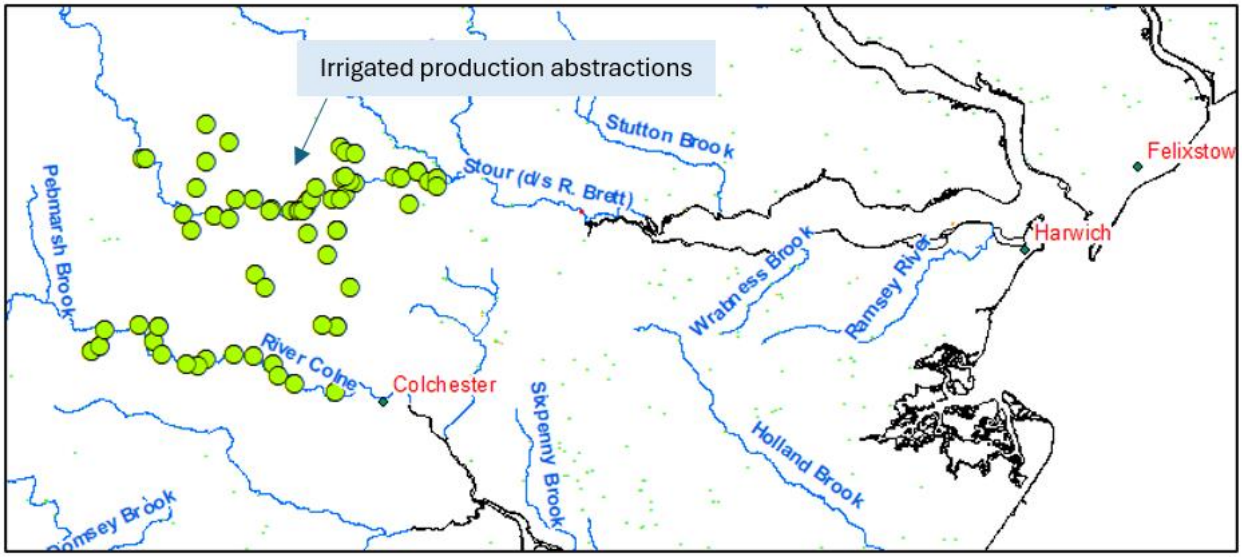


Figure 2-3 Mixed heavy industry and power area on the river Trent near Derby

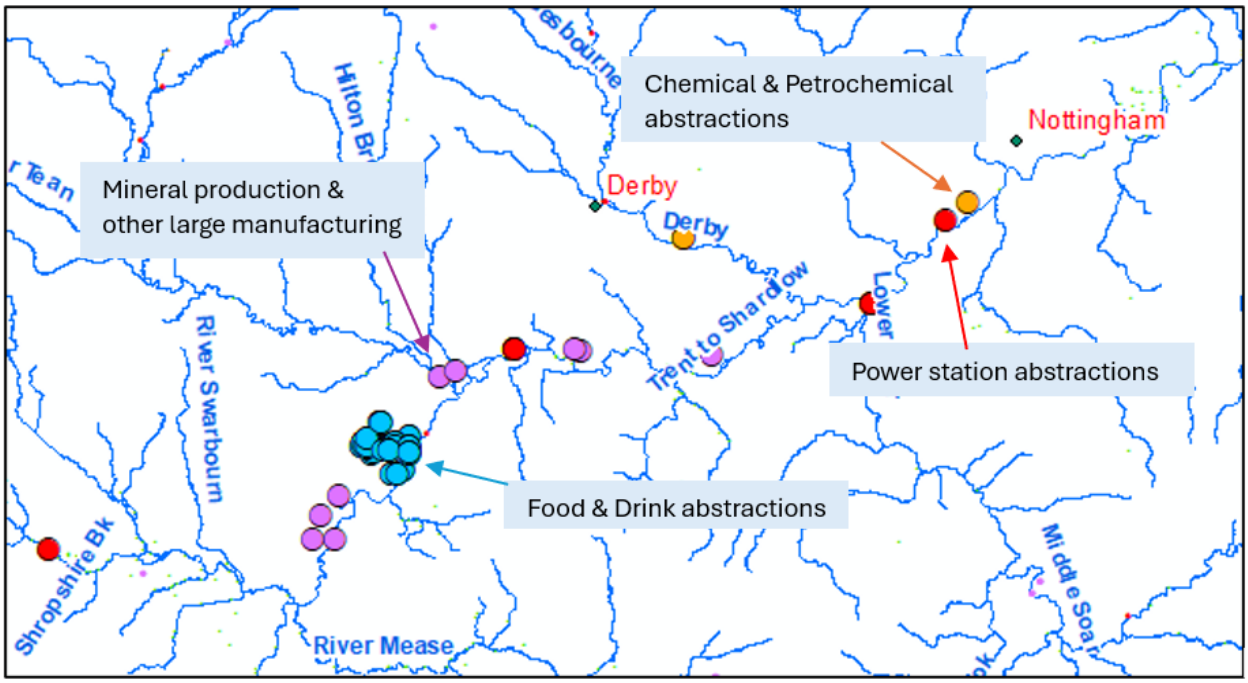
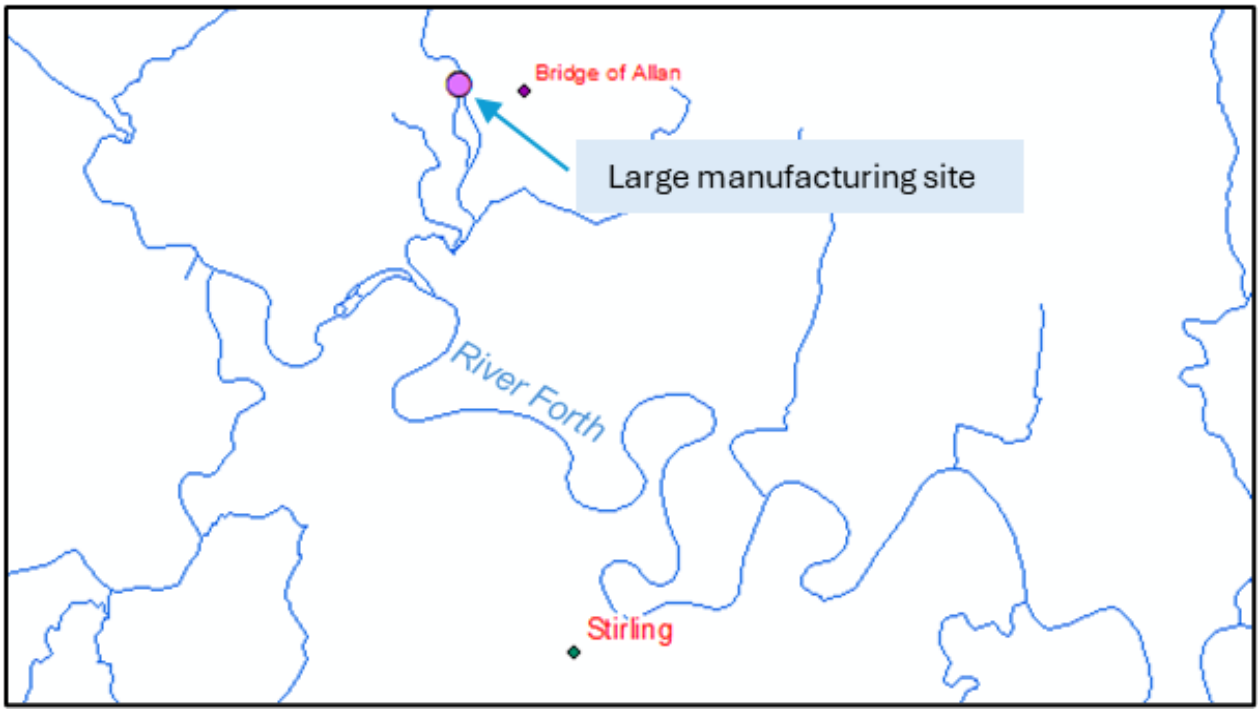


Figure 2-4 Individual large manufacturing abstraction North of Stirling in Scotland



Figures 2.5 to 2.7 display the surface water abstractions in operation for each sector and subsector across the UK, as well as those selected for modelling, for: industry (Figure 2-5), agriculture (Figure 2-6) and power (Figure 2-7).

Figure 2-5 **Industry abstractions locations selected for modelling (a) by megalitres per day, (b) separated by subsector typology (the smaller dots in map (b) represent existing abstractions not selected for this study, the larger circles are those selected)**

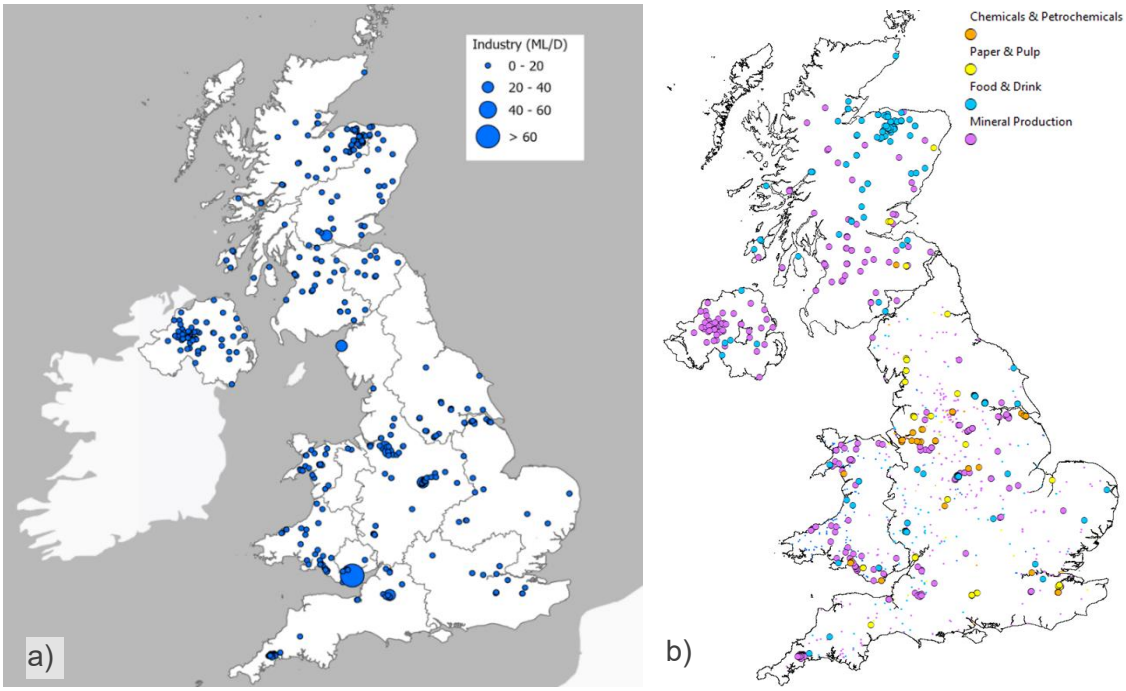


Figure 2-6 **Agriculture abstraction location selected for modelling (a) megalitres per day (b) separated by subsector typology (the smaller dots in map (b) represent existing abstractions not selected for this study represent existing abstractions not selected for this study, the larger circles are those selected)**

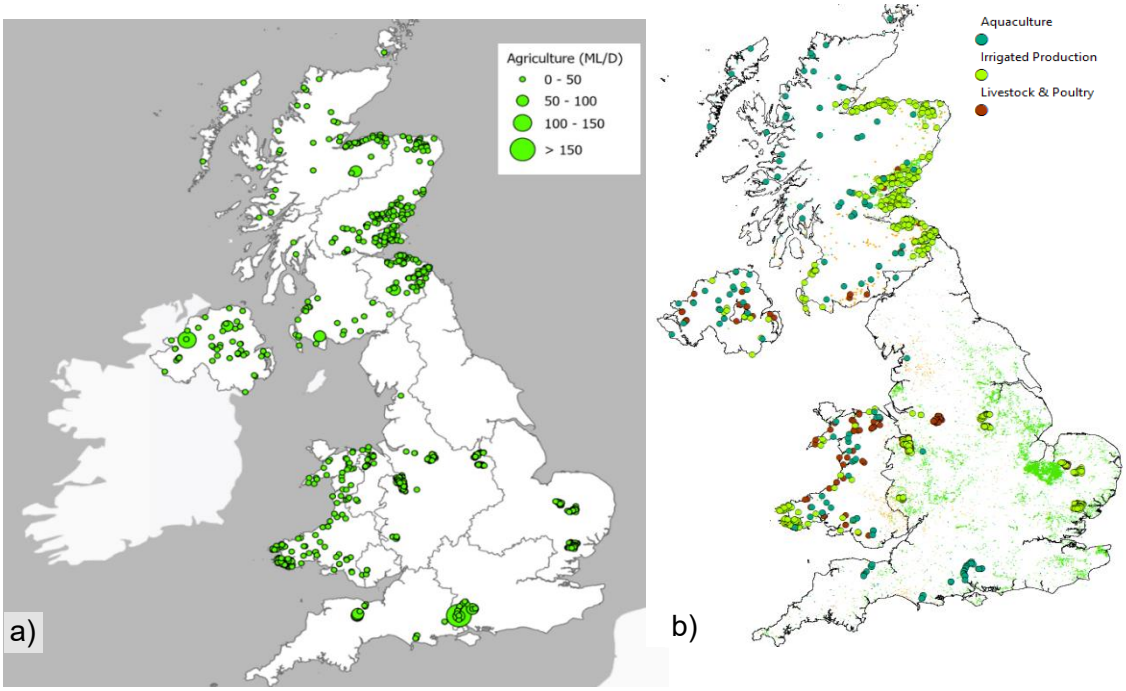
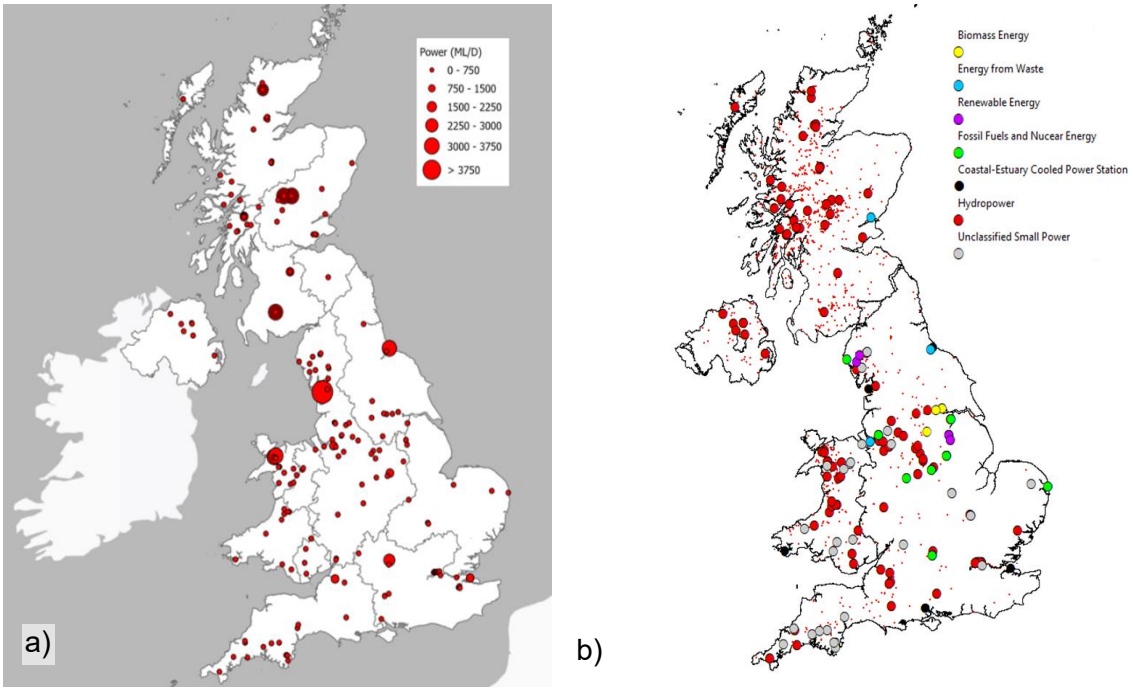


Figure 2-7 Power abstractions selected for modelling displayed (a) by size (megalitres per day) and location, (b) separated by subsector typology (the smaller dots in map (b) represent existing abstractions not selected for this study, the larger circles are those selected)



2.1.4.1 Abstractions selected

The number of surface water abstractions in existence for each sector and sub-sector across each nation is shown in Figure 2-8 to Figure 2-11, including the number of abstractions selected for modelling, as a percentage of the total in operation. The total absolute amount of water abstracted by the selected abstractions (in megalitres per annum) is also given.

As the more substantial abstractions were selected for modelling, the figures illustrate how they amounted to between a quarter and a third of the total water abstracted across the sectors and nations.

Figure 2-8 England - total number of surface water abstractions for each sub-sector (in megalitres per annum) and the number selected for modelling (as a percentage of total abstractions)

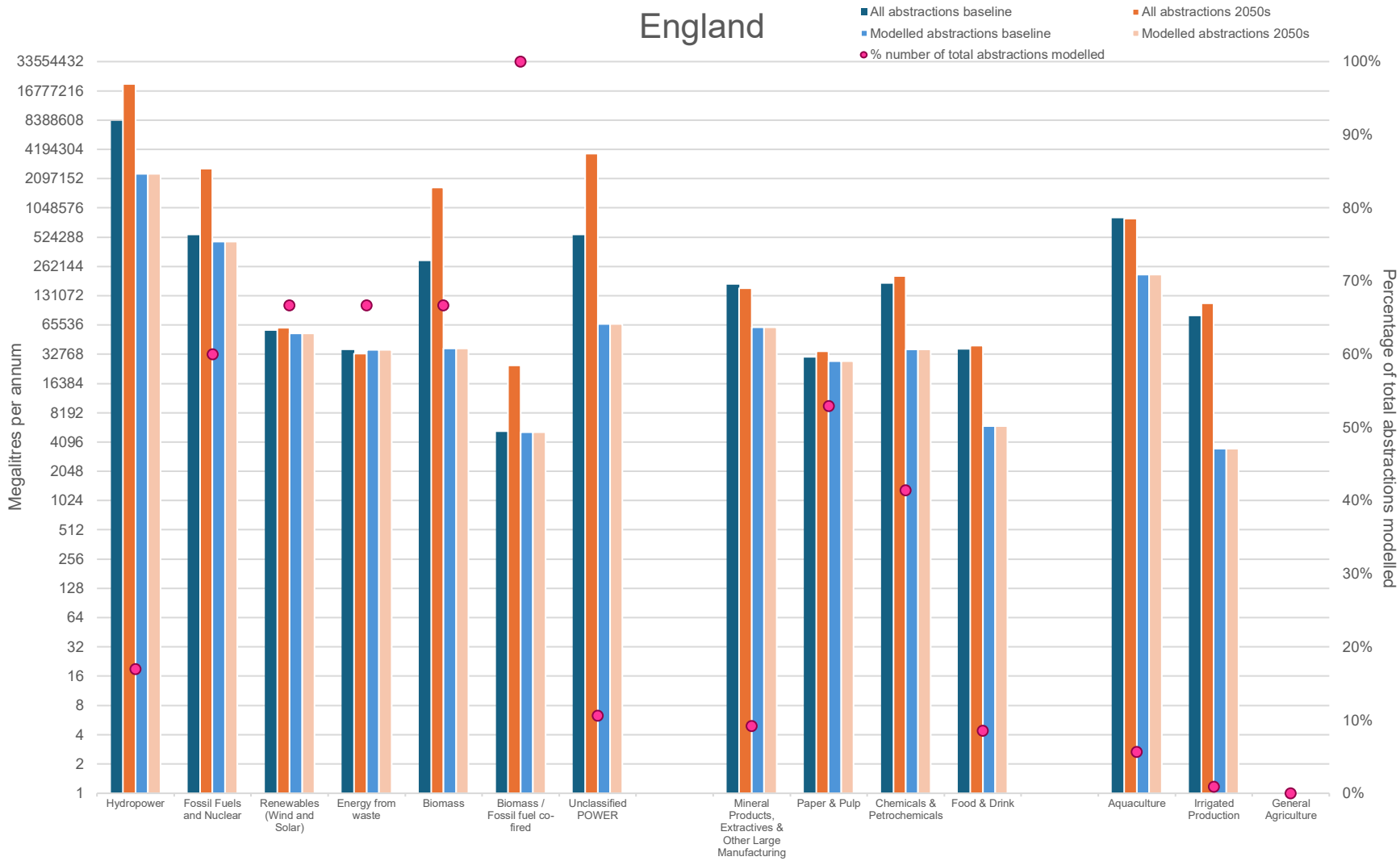
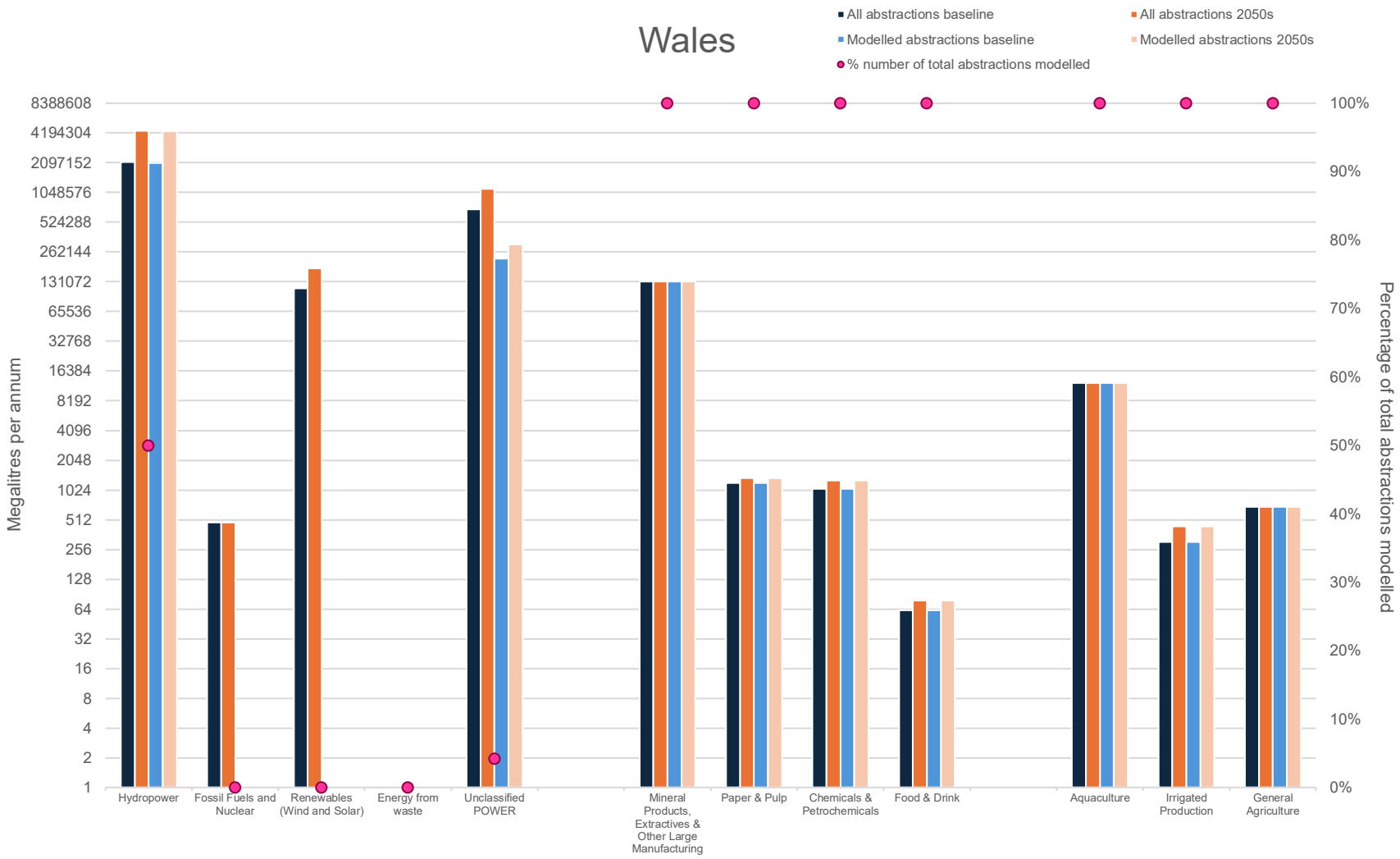


Figure 2-9 Scotland - total number of surface water abstractions for each sub-sector (in megalitres per annum) and the number selected for modelling (as a percentage of total abstractions)

Figure 2-10 Northern Ireland - total number of surface water abstractions for each sub-sector (in megalitres per annum) and the number selected for modelling (as a percentage of total abstractions)

Figure 2-11 Wales - total number of surface water abstractions for each sub-sector (in megalitres per annum) and the number selected for modelling (as a percentage of total abstractions)



2.1.5 Flow data

The WRGIS suite of tools provide information on river discharges and natural flows in the form of flow percentiles that describe the distribution of a waterbody's flow over time; further details are provided in Box 2-1.

Box 2-1 - WRGIS for England and the devolved nations

The WRGIS[62] (version 2024) is a Microsoft Access database and GIS tool developed for England, but it also holds data for Eastern Wales (the counties within Water Resources West regional group). It is primarily a series of large data tables holding data on aspects such as surface water abstractions, groundwater abstractions, sewage treatment works discharge returns and other more complex impacts such as reservoir storage and inter-catchment water transfers. It also includes a national dataset of the natural river flow levels of every waterbody in England and eastern Wales (calculated using Qube[63]). This allows natural river flow levels, human abstractions and discharges (what we term artificial influences) to be modelled simultaneously in a holistic assessment of river flow.

The dataset is updated and improved through an iterative process of upload from Catchment Abstract Management System (CAMS) Ledgers[64]. CAMS Ledgers are spreadsheets used by the Environment Agency to review and improve information on natural flows, abstraction pressures and other flow influences, as well as assessing water availability and regulating abstraction licences.

Surface water and groundwater models are used to characterise flows and impacts in CAMS Ledgers, and this conceptualisation is then reflected in the water balance calculations in the WRGIS. The WRGIS applies four flow percentiles 'snapshots' (Q95, Q70, Q50, and Q30). These 'snapshot' assessments are calculated independently and mathematically describe the distribution of flow levels over time.

Quantifying the balance between the available resource and the demand for abstraction is complex. Several caveats and assumptions are discussed in HR Wallingford (2015)[65] and although the WRGIS has undergone several updates in the last 10 years, the principle, that the tool is designed for national-scale assessment rather than detailed localised understanding of water resources, remains.

For the devolved nations, alternative WRGIS databases were utilised. These are, for Wales, the WRGIS15 version (as it includes data for the whole of western Wales as well as eastern), and for Scotland and Northern Ireland a WRGIS-lite version[66], which are two databases developed to mimic all the functionality of the more comprehensive WRGIS databases, and were developed in 2020 as part of CCRA3. Each WRGIS version was updated with the latest abstraction data where possible, but largely maintained the natural flows and assumptions applied when the databases were developed.

The WRGIS data tables were adjusted to match each specified scenario under assessment, adjusting abstractions and discharges (based on growth) and natural river flow levels (based on climate change) to develop a unique dataset aligned to each scenario (see Chapter 2.1.7). These datasets were

62 WIREs Water (2014), 1:207–217. doi: 10.1002/wat2.1012
63 Wallingford HydroSolutions. Qube. https://www.hydrosolutions.co.uk/software/qube/
64 Environment Agency (2014, updated in 2025) Abstraction licensing strategies (CAMS process). Available at: https://www.gov.uk/government/collections/water-abstraction-licensing-strategies-cams-process
65 HR Wallingford (2015) CCRA2: Updated projections for water availability for the UK. Final Report. Authored by: Eleanor Hall, Ralph Ledbetter and Chris Counsell for the Committee on Climate Change.
66 UK Climate Change Committee (2021) Independent Assessment of UK Climate Risk (CCRA3) Available at: https://www.theccc.org.uk/publication/independent-assessment-of-uk-climate-risk/

subsequently adapted into timeseries models and run through the unmet demand assessments (see Chapter 2.2).

Additionally, it should be noted that whilst the WRGIS15 for Wales and WRGIS-lite tools for Scotland and Northern Ireland comprise of data, used in a similar way, these other tools have not been subject to the same scrutiny, quality assurance or subsequent development of the WRGIS for England. As a result, there is a lower confidence in the underpinning data for Wales, Scotland and Northern Ireland, compared to that for England.

2.1.5.1 Climate change impacts on river flows

Generating the climate change adjusted future river flow time-series

There are a limited number of UK-wide scale datasets that provide future flows and align with the CCC's methodology[67], that recommends the use of either the UKCP18 regional or local projections. A review of possible climate change data for use in this assessment is provided in more detail in Appendix E.

It was determined that climate change flows provided by OpenClim data derived from the SHETRAN hydrological model (Smith et al., 2024)[68] was the most appropriate due to: 1) the large number of gauged sites included 2) it uses a distributed hydrological model and more representative projections in groundwater catchments and 3) potential evapotranspiration and precipitation data is bias corrected. The model is based upon the 12-member UKCP18 regional climate change projections, aligning it with the CCC's methodology, but is subject to the same challenges that affect the UKCP18 regional climate change projections as discussed in 1.1.3.

2.1.6 Future scenario variables

2.1.6.1 Overview

This assessment considers water stress through to the 2050s. Climate change is the focus of this assessment, however there are other important factors changing during this time which need to be incorporated to understand the impact on water stress, these include:

- **Environmental policies**: the water environment depends upon the availability of water to thrive. Policies are advancing the protection of these environments, which can result in the reduction or removal of existing abstractions which are determined to be leading to harmful impacts on the environment. The key policy considered is Environmental Destination in England.
- **Public water supply**: water companies seek to secure a reliable, resilient and wholesome supply of water for their customers. They develop and implement long term plans to ensure this. Their operation and planned changes can impact upon water availability and distribution across catchments.
- **Sectorial and population growth**: a growing sector will likely lead to more water demand.

[67] Climate Change Committee (2024)
[68] Smith, B.A., Birkinshaw, S.J., Lewis, E., McGrady, E. and Sayers, P. (2024) 'Physically based modelling of UK river flows under climate change', Frontiers in Water, 6(October). Available at: https://doi.org/10.3389/frwa.2024.1468855.

Several scenarios have been developed to represent 'Central' and 'High Vulnerability' future pathways as required by the CCC's methodology[69] and to help explore the sensitivity of the results to possible future uncertainties in these drivers for change (see Chapter 2.8). The timeframe for this assessment aligns with the CCC's methodology, to end 2050s. The full set of scenarios developed can be found in Appendix C.

2.1.6.2 Climate futures

The CCC's methodology defines two global climate futures:

- Central: 1.5ºC global warming in 2030s and 2ºC in 2050s; and
- High: 2ºC global warming in 2030s and 2.5ºC in 2050s.

To account for uncertainty in UK climate change associated with any given global warming level, a set of possible climate change impacts for the UK are represented by selecting different 20-year samples of scenario flows projected using the 12 members of the UKCP18 RCM ensemble. The year that an RCM member hits these global warming levels is defined using the 20-year average of global warming from the global model driving that individual RCM member, and these years are different for each member.

The baseline in this assessment is driven by the assumptions and data within the WRGIS and is therefore a future, modelled baseline of 2027 when anticipated abstraction licence reductions will be enacted. As many of the UKCP18 RCMs have exceeded present-day warming by the year 2027, a current global warming level (CGWL) of 1.3 degrees above pre-industrial levels was selected as a central case for the present-day year.

The CGWL was determined from Met Office (no date)[70] publication using the definition within Betts et al., 2023[71], with 10 years of observations prior to 2023, and 10 years of UKCP18 RCP4.5 warming into the future, providing a window around 2023. This approach was selected because it represents the most up-to-date evidence that is consistent with the UKCP18 projections, and a central window, aligning with the definition of the warming levels for the 1.5, 2.0 and 2.5 degrees of warming.

Table 2.2 shows the central year for each of the RCM members for the four warming levels used in this assessment. A 20-year averaging period around the central year is used. It demonstrates that there is overlap between the global warming periods.

[69] Climate Change Committee (2024)
[70] Met Office (no date) Indicators of Global Warming. Available at: https://climate.metoffice.cloud/current_warming.html (Accessed: 12 June 2025).
[71] Betts, R.A., Belcher, S.E., Hermanson, L., Tank, A.K., Lowe, J.A., Jones, C.D., Morice, C.P., Rayner, N.A., Scaife, A.A. and Stott, P.A. (2023) 'Approaching 1.5C: how will we know when we've reached this crucial warming mark?', Nature, 624(July), pp. 33–35.

Table 2.2 Regional climate model ensemble member central year for warming levels over a 20-year averaging period

RCM ensemble member	1.3 degrees	1.5 degrees	2.0 degrees	2.5 degrees
RCM01	2012	2017	2027	2038
RCM04	2010	2014	2024	2034
RCM05	2013	2017	2029	2040
RCM06	2011	2016	2026	2036
RCM07	2010	2015	2028	2039
RCM08	2011	2016	2029	2040
RCM09	2008	2012	2025	2034
RCM10	2013	2018	2029	2039
RCM11	2010	2015	2026	2036
RCM12	2016	2021	2032	2042
RCM13	2009	2014	2026	2036
RCM15	2011	2016	2029	2041

2.1.6.3 Growth projections

Growth is represented by the potential increases or decreases of existing abstractions and discharges resulting from factors such as population growth, industrial or agricultural development, implementation of water efficiency measures, and other aspects influencing water use, including expanded use in power generation.

The factors used in this study were derived from the Environment Agency's ongoing sectoral demand studies and projects, examining changing demands from the energy industry and agricultural sectors,[72] [73] and aligns with the factors recently applied in the Environment Agency's NF2.0[74]. The factors are presented in Appendix A.

These growth factors were derived for England. No equivalent was available for the devolved nations, so they have also been adopted for the other UK Nations. This provides a consistent level of growth in water demand across the UK by the 2050s.

2.1.6.4 Environmental policies

Environmental Destination is a policy for water resources which has been developed for England, and it outlines the Environment Agency's environmental ambitions to improve the hydrological health of rivers. It identifies where, and by how much, water abstraction needs to change to achieve and maintain a healthy water environment, both now and in the future.

Environmental Destination is developed by defining the long-term environmental outcomes needed to ensure abstraction from rivers, lakes, wetlands and estuaries that is environmentally sustainable, both to

[72] EA (2020), Water resources national framework, Appendix 4: Longer term environmental water needs (publishing.service.gov.uk)
[73] Wood Ltd (2020), Understanding future water demand outside of the water industry, work completed by Wood Environment & Infrastructure Solutions UK Limited
[74] WSP (2025). WRGIS NF2 – Refreshing the National Framework for Water Resources – Second Assessment Report

address current unsustainable abstraction and future pressures[75]. Further detail is provided in Appendix B.

The NF2.0 examined several different scenarios of Environmental Destination, calculating where and by how much abstractions would need to be reduced to meet a given set of environmental conditions. These conditions were largely in the form of a raising or relaxing of the levels of flow in the different waterbodies deemed acceptable to the environment (known as the Environmental Flow Indicators (EFIs)). For instance, a 'Current' Environmental Destination scenario reflected an implementation of EFI levels aligned with current regulatory levels (based on the River Basin Management Plan (RBMP) cycle 3 objectives for 2027), whereas a 'Full' Environmental Destination scenario reflected higher EFIs in certain waterbodies to afford more flow to the environment for priority catchments, such as Sites of Special Scientific Interest (SSSIs), salmon or chalk streams.

In this project, the two NF2.0 Environmental Destination scenarios were assessed to examine the full range of Environmental Destination impact on the risk assessment:

- Current – changes to water abstraction required to meet RBMP cycle 3 objectives in 2027 based on the Environment Agency's current regulatory approach.
- Full – changes to water abstraction required by the 2050's to ensure greater environmental protection for SSSI rivers and wetlands, principal salmon and chalk rivers. It also assumes good status will be achieved for all Water Framework Directive (WFD) waterbodies (including those currently exempt) in line with government policy.

For both the central and high climate scenarios the 'current' Environmental Destination scenario was applied. The 'full' Environmental Destination scenario was then tested within the sensitivity assessments. The abstraction reductions required to meet the environmental flow conditions of each scenario were first assessed and implemented for each waterbody in England, prior to carrying out the unmet demand assessments. This ensured that appropriate groundwater and surface water abstractions were reduced or switched off around the country to align with the government's plans for Environmental Destination.

2.1.6.5 Public water supply plans

Each water company produces a Water Resources Management Plan (WRMP) which sets out a comprehensive framework for securing water supply and protecting environmental resources over a 25-year horizon. The most recent to be produced was in 2024 (WRMP24). These initiatives are currently being delivered through the UK Water Company Asset Management Planning (AMP) Cycle 7 (2020-25), with increased implementation planned into AMP8 (2025-30).

The next AMP Cycle (8) includes emphasis on:

- Planned (but not yet committed to) delivery of strategic resource options (SROs), such as new reservoirs, interconnectors, and recycling schemes.
- Achieving net zero emissions and meeting climate change targets.
- Improving the resilience of water systems.

[75] Environment Agency (2025) Environmental Destination Technical Report. Available at: https://assets.publishing.service.gov.uk/media/6847ff5189d002b886e787ad/Developing-the-revised-Environmental-Destination-figures-technical-report.pdf

2.1.7 Assessed scenarios

A central scenario has been developed which balances uncertainty and forms the backbone to this assessment, the following key variables have been incorporated:

- **Central climate future**: 1.5ºC in 2030s and 2ºC in 2050s.
- **Growth and sector consumption**: included, in line with other assessments.
- **Environmental Destination:** current commitments only**.** Full ambition is not committed to and could change.
- **Water company plans**: currently committed to AMP7 plans only. Future plans are not committed to and could change.

The variables (such as a high climate future), have been systematically tested through sensitivity analysis, see Chapter 2.9. Further information on the scenarios is provided in Appendix C.

2.2 Method for assessing unmet demand

Unmet demand refers to the volume of water that an abstractor intended to withdraw but was unable to access, either due to licensing restrictions or limitations in available river flows. To calculate this metric, it is necessary to determine:

- The total volume of water available (i.e. the natural flows).
- The volume of water abstracted and discharged in the same waterbody.

The following chapters summarise how each of these have been determined, to calculate the unmet demand.

2.2.1 Estimating total water availability

Assessing water availability at each abstraction location requires the development of a time series of naturalised historical and projected future flows. For each sector reference location (see Chapter 2.1.4 for further information), an appropriate SHETRAN site has been identified to guide the provision of natural flows (the donor site). In England and eastern Wales, selection of the donor site is primarily based on its proximity to the relevant abstractor. In western Wales, Scotland, and Northern Ireland, a single SHETRAN site is chosen to represent each UKCP18 river basin[76].

To adjust the SHETRAN donor's modelled flow series to the selected abstractor location, the naturalised flow duration curve (as available in the WRGIS) is utilised. This adjustment is done using a process known as quantile-quantile mapping: a statistical technique used to align the statistical distribution of one dataset with another by matching the quantiles in their respective distributions, see Box 2-2 for more information. The quantile-quantile mapping was developed over a 1990-2010 reference period and then used to adjust the modelled flows from each climate projection for the full projected time-series.

The result of this step is a naturalised flow series for each climate model ensemble member over the full period. Full details of this process are available in Appendix E

[76] The difference in the methodological approach is due to the way in which the underpinning Water Resources GIS tools operate.

2.2.2 Incorporating water demand

Most watercourses have activities which impact their flow conditions, such as other abstractions and discharges; it is therefore necessary to adjust the natural flows for these. There are several additional considerations, such as:

- The consumptive nature of upstream abstractions (is the water removed or returned to the system for example when it is used in cooling).
- Any licence conditions, such as HOF, which means abstractions must stop when the river level drops below a defined point.
- Planned changes in licences, such as those imposed through Environmental Destination.

The aggregate alterations to the natural flow resulting from these factors are collectively referred to as modified net impacts.

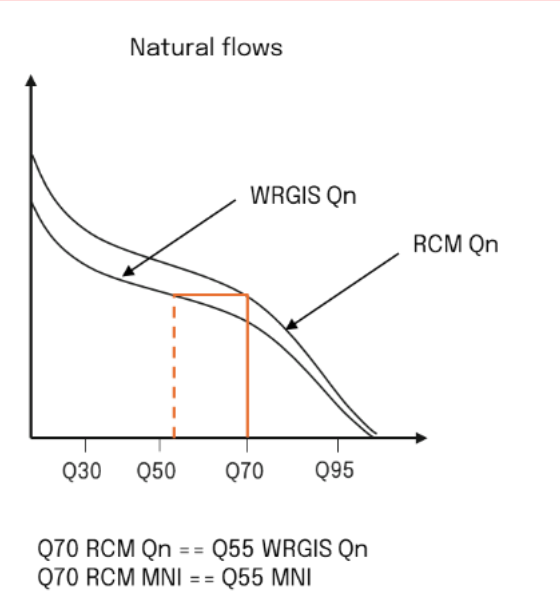
The NF2.0 incorporates two climate projections from the Enhanced Systems Modelling Environment (ESME) dataset in its assessment: RCM04, representing generally wet conditions, and RCM11, representing generally dry conditions.

The effect of licence reductions due to Environmental Destination varies according to the RCM used. To estimate scenario flows for the ten additional RCMs in the UKCP18 ensemble and capture a wider range of potential unmet demand, RCM7 and RCM13 were also processed using the NF2.0 WRGIS models. These models were chosen to represent wetter and drier ends of the Enhanced Future Flow and Groundwater (eFLaG) spectrum, respectively.

Results from these four WRGIS RCM runs are utilised to develop a statistical relationship between modified net impacts and natural flows, enabling estimation of modified net impacts in the remaining RCMs for the 2050s. The outputs of this step are multiple timeseries of historical and future ‘scenario’ flows for each of the selected sites.

Box 2-2 - Estimating the modified net impacts for the 2030s

The 20-year time slice was selected from the SHETRAN flows which corresponded to when each UKCP18 RCM reaches a GWL of 1.5°C (representative of the 2030s). This time slice of naturalised flows was converted into a flow duration curve. Quantiles from the WRGIS flow duration curve for the 2030s scenario were matched to those in the SHETRAN flow duration curve and then used to extract values from the modified net impacts.



RCM = UKCP18 regional climate model

MNI = Modified Net Impacts

Qn = Natural Flows

2.2.3 Estimate unmet demand

For each reference location, the unmet demand was calculated by comparing scenario flow with abstraction demand from the relevant licence(s), factoring in the licence consumptiveness and hands-off-flow requirements.

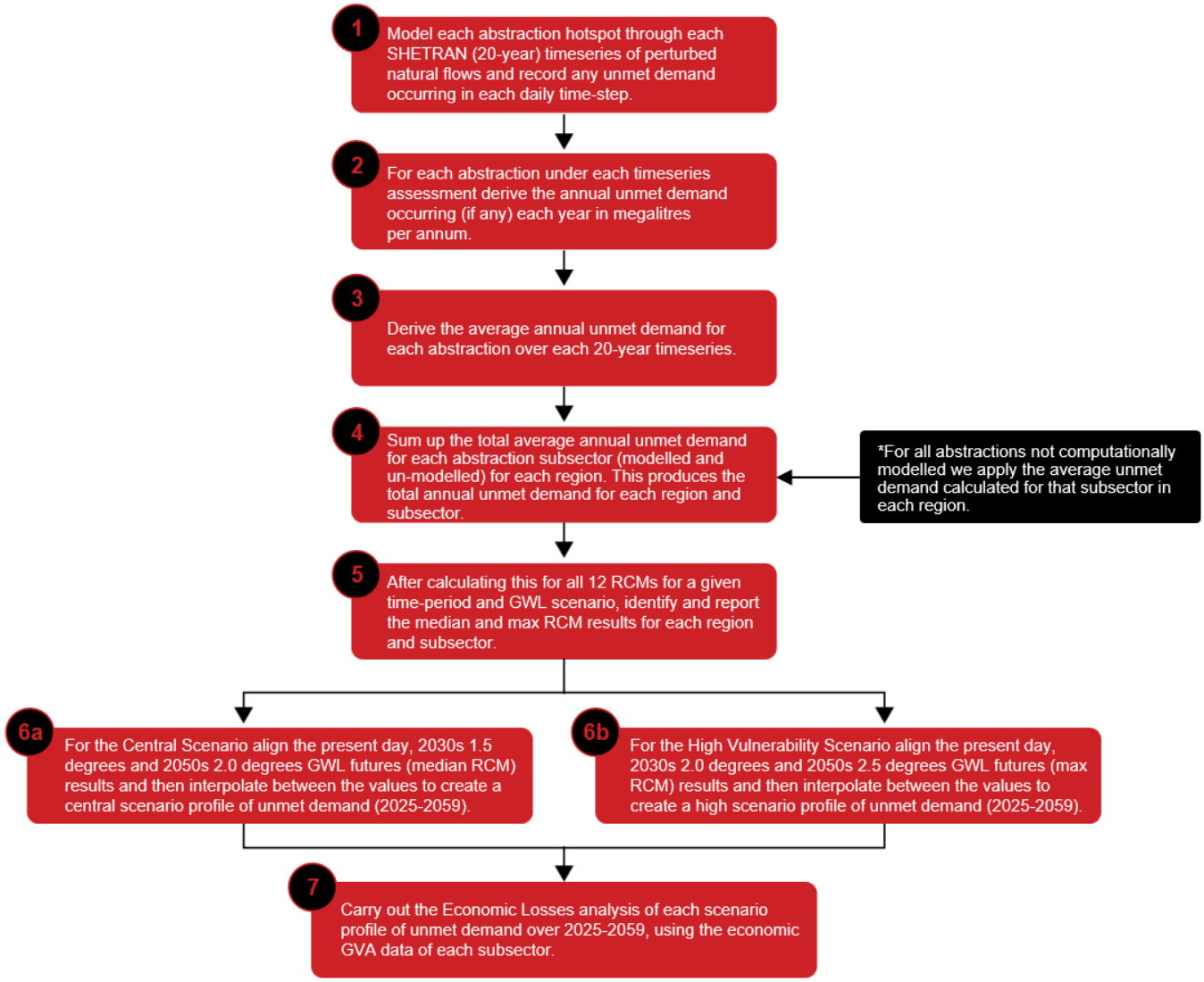
It was assumed that the abstractor's demand is always equal to its recent actual demand (i.e. the average demand over the last <6 years, spread across the days where abstraction is permitted in their licence and according to the monthly profile held within the WRGIS for RCM04).

Where sites are in the same catchment, they are determined sequentially from upstream to downstream to account for cumulative impacts.

2.3 Assessing chronic water stress

The unmet demand results are subsequently aggregated up into national and UK-level projections of unmet demand for each subsector for use in the economic losses assessments. This process is presented in Figure 2-12.

Figure 2-12 Flow diagram showing the steps of aggregating unmet demand results into water stress following unmet demand modelling assessments



The average unmet demand (water stress) for abstractions not directly modelled was determined based upon the average according to:

- The licence conditions (if there were HOF rules).
- The region.
- The subsector.

If abstraction data for a particular sub-sector was unavailable in an associated region, the average from the two nearest regions was applied. For example, when lacking chemical and petrochemical data for Water Resources East, we used the mean unmet demand from Water Resources South-East and North to estimate likely impacts in Water Resources East.

2.4 Assessing acute water stress

The chronic water stress assessment examined average modelled levels of water stress, while the acute water stress assessment considers extreme events of water stress. Different sectors and their sub-sectors may experience varying levels of exposure and vulnerability to different types of acute water stress event, even within the same geographic area, due to their specific water usage requirements. The acute water stress assessment has focussed on 'hydrological droughts', specifically the influence on flows and the impact this has on an abstractor's ability to abstract.

To assess water stress, an inventory of "weather-events" was created for each abstraction licence. These events represent periods used to compare water stress levels across scenarios. The river flows at each reference location for each RCM were used to evaluate a monthly flow anomaly as a deviation from the baseline long-term average at each site over each 20-year period[77], along with the corresponding unmet water demand. Events were ranked by flow deficit intensity or unmet demand volume, allowing for analysis of stress duration, timing, and severity.

The acute water stress method was developed to examine both the timing and duration of events. The inventory includes events of varying durations and start months tailored to each sector's operational patterns. For power, events of 3, 6, 9 and 12 month duration, starting in January, April, July and October were included. For agriculture, the inventory includes events of 3, 6, 9 and 12 month duration, starting in March and October. For Industry, the water stress events include 1, 2, 3, 6, 9 and 12 month duration, starting in January, April, July and October. This was to explore how the timing of water stress throughout the year can affect abstractors differently, depending on the point in time at which they require water (for example, rain-fed crops are more vulnerable during the spring months when root systems are still developing) and the duration of the water stress event.

These acute water stress events were computed at a site level and aggregated to a regional scale by summing the event driven unmet demand across sites for the same scenario and RCM, providing a regional level estimate per scenario and sub-sector.

The use of the full 12-member RCM ensemble means that for each region, scenario, sub-sector and "event" combination there are some 240 data points describing the aggregated unmet demand. We have defined an acute water stress event as the average of the top 10 worst events, measured in terms of "weather-event" driven unmet demand value, at a regional scale, for a given scenario.

2.5 Key assumptions and methodological limitations

There are large uncertainties at several stages in the workflow developed to assess both chronic and acute unmet demand due to the modelling approaches and availability of data. This includes, but is not limited to the:

Regional climate models

RCMs represent the best source of information as to what the future climate will look like; however, they are well reported not to capture extreme dry periods well, with the following specific considerations:

- The sample size of 12 models is small.

[77] Based upon the baseline for 1.3ºC warming, average for that period, the reference mean

- Long periods of dry or wet conditions are not simulated well.
- Bias correction method applied potentially influences future changes.
- Spatial averaging to the UK scale may hide the magnitude of the changes at the regional or local scale.

Acute stress

Water stress events will be assessed based on duration, timing, intensity, frequency, and spatial extent, but specific return periods will not be calculated. Although extreme value analysis could technically be used, the high uncertainty, especially for infrequent events, meant that the assessment would not have been robust.

Future uncertainty

The future is uncertain. While the best available data has been used to inform key variables, uncertainty persists. The effects of these variables on the assessment outcomes have been evaluated using sensitivity analysis.

Data

The determination and extrapolation of flows follow a simplified process. This simplifies the complex operational practices and influence of storage on regulated and heavily modified water bodies.

Unlike the public water supply sector, the power, industry and agriculture sectors have less stringent regulations for water use, except for the abstraction and discharge licencing process. As a result, the available data for these sectors on either current or planned future water use is poor: limited to the abstraction licences themselves and the annualised returns data that abstractors provide to the relevant regulator on their annual water use. A key assumption is the split of abstracted water equally across the year.

This assessments methodology has been aligned to the NF2.0 and WRGIS tool. These tools represented the best sources of information to base this project upon; however, they were not designed for estimating how water demand may change in the future. They do not generally include either future planned abstractions or detailed, complex rules for heavily regulated rivers. The unmet demand represents the current abstractors with growth factors, rather than specific details on actual demand.

Scale

Due to the data and tools available, along with the objective of this study, the methodology has been determined to provide results suitable for assessment at a national scale. The methodology is not suitable for site specific assessment of risk or adaptation requirements.

2.6 Estimating the economic impacts of chronic water stress

2.6.1 Approach overview

The assessment of economic impacts began by mapping impact pathways. These illustrate the range of different impacts that the assessed sectors are likely to face when experiencing future water stress. The economic losses quantified in this analysis do not cover all the aspects of the impact pathways, but only direct GVA losses in the relevant sectors. Appendix F sets out the methodology used to quantify

economic losses in full detail. This chapter provides an overview of the method, assumptions and limitations of the approach.

Economic losses are measured in terms of GVA, which is the economic value-added during production processes (i.e. the difference between the value of the final output and the input costs, including taxes, profits and wage costs). Economic losses are calculated in real terms, in 2024 price base Great British Pounds. In some cases, it may be that economic losses are greater than value added (i.e. inputs to production are also wasted), but for most of the kinds of economic damage that are expected to occur because of chronic water stress, value added is the best proxy for overall economic losses. Economic impacts are calculated at a national level. UK-level economic losses are the sum of the losses across the four nations.

Rather than calculating economy-wide impacts, specific methodologies were developed that best captured the potential economic losses from key sectors (see Chapter 2.1.2) that are most adversely affected by water stress. This means that the assessment represents the aggregation of these sub-sectors, not the sector in its entirety. Estimated annual average damage is the economic damage arising from the unmet water demand across the year. The calculation method varies by broad sector:

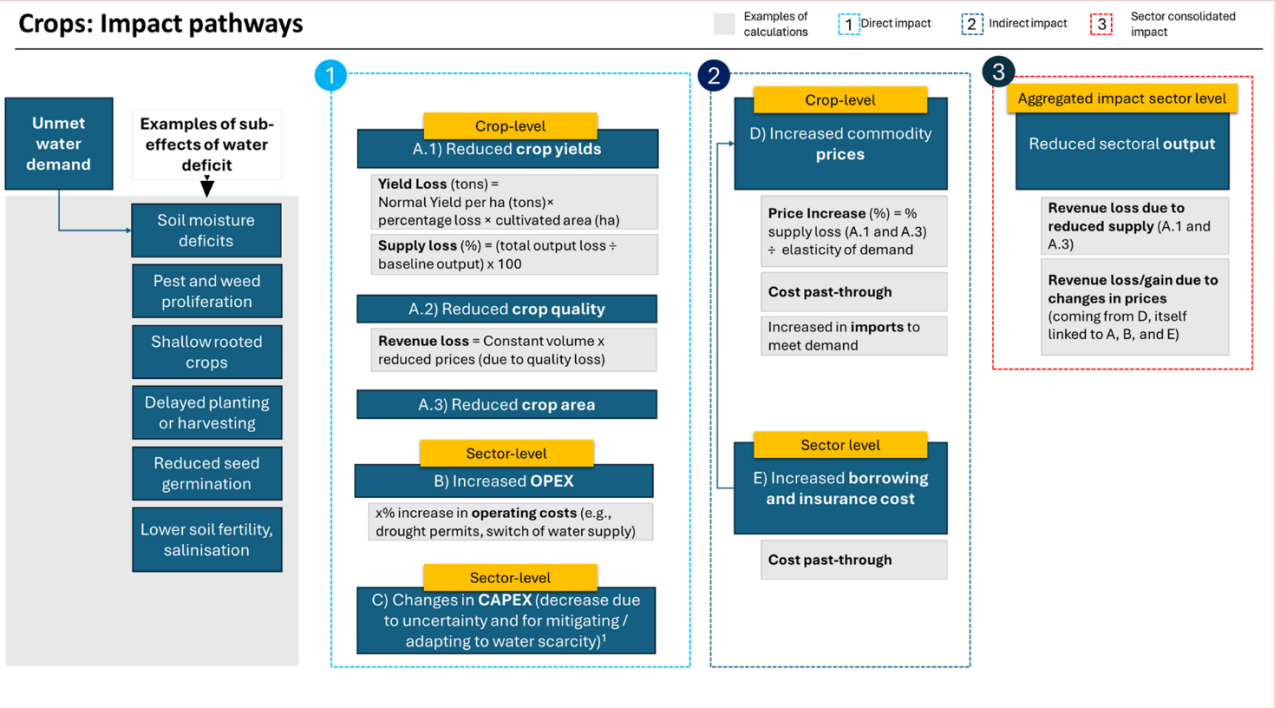
- For the power sector, it is the additional system cost to the UK from sourcing electricity from more expensive alternative sources when water is not available for specific generation technologies.
- For industry, we assess production that is foregone because of the unmet water demand.
- For agriculture, we separately quantified the impacts on both crop yields and quality (based on prices achieved for different grades of produce). An overview of these methods is provided below.

In all cases, assumptions and simplifications are required to aggregate from site- and day-specific impacts that would be felt to estimate effects upon a whole sector based on annualised unmet water demand (see Chapters 2.5 and 2.6.6, respectively).

2.6.2 Impact pathways

To inform the quantification of economic losses, impact pathways were developed for each broad sector, which set out the different channels through which unmet water demand affects the sector, and ultimately translates to changes in output for that sector. Not all these pathways are quantified in the economic analysis, as the focus is on the ultimate direct output losses that are incurred because of the unmet water demand. These impact pathways are used here to frame the economic loss quantifications, and during the research were used to make sure that major impacts were not missed because of the quantification methods that were developed. Box 2-3 presents the impact pathway for crops as an example.

Box 2-3 - Crop impact pathway



Impacts on crops include reduced yields, reductions in the quality (and therefore achievable market price) of crops due to water stress, and changes in domestic prices that result from market dynamics. Impacts at the firm and sector levels are increases in operating costs as a result of changes to production processes (including changing water supply away from direct abstractions), increases in capital expenditures (CapEx) (e.g. to invest in new infrastructure to provide more reliable water sources and to allow water to be used more efficiently) and increases in borrowing and insurance costs as a result of exposure to greater production risks.

2.6.3 Agriculture

As discussed in Chapter 2.1.2.1, the selection of representative crop commodities was made based on the following criteria:

- Irrigation: Given that unmet water demand in agriculture primarily results from irrigation abstraction restrictions, it was essential to select the most important crops that are dependent on irrigation. Without irrigation, water scarcity would have limited direct effects on yields and quality.
- High-value product: The selected agricultural products should account for a substantial proportion of the UK's agricultural sector by area and production value.
- Regional coverage: Where possible, the selected products should be cultivated across all nations.

Taking these factors into account, four crops were selected for analysis: potatoes, carrots, onions, and strawberries. Although animal-based products, such as raw milk, are of high value within UK agriculture, the sector is not in the large part directly dependent on surface water abstraction – for example, grass, used for feeding animals currently makes minimal use of abstracted water for irrigation.

The economic loss calculation derives the annual GVA losses from the relative annual unmet water demand figures. Unmet water demand is assumed to translate into a proportion of the relevant product receiving no water for irrigation (i.e. a subset of the crop bears the entire impact of scarcity, rather than sharing losses across the entire crop within a given nation). Unmet water demand is assumed to be spread equally (in percentage terms) across all agricultural products. Water stress impacts each product in terms of crop yield and quality losses were based on Morris et al. (1999)[78]. This evidence provides the most recent estimates of the attribution of yield and quality losses, by crop types. Whilst it is not that recent, the reported split in losses is considered unlikely to have changed substantially.

2.6.4 Industry

A substantial share of UK industrial activity has economic loss quantified, categorised into four sub-sectors:

- Food & drink.
- Mineral products, extractives & large manufacturing.
- Paper & pulp.
- Chemicals & petrochemicals.

These sub-sectors are those which are most dependent upon abstracted water. The impact of water scarcity on industry is modelled as linearly proportional to the relative unmet water demand. For instance, a 5% annual unmet water demand results in a corresponding 5% economic loss within the sector. This approach assumes that industries currently have minimal resilience to minor shortages and substantial unmet water demand does not lead to permanent closure of production facilities, only temporary shutdowns. For more on this key assumption, see 2.6.6, below.

2.6.5 Power

In the power sector, water is commonly used for cooling thermal power plants – including fossil fuel, biomass, and nuclear facilities – as well as during the condensing process. Based on the expected future evolution of the electricity grid in the UK, and the water usage of different technologies, the quantification of economic loss centres on three; hydropower, biomass & waste, and gas fired turbine plants.

Electricity generation technologies can substitute for one another in the case of water scarcity. On that basis, damages are calculated based on the additional cost incurred in switching to the next-best (and next-lowest cost) like-for-like technology. Each of the three technologies (biomass, hydropower, gas-fired turbines) are dispatchable; biomass and hydropower are substituted for additional gas-fired generation. Since there are no other dispatchable generation technologies available higher up the cost curve, it is assumed that gas-fired generation would instead be replaced by imported electricity. The analysis assumes that future generation is reduced in a linearly proportional way because of unmet water demand, i.e. unmet water demand of 1% of total water demand reduces generation from the relevant technology by 1%. Cost differentials are constructed based on DESNZ projections of the future Levelized Costs of Electricity (LCOE) from the different types of power plant.

[78] Morris, Jl & Weatherhead, Keith & Mills, Jane & Dunderdale, J. & Hess, Tim & Gowing, David & Sanders, C. & Knox, Jerry. (1999) Spray irrigation cost benefit study.

2.6.6 Key assumptions and limitations

Climate change can increase river flows, as well as cause water stress. This assessment has only considered the impacts of water stress on losses, not any potential gains (e.g. for hydropower from increased flows), or losses due to the adverse impacts of having too much water (e.g. flooding).

This study has been limited to determining the direct impacts of water stress. The indirect impacts, for example of lost power, on the nation could be substantially larger.

The adopted methodologies are necessary simplifications, reflecting available data from the underlying water demand modelling and the supporting data, assumptions and methodologies that have been drawn from academic and grey literature.

The most important simplification is the linear assumptions around economic loss in Industry sectors. While many studies use a proportional approach, the elasticity of output with respect to water varies; for example, Jenkins et al (2021)[79] assumes all manufacturing sectors have an elasticity of 0.19, and mining & quarrying has an elasticity of 0.18, while EA (2016)[80] uses the same unitary (1) elasticity assumed in this work.

The adoption of unitary elasticities in this project is based on

1. The feedback provided by the SSG that industry, in particular water-dependent subsectors, will not be able to manage anything more than minimal water scarcity before experiencing temporary closures. This suggests that the Jenkins et al assumption that water is a factor of production that can be readily substituted for capital or labour is not appropriate in the sectors evaluated.
2. The fact that lesser elasticities such as those used in Jenkins et al. are applied to broader sectors, rather than the specific water-intensive sub-sectors considered in this analysis, which are likely to have much higher elasticities of output with respect to water than the broader sector. Essentially, the approaches taken in the literature either assume that water as a factor of production can be perfectly substituted by capital or labour (leading to low estimates of elasticity of output with respect to water) or that water cannot be substituted at all by capital or labour (leading to higher estimates of elasticity).

Given these divergent methodologies, it was felt to be more appropriate when assessing the risks from water stress to assume that water cannot be substituted as an input to production, a view that was supported by stakeholder engagement.

Economic losses are calculated based upon unmet annual water demand – the chronic drought analysis does not consider how this unmet demand varies across the year (so a 12-month 8% shortage of available water and 1-month 100% shortage would incur the same economic losses).

Unmet demand is based on the best available information on the licence holders as discussed in Chapter 2.1.1. This means that it is not possible to incorporate current operational and resilience measures that individual abstractors may have to deal with any existing water shortages.

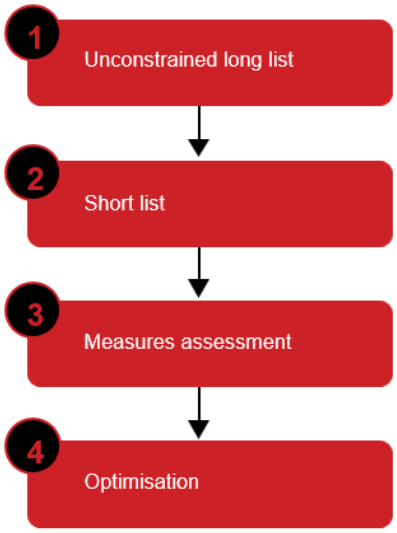
[79] Jenkins, K, Dobson, B, Decker, C & Hall, JW 2021, 'An integrated framework for risk-based analysis of economic impacts of drought and water scarcity in England and Wales', Water Resources Research, vol. 57, no. 8, e2020WR027715. https://doi.org/10.1029/2020WR027715

2.7 Adaptation options appraisal

2.7.1 Approach overview

The appraisal of adaptation options followed the steps highlighted in Figure 2-13.

Figure 2-13 Process for the appraisal of adaptation options



The assessment began with the compilation of a long list of adaptation measures identified for each sub-sector through extensive literature reviews (including water company water resource management plans) and insights from subject matter experts, including input from the SSG and Project Sector Leads.

All adaptation measures were systematically categorised by overarching type (e.g., structural and physical, social and institutional), sub-type (e.g., engineering and built environment under structural and physical, behavioural under social), objective (supply management or demand management), sector, and scale (e.g., system-wide, including catchment scale, or site-specific). Further details are presented in Appendix H.

The long list of measures was short-listed using the following questions:

- Do the measures have a direct and quantifiable impact on reducing water demand/ increasing water supply?
- Do the measures have direct and quantifiable costs?

Each of the short-listed measures was parameterised, including water saving or augmentation potential, associated costs (capital, annual operation, and maintenance), sector applicability and uptake rates, adaptation measure lifespan, delivery timeframes, and wider benefits such as carbon reduction and biodiversity enhancement. The assessment relied on both published literature and contributions from the SSG and Project Sector Leads. Given the scope and nature of the analysis, considerable uncertainty and variability exists among key parameters.

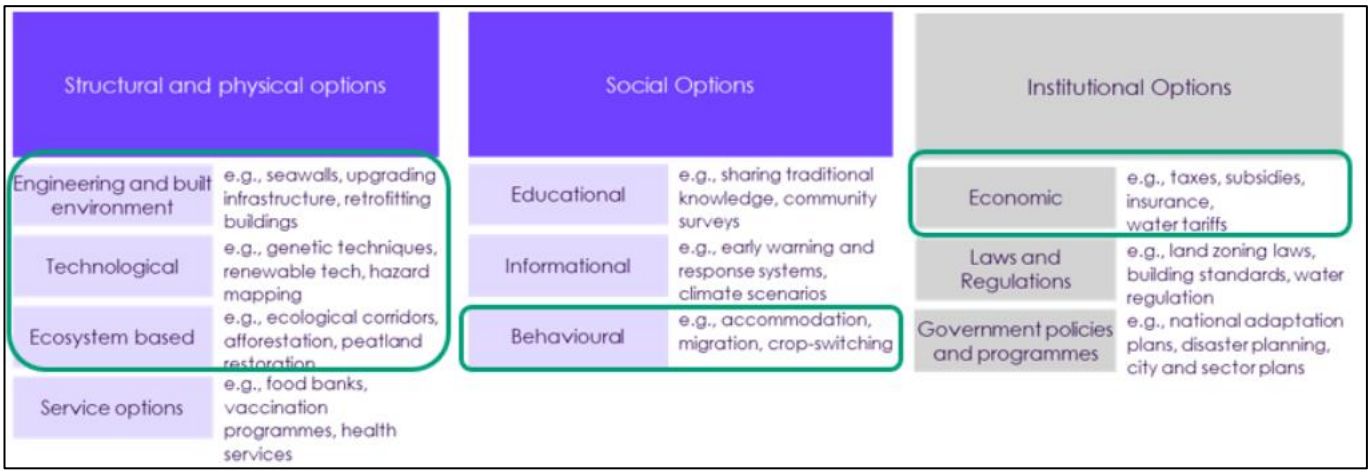
2.7.2 Types of individual adaptation measures

A wide range of adaptation measures across different sectors have been considered in the study, covering both demand and supply management options. All adaptation measures have first been

classified in terms of their overarching type and sub-type, in line with the CCC typology (adapted from the IPCC, see **Figure 2-14** below), including:

- Structural and physical (e.g. Engineering and Built Environment).
- Social (e.g. Behavioural).
- Institutional (e.g. water trading).

Figure 2-14 Types and sub-types of adaptation measures from the CCC methodology



In terms of the scale, adaptation measures have been categorised as:

- Site and sector specific measures – such as onsite water storge, implementing precision irrigation.
- Catchment / ecosystem scale measures – such as wetlands, bank infiltration, swales and percolation basins. Such options are mainly indirect adaptation measures that would promote more infiltration into the ground (replenishing groundwater) and support rivers during periods of drought, allowing abstractions to continue longer.
- System-wide measures – these are large scale options, such as desalination plants and water transfers. They will come at a large cost but yield substantial water volume. These solutions have been identified from water company and regional group plans where they have been considered but not selected. In the context of this assessment, a proportion of the water resources benefit has been assumed; as an example, by developing a strategic water transfer less water would need to be abstracted for public water supply, reducing water stress on other abstractors. The costs of this water have been factored, i.e. if 5% of the water yielded from a water transfer, the cost (CapEx and Operational Expenditure (OpEx)) would be 5% of the total.
- Institutional measures– these measures are focussed on optimising water use through practices such as water trading.

Many system and catchment level measures, such as water transfers, desalination plants, and the removal of accumulated sediments in reservoirs, are included as part of public water supply investments, with a small percentage of water (direct or indirect) allocated to other sectors. Although this represents a minor portion of the total, it can serve as a relevant component when smaller, site-specific, and more cost-effective measures have already been implemented.

The list of short-listed adaptation measures and their typology is summarised in Appendix H.

2.7.3 Measures assessment

2.7.3.1 Adaptation

All short-listed adaptation measures (except institutional options) have been assessed using a wide range of assessment criteria. The quantitative assessment criteria included:

- **Cost-effectiveness ratios** (£/Ml) using equivalent annual costs of measures. This is calculated based on:
  - **Costs of implementing adaptation measures** (including CapEx and OpEx): unit costs have been collated and ranges used to reflect uncertainty. Depending on the individual adaptation measure, unit costs were expressed in different units e.g. £/ha of land, £ per m^3 of water, £ per site etc. and converted into £/m^3 of water saved/ supplied. For system adaptations, costs have been assigned which are proportionate to the benefits provided, rather than the total measure cost. For example, if 5% of the water volume provided by a desalination plant is released, this comes at the cost of 5% of the capital and operational costs.
  - **Risk reduction**, i.e. effectiveness of different adaptation measures to reduce unmet demand through reducing water demand or increasing water supply; this criterion is quantified in terms of estimated water saved or supplied (Ml/d) for each option.
- **Scale of applicability** beyond baseline uptake rates for each adaptation measure. Uptake rates have been expressed as a range and represent additional further uptake potential of different adaptations over and above current applications (where applicable). Sectoral applicability of all adaptation measures has been defined as well as the scale, i.e. site/catchment/system wide measures.
- **Feasibility and capacity** for deployment and lifetime of all adaptation measures. Some adaptation measures have a long lead in time to implement, e.g. 5 to 10 years before they could become operational, and this is accounted for when developing cost-effective adaptation packages.

Parameters were determined from a variety of sources, such as published literature and industry specialists. A summary of uptake rates, time to complete, and a summary of water saving/adding potential of individual adaptation options is presented in Appendix H.

The results of the assessment of individual adaptation measures including water saving/ adding potential and associated costs by sector by country have then been subject to optimisation to develop cost-optimal adaptation packages.

2.7.3.2 Institutional measures

The assessment of adaptation measures included an illustrative appraisal of an institutional measure entailing water trading. The aim of this option was to explore the efficiency in distributing licences between different businesses in different regions (with no changes to overall total water availability). It is noted that this is a highly simplified exercise produced for illustrative purposes only and has assumed that the market design does not cost businesses anything. The benefits of this approach would require a

detailed assessment, incorporating the true constraints around water trading, such as relative location of abstractions along a waterbody.

The assessment was caried out in the following steps:

- Step 1: use data on i) total desired water quantity by sector/ region; ii) unmet demand by subsector for each region; iii) met water demand by subsector/ region and calculate value of unmet demand (£/l of water) by sector by country.
- Step 2: calculate total value of met demand.
- Step 3: maximise the value of met demand based on £/l considering unmet demand per subsector/ region. There are some sectors which would benefit from such trading and some sub-sectors which would face increased costs, but the overall benefit of water reallocation would be positive.

Box 2-4 - Water Markets in Australia

Australia is a world leader in the establishment and management of water markets. In 2018-19, Australian water markets generated $5.2 billion in turnover, reflecting their scale and economic significance[81].

The most active water market is in the Murray-Darling Basin[82], worth around $4 billion annually. Its high degree of hydrological connectivity and large number of users in the basin creates the necessary pre-conditions for water trading. Trades can be for entitlements or allocations. Entitlements are ongoing rights to a share of water from a water resource, whilst allocations are the volume of water allocated to an entitlement each year (usually expressed as a percentage of entitlement). Trades could be set up to be temporary (i.e. trading the allocation to cover a season) or a permanent transfer of water access rights (i.e. the entitlement). Trade restrictions exist to limit the volume of water that can be traded from one water system to another, to ensure future supply and protect the environment[83].

Water licence trading in the Murray–Darling Basin has led to substantial net benefits. Water is an asset to many irrigation businesses, resulting in net proceeds from selling water, lower water prices and more efficient use of water in relatively more productive activities[83] Water trading has enabled reallocation of water to higher value uses, such as almonds and cotton[84]. The Australian Bureau of Agricultural and Resource Economics and Sciences has estimated through modelling the benefits achieved by irrigators through inter-regional trade is AUS $ 117.1 million per year.

2.7.3.3 Co-benefits

In addition, the assessment of adaptation measures included co-benefits. Co-benefits relevant for some short-listed adaptation options (catchment only) included biodiversity and ecosystems and climate change mitigation (relevant to ecosystem-based options e.g. creation of wetlands). The following methods were used to quantify these co-benefits:

81 Productivity Commission (2021) Supporting paper B : Water trading and markers (Trading) - Inquiry report - National Water Reform 2020
82 Goesch, T., Donoghoe, M., Hughes, N. (2019) https://www.agriculture.gov.au/sites/default/files/abares/documents/SnapshotOfAustralianWaterMarkets_v1.0.0.pdf
83 The_Australian_Water_Markets_Report_2021-22.pdf
84 Select Committee on the status of water trading in New South Wales (2022) Report No. 1 - Select Committee on the status of water trading in New South Wales.pdf

- Climate change mitigation co-benefits of adaptation options have been quantified using the HMT Green Book and supplementary appraisal guidance for valuing Green House Gasses (GHG) emissions and energy use[85] (for measures with quantifiable carbon benefits).
- Ecosystem co-benefits associated with wetland creation have been quantified using the Environment Agency (2017)[86] Water Appraisal Guidance that sets out benefit values for wetlands.
- Co-benefits of riparian buffer strips have been monetised using Sustainable Farming Incentive scheme values for buffer strips next to water courses (BFS6 action)[87].

No readily quantifiable co-benefit information associated with health, cultural and society (recreation and heritage), broader resilience and innovation of the adaptation measures were identified.

This is a high-level adaptation assessment which considers a limited number of criteria typical of this type of assessment. It is noted that there are many additional criteria which have not been considered, particularly the dis-benefits, such as embodied carbon, potential environmental impacts and land trade-offs.

2.7.4 Assumptions and key limitations

The assessment of individual adaptation measures aimed to quantify the potential to reduce unmet demand and the associated costs across different sectors and countries. In practice, implementation of adaptation measures or packages will be highly site, operational, investment cycle and industry specific.

The adopted methodology is a necessary simplification, reflecting data availability. For some sectors (e.g. agriculture) access to recent national statistics was also a major constraint, noting that the last Defra Survey of Irrigation was in 2010.

The assessment was based on potential uptake rates of different adaptation options, associated unit cost and water saving potential sourced from different literature sources and sectoral expert inputs. No site-specific appraisal was carried out and some sectors/industries could adapt in other ways. Many factors could influence implementation of different adaptation measures such as asset age and capital investment cycles.

The power subsector of hydropower has not been included in the adaptation appraisal as this was considered a non-feasible subsector to replace unmet demand from. As run of the river hydropower stations can often still operate at a reduced flow level, albeit at a loss of power output, therefore it is considered non-feasible (or highly non-cost-effective) to replace the reduced supply with additional water supply. The more adaptive option for hydropower would be to switch to an alternative source of energy during the low flow river periods.

[85] Department for Energy Security and Net Zero (2012) Green Book supplementary guidance: valuation of energy use and greenhouse gas emissions for appraisal Available at: https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal

[86] Environment Agency (2017) Water Appraisal Guidance; Assessing Costs and Benefits for River Basin Management Planning

[87] Department for Environment, Food & Rural Affairs and Rural Payments Agency (2024) BFS6: 6m to 12m habitat strip next to watercourses. Available at: https://www.gov.uk/find-funding-for-land-or-farms/bfs6-6m-to-12m-habitat-strip-next-to-watercourses.

2.8 Cost effective adaptation analysis

2.8.1 Optimisation of adaptation packages

Optimisation is the process of identifying the optimal sequence and combination of decisions over a planning period, considering constraints and objectives. Decision optimisation in this format is applied across various sectors, such as utilities, transport, and the built environment, to support decision makers in developing plans. This approach considers factors including:

- Multiple investment options with varying costs, benefits, and timelines.
- Several objectives that may compete (e.g., service levels, performance, regulatory compliance), often necessitating trade-offs or balancing, as well as adherence to multiple constraints such as resources and budgets.

Frequently, the number of possible investment combinations is too extensive to be evaluated efficiently using traditional tools and techniques. An optimisation algorithm can be used to create a plan that identifies beneficial options and sequences them in a way that satisfies all objectives at optimal whole life value. In this study four important aspects to the optimisation process are:

- Measures to implement and or packages of measures.
- Profiles of unmet demand to reduce or satisfy entirely.
- An optimisation algorithm to select the optimum measures to meet the given unmet demand profiles.
- Reduction of the adaptation costs according to the co-benefits provided by the solutions.

2.8.2 Measures and packages

Unmet demand was determined at a regional level for each sub-sector. For optimisation, measures are determined at the regional level and optimised into regional packages according to preference over the project timeline (i.e. 2025 to 2059). Each sub-sector optimisation is carried out separately for each region and then aggregated at a sector level.

The primary adaptation measure data utilised in the optimisation are: the costs, in terms of construction CapEx and yearly operational OpEx; expected time to implement the given measures; any constraints on mutually exclusive options (i.e., ones that cannot be constructed if another is implemented); and finally the measure's benefit, which in this case is the water capacity added to the system by a given measure, either as a reduction in demand (such as water efficiency measures) or as an increase in supply (such as on-site reservoir storage).

2.8.3 Optimisation algorithms

For the optimisation of adaptation packages over time, the Gurobi best-in-class optimiser was used. This optimiser is run in a Simple Portfolio Optimisation Tool, developed by WSP to enable decision makers to investigate different scenarios to aid choosing the optimal project at the right time based on several constraints over different time horizons.

2.9 Sensitivity analysis

The approach for modelling in England is different to the other nations, due to the availability of existing modelling. The available modelling to build upon is more mature for England. The key variables tested as part of the sensitivity analysis were:

- In England, high climate future (2ºC in 2030s and 2.5ºC in 2050s), differing levels of Environmental Destination and future water company plans.
- In the other nations, only the high climate future (2ºC in 2030s and 2.5ºC in 2050s) is tested.

The approach taken to sensitivity analysis follows a standard variance-based sensitivity approach[88] where the analysis was re-run, whilst systematically changing one key variable at a time to determine the overall impact on the outcome of the economic analysis.

[88] Saltelli, A., Ratto, M., Andres, T., Campolongo, F., Cariboni, J., Gatelli, D. Saisana, M., and Tarantola, S., 2008, *Global Sensitivity Analysis. The Primer*, John Wiley & Sons.

3. Understanding the risk

3.1 Chronic water stress

3.1.1 Overview

Following the methodology outlined in Chapter 2, annual economic losses of key components of the sectors have been determined, including:

- Four agricultural products: potatoes, carrots, onions and strawberries.
- Four industry sub-sectors: food & drink, mineral products, extractives & large manufacturing, paper & pulp and chemicals & petrochemicals.
- Three power generation technologies: hydropower, biomass & waste and combined cycle gas turbines.

It is noted that these key components do not represent the full sector losses. The quantification of economic losses is principally based upon the modelling of unmet water demand which is described in Chapter 2 of this report. The methodology does not account for the substitution of water from different sources – for example, if changes in weather reduce the availability of rainwater for some agricultural crops, farmers may want to make greater use of abstracted water (or, similarly, a scarcity of abstracted water may lead some sectors to make greater use of public water supplies). This is a necessary simplification as each operational practice would be highly site specific, which cannot be represented at the national level of this assessment.

Existing water stress is calculated to lead to losses across the sub-sectors of around £3.8 billion per year today, implying that there could be opportunity to reduce these existing inefficiencies. As water stress increases in the future, these economic losses have been calculated to increase by a further £2 billion, reaching £5.8 billion per year by the middle of the 2050s (see Figure 3-5).

Losses from industry sub-sectors dominate the economic losses in absolute terms. There are two principal reasons for this:

- First, these sub-sectors are a much larger part of the UK economy than agriculture or power generation, meaning that there are more people employed, and GVA generated, that could be placed at risk by water stress.
- Second, industry sub-sectors (and agriculture) are expected to remain heavily dependent on abstracted water. By contrast, the power sector will continue to shift away from thermal technologies that are heavily dependent on abstracted water for cooling as it decarbonises, thereby reducing the economic value that is dependent upon water abstraction over time.

The overall trajectory of the economic losses shows them increasing over time in absolute terms, reflecting two separate evolutions:

- First, that water stress increases over time, resulting in increased unmet water demand across many of the examined sub-sectors.

- Second, that the size of many of these sectors is expected to increase, in absolute terms, over the period.

In aggregate, economic losses are substantially larger in England than the devolved administrations, reflecting the economic structure of the UK and the nations; the English economy is substantially larger than that of the other nations. However, differences emerge at the sub-sector level. For example, economic losses in hydropower are heavily concentrated in Scotland, with losses also in Wales. By contrast, there are minimal hydropower economic losses in England or Northern Ireland, reflecting the fact that there is substantive hydroelectric capacity in Scotland and Wales and not in England or Northern Ireland.

The assessment indicates that hydropower could be substantially affected by water stress. This electricity would likely be replaced by more expensive thermal generation. However, it is noted that this figure is highly dependent upon the type of hydropower. No details of storage were available which could materially impact this loss, so these figures should be treated as maximums and likely to be lower. Paper & pulp is also particularly vulnerable to changes in water availability and could suffer losses equivalent to around 13% of output over the same time horizon.

Considering relative impacts across the nations, agricultural subsector losses are largest in England but are a much lower percentage than industry. The economic losses by industry subsector are disproportionate across nations, with important impacts in Wales from chemicals and food and drink, Scotland with food and drink and England for paper and pulp. In Northern Ireland, the only impacts observed in industry are in the minerals and large manufacturing sub-sector: these are higher than the impacts for all other nations, except for Scotland in the 2050s. For power, the relative losses present a similar picture to the absolute values.

The following sections assess risks for each sector and selected subsectors—agriculture, industry, and power. Maps and graphs illustrate regional and total economic losses (GVA, £m 2024 prices). In the graphs (e.g., Figure 3-2), lines appear smooth due to interpolation between averaged median RCM economic values for each epoch.

3.1.2 Agriculture

3.1.2.1 Overview of results

In the agricultural sector the losses have been evaluated across four key crops: potatoes, carrots, onions and strawberries. These crops have been chosen as representing a substantial proportion (c75%) of irrigation demand from UK agriculture[89] and covering different production profiles (pre-packed vs processed). Livestock was considered, but economic losses are not quantified as the sector currently makes extremely low use of abstracted surface water (predominantly mains and private water supply small enough not to require an abstraction licence).

To calculate the cumulative impact of water stress on these crops, annual economic losses are calculated (as detailed in Chapter 2.6.3), and a Net Present Value (£NPV) (2024 prices) for the sector is constructed by summing across these crops and applying a discount factor.

[89] E.K Weatherhead, J.W Knox, (2000) Predicting and mapping the future demand for irrigation water in England and Wales, Agricultural Water Management, Volume 43, Issue 2, Pages 203-218, ISSN 0378-3774, https://doi.org/10.1016/S0378-3774(99)00058-X.

As presented in Figure 3-2 and Figure 3-3, while strawberries see the largest estimated relative losses across the agricultural sector (more than 6% of output by 2050s), impacts are also substantive across the other products assessed (carrots, potatoes and onions), which will all experience losses of 2-3% by 2050s. In absolute terms, strawberries and potatoes will experience the largest economic losses. Strawberries are completely reliant upon abstracted water in the UK (they are grown in polytunnels), and are a very high value crop, which results in the largest losses in both relative and absolute terms. Potatoes are one of the largest volume crops in the UK in value terms, despite a lower unit value than strawberries, meaning that a smaller relative loss translates to a larger loss in absolute value terms.

Figure 3-1: Discounted net present value of aggregated costs caused by un-met demand in the agricultural sector over the period 2025 to 2059.

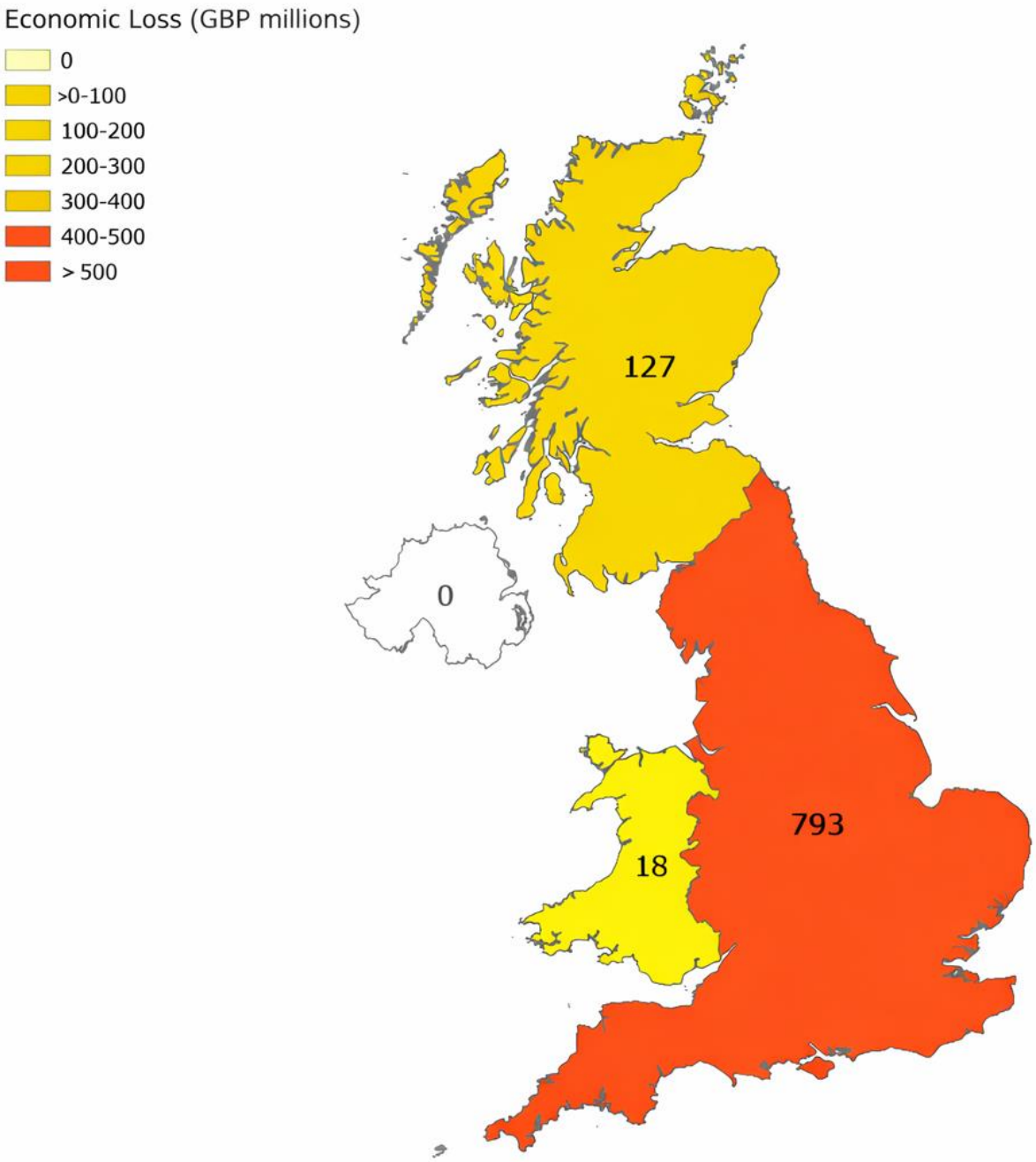


Figure 3-2 Economic losses in absolute terms (GVA losses, £m 2024 prices) in selected agricultural products

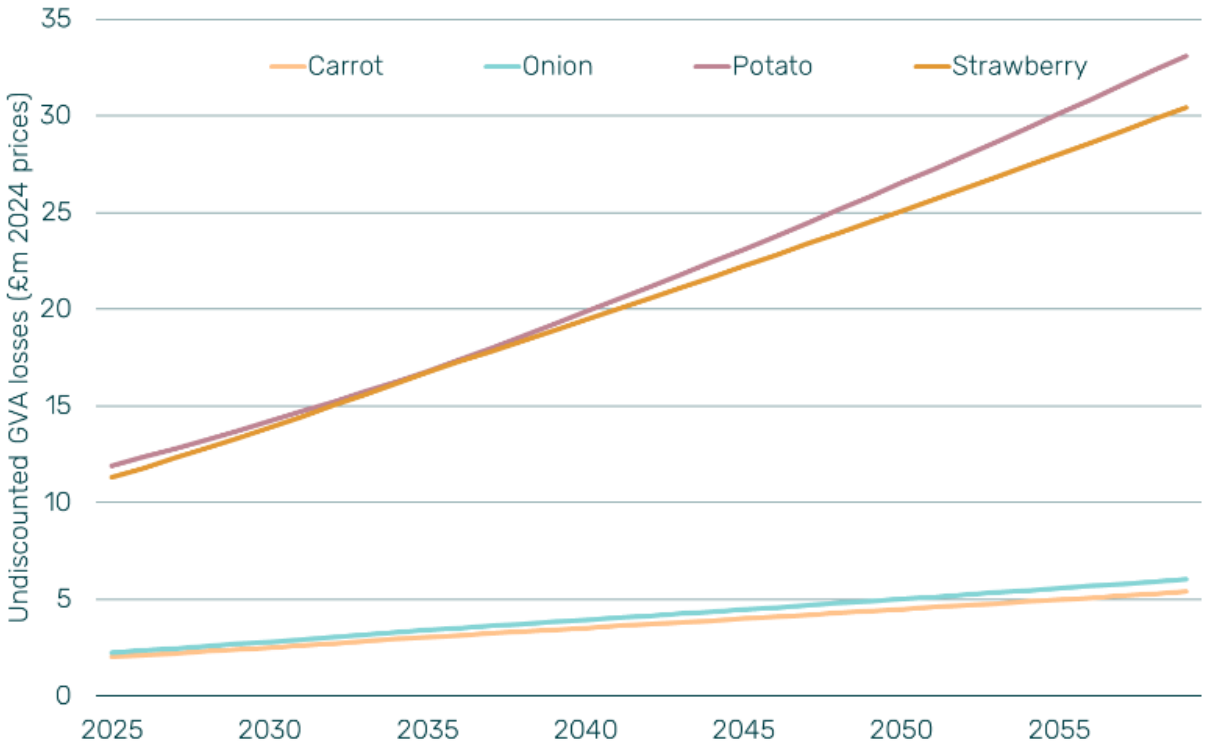
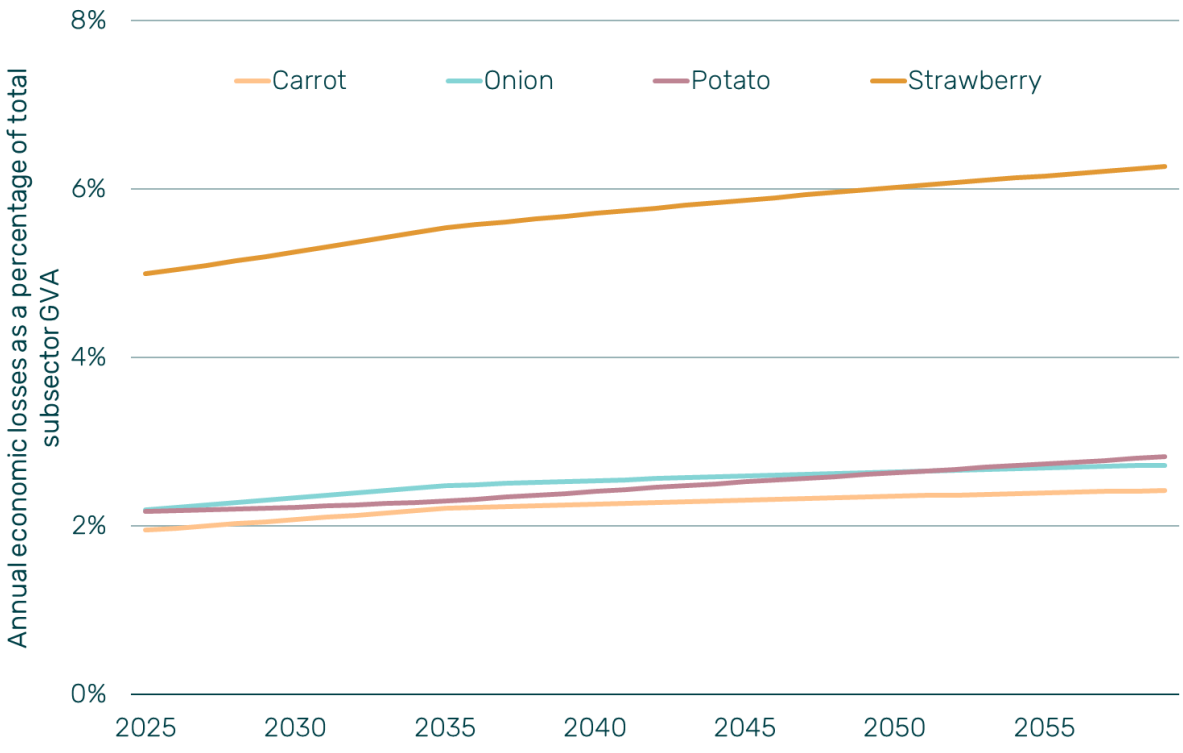


Figure 3-3 Economic losses as a percentage of total sub sector GVA in selected agricultural products



Calculated economic losses are largest in England, due to the scale of production of these crops across the nations. Conversely, losses are very small in Wales, and zero in Northern Ireland; this is predominantly due to the fact that most agriculture in these locations is focussed on non-irrigated farming (such as sheep farming) and the limited abstractions are predominantly groundwater (see Figure 3-1).

Considering relative impacts across the nations, as presented in Table 3.1, losses are most substantial in England across each of the four crops evaluated, reflecting the scale of water demand for agricultural use that is expected to be unmet in future years, while the relative scarcity is smaller in Scotland and Wales (and, as noted above, Northern Ireland is largely unaffected, notwithstanding the possibility that farms that are currently not reliant on abstractions have to change their methods of sourcing water as the climate changes).

Table 3.1 Economic losses as a percentage of output for agriculture

Economic losses as % of output	England			Wales			Scotland			Northern Ireland			United Kingdom		
	2025	2035	2055	2025	2035	2055	2025	2035	2055	2025	2035	2055	2025	2035	2055
Carrot	2%	3%	3%	2%	2%	2%	1%	1%	2%	0%	0%	0%	2%	2%	2%
Onion	2%	3%	3%	2%	2%	2%	1%	1%	2%	0%	0%	0%	2%	3%	3%
Potato	3%	3%	3%	2%	2%	2%	1%	1%	2%	0%	0%	0%	2%	2%	3%
Strawberry	6%	7%	7%	4%	4%	4%	3%	2%	4%	0%	0%	0%	5%	6%	6%

3.1.2.2 Wider context

Agricultural crop products (e.g. cereals) which are predominantly dependent on rainfall and/or private sources for water (including livestock), were outside of the scope of this analysis. As the weather patterns change in the future, the availability of water from these sources at the time they need them in the growing season will likely be reduced. This is likely to lead to increased demand for abstracted water in the future (notwithstanding changes to the availability of abstraction licenses because of Environmental Destination and related policies). However, this impact was not captured in the analysis presented above – as such, the economic losses could be higher than outlined as businesses previously reliant on rainfed production need to switch to supplemental irrigation to maintain yields.

As outlined above, the quantitative analysis assumes that all farms and agricultural produce continue to rely on their existing water sources, and do not switch between them. However, the changes to climate and weather expected over the coming decades will increase water stress across all sources. As a result, some farms/products that currently rely substantially upon entirely rainfed production are likely to try and switch water sources and/or invest in alternate sources of supply (e.g. high flow storage for outdoor crop irrigation and rainwater harvesting for protected cropping). There could also be increased dependence on water from public water supplies, where available.

3.1.3 Industry

3.1.3.1 Overview of results

Across industry, our assessment focussed on four sub-sectors: 1) chemicals & petrochemicals, 2) food & drink, 3) mineral products, extractives & other large manufacturing and 4) paper & pulp. These sub-sectors cover a substantial proportion of abstracted surface water demand across industry (more than 90%), but it should be noted that they are vastly different in size – most notably, mineral products, extractives & other large manufacturing is more than twice the size (in output and GVA terms) of the other three sub-sectors combined. This means that a relatively small economic loss in this sub-sector translates to a comparatively large loss in absolute terms.

Economic losses in industry are expected to occur through temporary plant shut down or production reduction. Engagement with industry stakeholders through the course of this analysis has highlighted the limited current flexibility that most facilities must respond to more than very minor (c5%) reductions in water availability. Where possible, this response takes the form of short-term measures such as buffer water storage or alternative water sources. Short periods of water scarcity will therefore incur costs (e.g. to source water from alternative sources) but are likely to be manageable. More substantial shortages will necessitate complete shutdowns until availability improves sufficiently. This is consistent with the assumptions made in the calculation of economic loss that output loss is directly proportional to reductions in abstracted water availability (see Chapter 2).

Figure 3-5 and Figure 3-6 present the economic losses for the industry sub-sectors. There are different narratives at play in the absolute and relative losses, reflecting relative vulnerability of the sub-sectors and their relative size. Across the period to 2035, absolute losses are highest in the minerals & large manufacturing sector, although by the end of the study period (the late 2050s), losses in the food & drink sector become larger.

This project's analysis suggests that present day economic losses are substantial for industries because of water stress. As discussed in Chapter 3.1.5, this level of economic loss from chronic water stress is outside the estimates in the literature, which typically do not start from an assumption of economic losses from present day water stress. The level of present-day economic loss estimated in this study is consistent with some of the very high levels of water stress (e.g. 3-year droughts) reported in the literature, although there is a wide range of methodologies applied which make direct comparison difficult.

The methodology used to calculate current levels of unmet water demand, and its relationship to economic activity, is consistent with interpreting this economic loss as an inefficiency compared to a world in which water resource constraints do not exist. However, these firms do not operate in this perfect world, and they have instead built their business models around the challenges that water stress already presents. This is likely to mean that there is less room for further adaptation without substantial investment (i.e. easy options have already been exhausted). These losses should therefore be considered as inefficiencies in the existing sectors that are currently well known and managed.

Figure 3-5 and Figure 3-6 show declines in the losses in the minerals & large manufacturing sector beyond 2035, which are a result of changes to licensing arrangements over the period related to Environmental Destination policy, see Chapter 2 for further details. Environmental Destination policy requirements result in a reduction or removal of abstractions to improve downstream flows and environmental health. This can have two impacts on abstractors:

1. First, if they are the sites which have their licenses eliminated, they will not suffer from future unmet water demand (since they are assumed to no longer be using abstracted water); and
2. Second, they may be downstream of the licensing limitations and therefore benefit from the improved flow (and therefore experience a reduction in unmet water demand).

The economic losses relating to firms that have their licenses removed or restricted (due to Environmental Destination) have not been included. However, the project does account for the reduced water stress either directly (i.e. point 1 above) or indirectly (i.e. point 2 above) because of these changes. In practice, there would be some form of economic loss from the sites which have abstraction licenses removed or limited.

Economic losses in the paper & pulp and chemicals sectors are much smaller in absolute terms. However, paper & pulp is by far the most vulnerable sub-sector in relative terms, with more than 11% of GVA lost due to water stress by the 2050s. Food & drink is the next most exposed, with economic losses reaching 4% of total sector GVA by the same period. Losses in chemicals and minerals, extractives & large manufacturing are only around 1% of GVA across all modelled years.

Figure 3-4 :Discounted net present value of aggregated costs caused by unmet demand in the industry sector over the period to 2059.

The metric is presented through colour and absolute figures on the map.

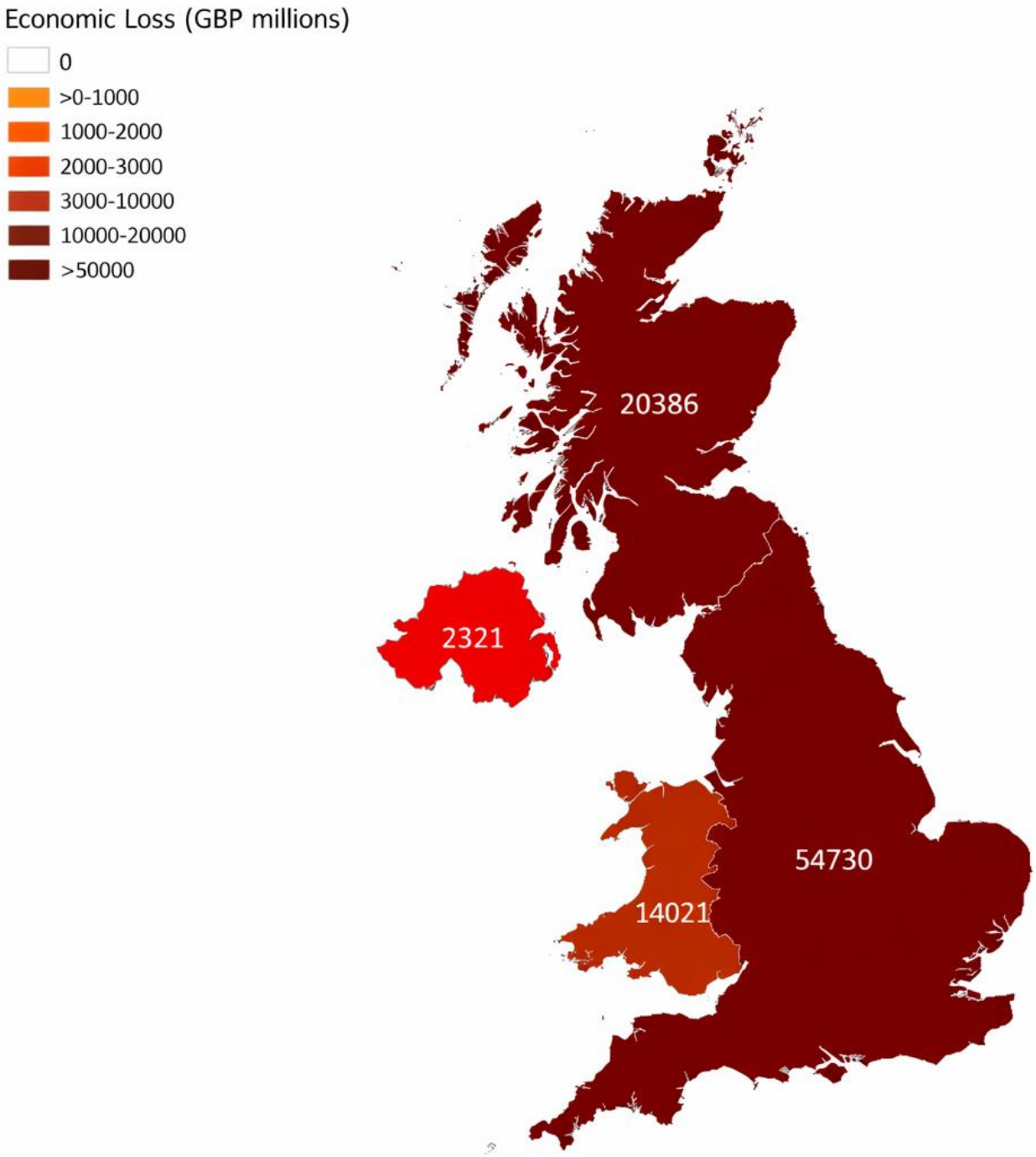


Figure 3-5 Economic losses in absolute terms (GVA losses, £m 2024 prices) in selected industry sub-sectors

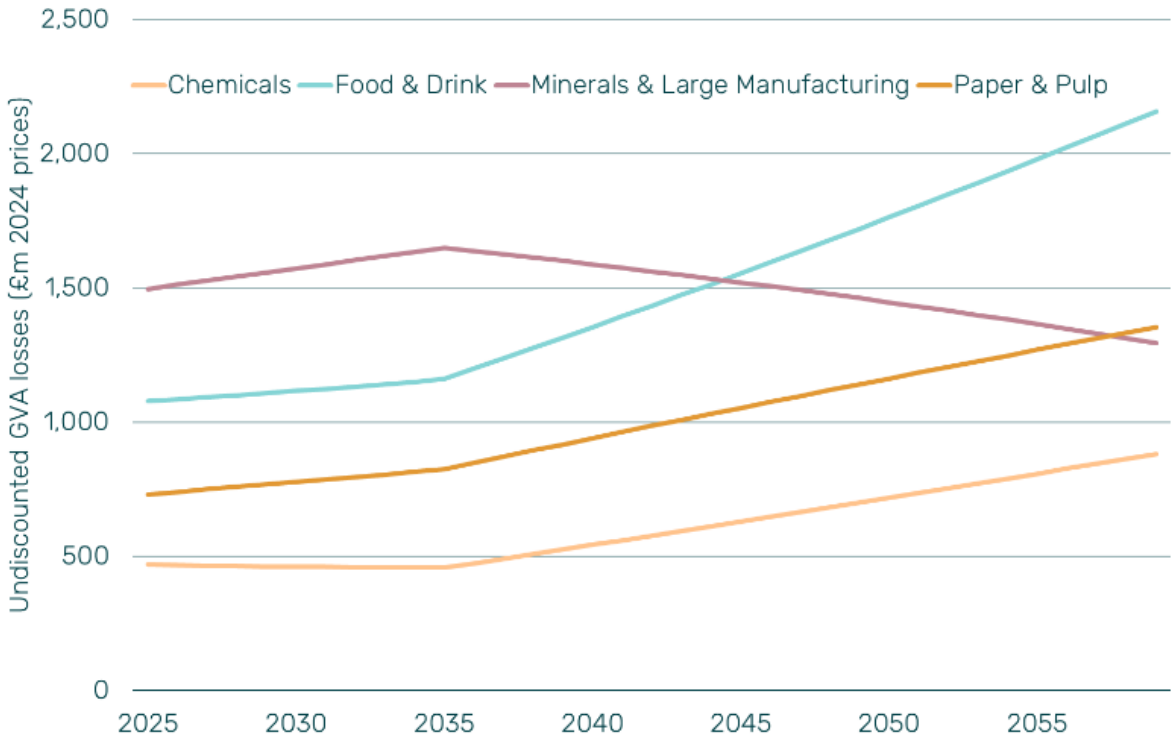
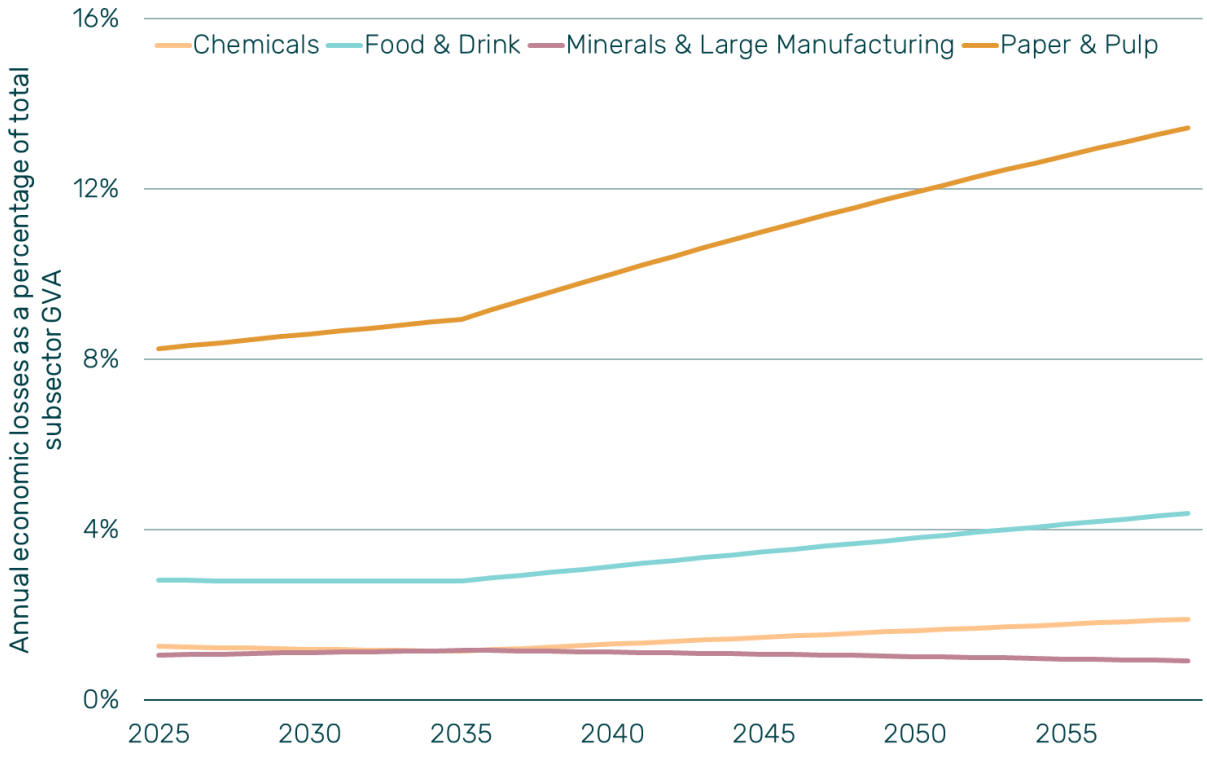


Figure 3-6 Economic losses as a percentage of total sub sector GVA in selected industry sub-sectors



The spatial distribution of impacts at the sub-sector level varies – for example, there are more substantive impacts on the food & drink sector in Scotland and Wales, and the chemicals sector in Wales, reflecting the location and dependency of some high value production (such as whisky distilleries) on water sources that are particularly vulnerable to climate change.

Table 2.1 presents the economic losses by industry subsector as a percentage of the output per nation. This indicates that there are disproportionate and important impacts in Wales from chemicals, and food and drink, Scotland with food and drink and England for paper and pulp. In Northern Ireland, the only impacts observed in industry are in the minerals and large manufacturing sub-sector: these are higher than the impacts for all other nations, except for Scotland in the 2050s.

Table 3.2 Economic losses as a percentage of output for industry

Economic losses as % of output	England			Wales			Scotland			Northern Ireland			United Kingdom		
	2025	2035	2055	2025	2035	2055	2025	2035	2055	2025	2035	2055	2025	2035	2055
Chemicals	1%	1%	1%	6%	4%	10%	1%	0%	1%	0%	0%	0%	1%	1%	2%
Food & Drink	1%	1%	1%	19%	21%	25%	9%	8%	14%	0%	0%	0%	3%	3%	4%
Minerals & Large Manufacturing	1%	1%	1%	1%	0%	0%	2%	2%	4%	3%	3%	3%	1%	1%	1%
Paper & Pulp	9%	10%	14%	0%	0%	0%	4%	4%	8%	0%	0%	0%	8%	9%	13%

3.1.3.2 Wider context

Whilst most manufacturing firms could have alternative supplies of abstracted water (albeit typically for limited volumes and at elevated costs), there are several firms operating in specific niches in the food & drink sector (see Box 3-1) for whom the point of origin of their water is likely to be firmly established into their brand and not easily replaced.

The transition towards net zero will require several industries with high heat processes that are hard to electrify such as those found in the chemicals and minerals sub-sectors (e.g. cement and lime production) to switch to alternative power sources, such as hydrogen, and abate emissions with Carbon Capture and Storage (CCS). The additional water footprint associated with these technologies will likely be minor at the national scale but would result in localised changes in patterns to water demand. Further discussion on these emerging technologies is provided in Chapters 3.1.4.1 and 5.

A clear challenge for the industrial sector in the future is how much flexibility remains in their business model with respect to increasing levels of water stress, and the extent to which further losses can continue to be managed similarly or will instead lead to large realised financial losses (and potentially challenges to the entire business model for some affected sites).

Box 3-1 – Important water sources

While water quality is important for most industries, there are some food & drink manufacturing sites where the source of water is a key part of their brand identity. These businesses are particularly vulnerable to water scarcity, given the weight that they place upon the specific source.

The most prominent examples include firms which supply bottled water, high value brewing and distilling. Some sites in Scotland have already faced temporary shutdowns because of water scarcity.[90]

However, distilleries are already implementing new technologies to improve the efficiency of water use. Industry-wide measures[91] focus on risk management strategies including engaging in catchment-scale collective action and improving monitoring.

In addition, as discussed in Chapter 1, there is a clear dependence on these businesses for other sub-sectors at risk from water stress, such as barley.

3.1.4 Power

3.1.4.1 Overview of results

Water is currently widely used for the cooling of thermal electricity generation plants in the power sector. The focus of this assessment is on electricity generation technologies that are reliant upon abstracted surface water – gas and biomass and waste power plants, plus hydroelectric plants. Due to the volumes required, existing nuclear power plants (in the UK) use coastal sources and therefore are not vulnerable to water stress.

[90] Centre of Expertise for Water (2024) Future Predictions of Water Scarcity in Scotland: Impacts to Distilleries and Agricultural Abstractors. Available at: https://www.crew.ac.uk/publication/water-scarcity-impacts-distilleries-agricultural

[91] Scotch Whiskey Association (2023) Whisky industry launches Water Stewardship Framework. Available at: https://www.scotch-whisky.org.uk/newsroom/whisky-industry-launches-water-stewardship-framework/

Figure 3-8 and Figure 3-9 illustrate that economic losses from hydroelectric dominate in the power sector, both in absolute and relative terms but should be noted that currently in hydropower makes up approximately 5% of the UK's generation capacity[92]. By 2055, the assessment indicates that substantial generation from hydroelectricity plants could be lost due to water stress. However, several forms of hydroelectric power stations exist, notably run of river and with storage; the abstraction data does not differentiate between these, but the former is substantially more vulnerable to short term river level changes than the latter. It has been assumed that all are run of river, and therefore these losses are likely to represent an upper bound.

Although the percentage of losses from gas-fired generation is much lower, in absolute terms it still records substantial economic losses of over £100 million per year in the 2050s. Whilst it is anticipated that the significance of thermal generation (primarily natural gas) with CCS declines in the long term as generation shifts toward renewables, it still remains an essential part of the dispatchable power generation and capacity within the CCC's Advice on the Seventh Carbon Budget (CB7) up to the 2050's[93]. Given its position at the top of the merit order cost curve, it is assumed to be replaced by imported electricity and therefore the full value of the generation is lost to the UK.

Work by the Energy Systems Catapult[94] (outlined further in Box 3-2 below) indicates that the current energy mix remains resilient to periods of low water availability combined with high energy demand, including projections through 2050. Regarding the resilience of existing fossil fuel thermal generators specifically, Figure 2-7 shows that most freshwater-dependent generators are located along the River Trent and Soar. Although these generators may experience periods of unmet water demand according to modelling, the Environment Agency's mapping of water resource reliability finds that these abstractors have water available at least 95% of the time[95] [96], suggesting that risk to these generators is likely minimal. The Energy Systems Catapult also notes that future resilience of thermal generation provision can be supported by strategically locating new sites near sea water, adopting less water-intensive cooling methods, and increasing renewable energy generation. These changes align with the CCC's advice on CB7, which anticipates a substantial transition to renewable sources (primarily off-shore and on-shore wind), reducing water demand and making more freshwater available for other low-carbon generation technologies.

[92] Accredited official statistics, Digest of UK Energy Statistics (DUKES): renewable sources of energy. DUKES chapter 6: statistics on energy from renewable sources.
[93] The Seventh Carbon Budget - Climate Change Committee
[94] Energy Systems Catapult (2025) Impacts of water constraints on the UK's energy system. Available at: https://es.catapult.org.uk/report/impacts-of-water-constraints-on-the-uks-energy-system/
[95] Soar Abstraction Licensing Strategy
[96] Lower Trent and Erewash abstraction licensing strategy - GOV.UK

Figure 3-7 :Discounted net present value of aggregated costs caused by un-met demand in the power sector over the period to 2059.

The metric is presented through colour and absolute figures on the map.

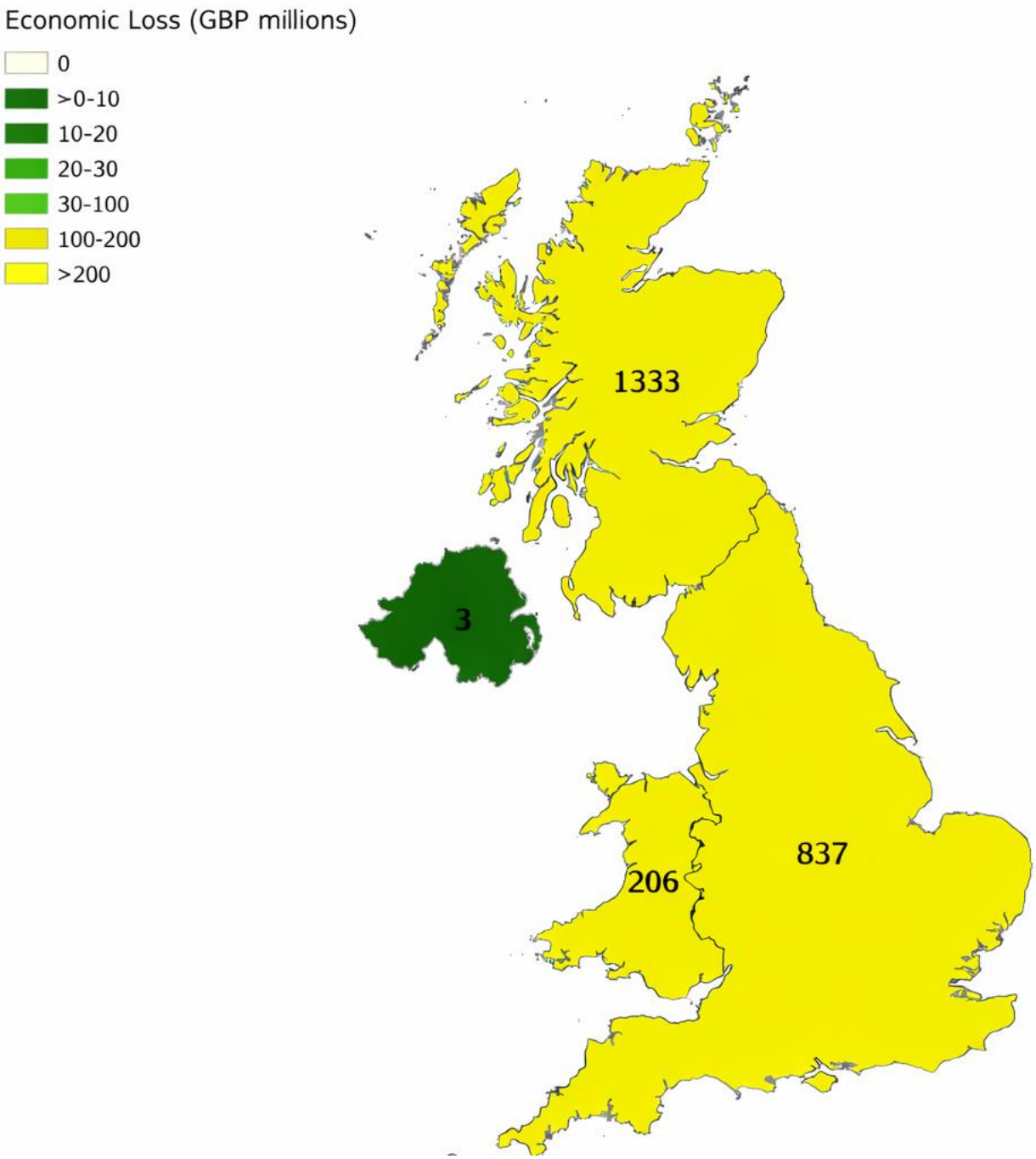


Figure 3-8 Economic losses in absolute terms (GVA losses, £m 2024 prices) in power sector for selected generation technologies

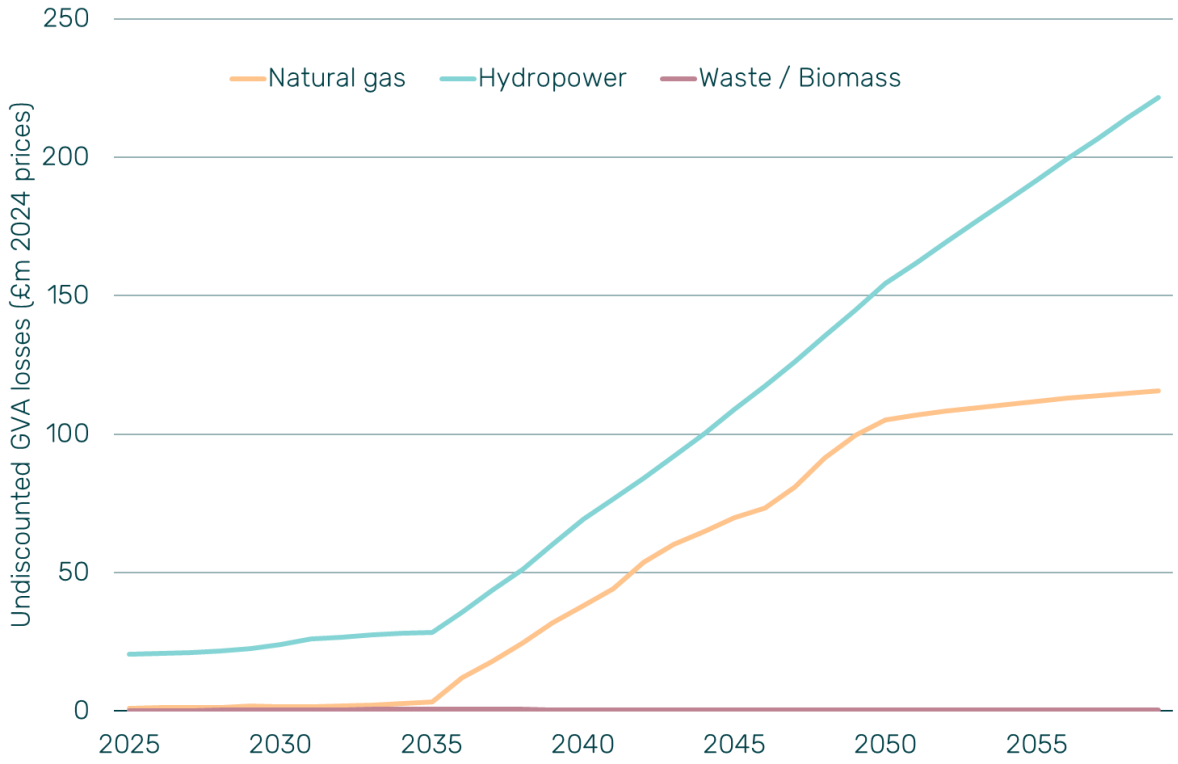
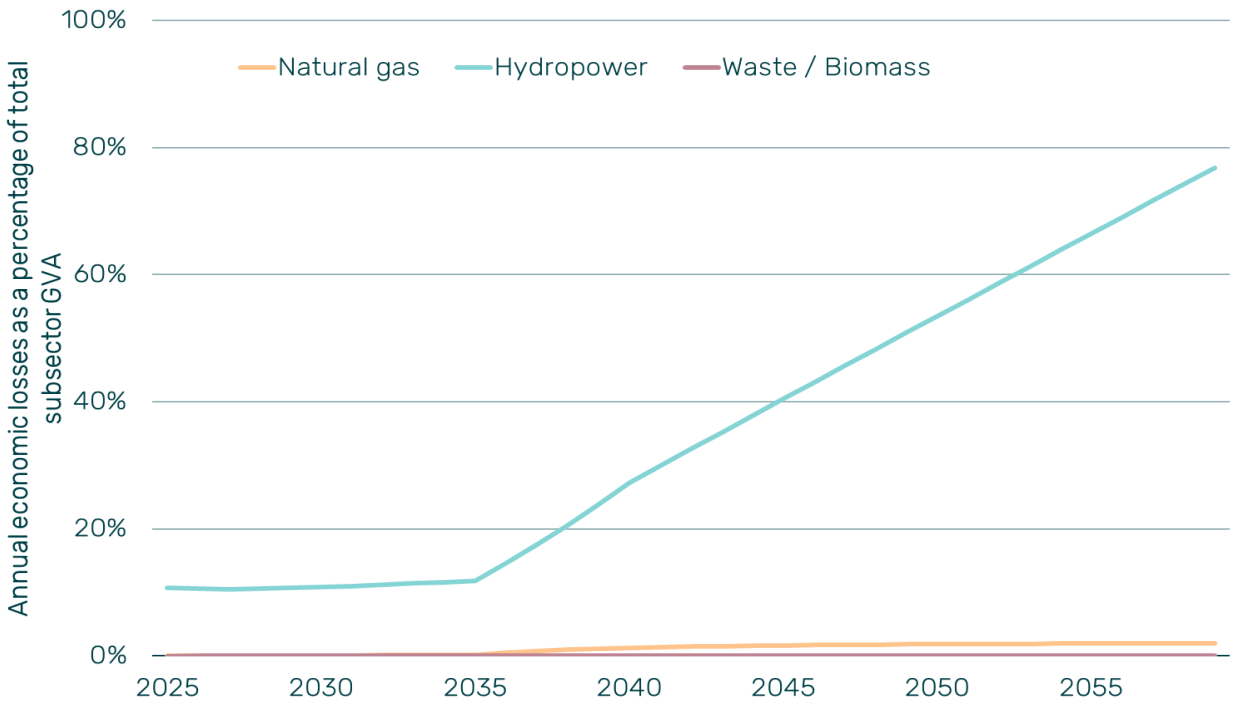


Figure 3-9 Economic losses as a percentage of total sub sector GVA in selected power generation technologies



Economic losses from hydroelectric generation are largely concentrated in Scotland, where most the UK's hydropower facilities are (with a smaller number in Wales). Therefore, although the losses to gas power plants occur exclusively in England, absolute economic losses from power generation are largest in Scotland. All the major power plants within Northern Ireland abstract water from estuarine or coastal sources, so the losses are low. The relative losses presented in Table 3.3 reinforce this narrative; although in percentage terms there are substantive losses to hydropower in all nations (but applied to different levels of capacity in each nation). Losses occur to gas-fired electricity generation only in England.

Table 3.3 Economic losses as a percentage of output for power

Economic losses as % of output	England			Wales			Scotland			Northern Ireland			United Kingdom		
	2025	2035	2055	2025	2035	2055	2025	2035	2055	2025	2035	2055	2025	2035	2055
Natural gas	0%	0%	3%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	2%
Hydropower	1%	3%	25%	17%	31%	77%	10%	10%	67%	2%	2%	28%	1%	12%	67%
Waste / Biomass	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

3.1.4.2 Wider context

Economic losses are modelled as the cost of temporarily switching to alternative (more expensive) sources of electricity generation; the wider economic impact of changes in electricity prices faced by both consumers and industry in the UK are not quantified. However, it is likely that the direct impacts would be dwarfed by these price effects, with changes in costs passed through the entire economy. These impacts are anticipated to be significant, given that electricity is essential across all sectors of the economy and plays a critical role in the production of manufactured goods.

Increases in electricity prices will therefore feed through as increased prices across the economy (with the rises in different sectors reflecting the extent of the role of electricity in production), ultimately being reflected in the price of goods and services that are paid by consumers. Higher prices for these goods and services depress real consumer spending power and lead to worse economic outcomes overall, in addition to the direct impact that higher electricity prices have on consumer energy bills. Both channels of impact will lead to less economic activity overall across the economy, and to an extent that would be expected to be greater than the direct economic impact on the electricity generation sector, which is only a small part of the economy. Sharp increases in energy prices can also lead to lower output from sectors that are particularly dependent upon energy and are sensitive to price changes. For example, the Office of National Statistics have highlighted the strong correlation between high energy prices in the UK from 2021-2025 and a sharp reduction in output from energy-intensive manufacturing industries over the same period[97].

The analysis also does not consider the impacts of any ancillary roles played by the sites affected by water stress. It is assumed that alternative sources of generation brought online to replace the foregone generation will be able to provide those services; but additional investments in grid flexibility may be required (or may be a prudent way of addressing increased risk in the electricity system as a whole).

Box 3-2 presents the findings from a recent study regarding the energy network and water stress.

Box 3-2 - UK's energy system resilience to water stress

The Energy Water Nexus project[98] used the Energy System Catapult's ESME to explore the impacts of climate driven water stress alongside the transition to Net Zero. Alongside understanding the potential risks and impacts of water stress to the current system, the assessment considered a range of responses to water stress including:

- New power generation cooling – fresh, saline or estuarine.
- Water efficient process improvements, such as once-through water cooling over evaporative.
- Technologies which are lower in water consumption, such as renewables.

The key outcomes pertinent to this project are:

- The current energy system is resilient to periods of low water availability combined with high energy demand; this includes a climate changed future to 2050. The period of water stress is generally managed (by the current system) through using more estuarine/coastal water, less-intensive

[97] https://www.ons.gov.uk/economy/economicoutputandproductivity/output/articles/theimpactofhigherenergycostsonukbusinesses/2021to2024
[98] Energy Systems Catapult (2025) Impacts of water constraints on the UK's energy system. Available at: https://es.catapult.org.uk/report/impacts-of-water-constraints-on-the-uks-energy-system/

cooling methods and more renewable generation. There is however an increased cost in providing the energy during the periods of low water availability (reflecting the higher cost of generation).

- The future optimal composition of regional electricity generation technologies and cooling methods is not that sensitive to freshwater availability alone. To optimise future energy costs and demands, the ESME promotes new coastal and estuarine cooled energy generation technologies, reducing the cost of energy during periods of low water availability.
- There is a balance between water need, consumptiveness and cost for cooling of thermal technologies. Once-through water cooling requires substantial volumes of water but is not consumptive and least expensive. Evaporative cooling needs less water than once-through but it is consumptive and more expensive than once-through. Air cooling is non consumptive but the most expensive.

This analysis found that when water was most limited, the less intensive cooling methods were deployed much more, increasing total system cost. Innovation which could improve these cooling methods could reduce cost in a future water-constrained energy system.

Energy Systems Catapult, 2025[94]

3.1.5 Validating the findings

A challenge throughout this analysis has been to verify the scale of economic loss that is being attributed to water stress, both in terms of the losses estimated for the current day, and the increase in economic losses modelled over the period to the 2050s. There are three principal ways in which this has been done:

- By comparing to existing estimates of historical losses.
- By comparing our findings to other modelling studies estimating future losses due to water stress.
- By engaging with stakeholders in industry and the public sector for validation.

Each of these methods presents challenges:

- Historical estimates of losses tend to focus on acute weather events (in the context of water stress, acute droughts), rather than chronic impacts. Data availability is typically limited (in part due to commercial considerations), meaning that often such estimates include their own assumptions or modelling approaches to construct broad estimates of losses.
- Previous modelling studies make a wide range of design choices and assumptions which change the scale of results obtained, limiting the ability to make direct comparisons. For example, many studies examine impacts across the economy using input-output models, or consider the impacts on households, neither of which are within the scope of this analysis.
- Stakeholders often have a limited viewpoint; industry organisations might have a sense of the level of disruption that such events would have on their business or sub-sector, but not how that scales up to wider sectors or the economy as a whole; or have a qualitative view that cannot readily be used to check quantitative estimates of losses. Further, many organisations have dealt with existing water availability as part of their operation, such as hydroelectric plants, where essential maintenance is typically planned over periods of water stress.

Table 3.4 summarises the key alternative information sources that have been reviewed, what their central estimates are, and key identified differences from the approach taken in this study. The literature mentions other studies[99;100], although these are no longer in the public domain so have not been included in the summary below.

Table 3.4 Sources of information used to validate results

Source	Estimate of economic loss	Key comments
This study	Up to £3.8 bn annually today reaching £5.8 bn per year by the middle of the 2050s	
The Cost of Water Scarcity, Public First, 2025[101]	Up to £8.5bn annually by 2030 £2.1bn to industry annual by 2030.	Industry focus is on productivity gains foregone in AI (£1.3bn) and economic activity foregone in the OxCam growth corridor (£0.8bn).
Strategic Water Infrastructure & Resilience, AECOM for the Environment Agency, 2016[102]	Up to £260m for a one-year drought in 2011 Up to £880m for a three-year drought in 2011.	In the most severe future scenario, annual economic losses in the 2050s are 1-2% of industry GVA, 5% of power sector GVA and 9% of agriculture GVA (absolute figures are very large, up to £43.5bn over a 3-year drought, because of underlying assumptions around economic growth).
Water resources long term planning framework (2015-2065) Technical Report, Water UK, 2016[103]	GVA reductions of 75% per day of severe water restrictions for manufacturing sectors; 100% for strawberries; 30-59% for potatoes; 30-37% for other crops; 50% for electricity supply.	Central elasticities are as noted, with a 50% confidence interval (i.e. high estimates for manufacturing sectors would be 100% and for electricity supply 75% of total GVA lost per day of restrictions).
Jenkins, K., Dobson, B., Decker, C., & Hall, J. W. (2021)[104]. An integrated framework for risk-based analysis of economic impacts of drought and water scarcity in England and Wales. Water Resources Research, 57, e2020WR027715.	Expected annual loss to GVA central estimate of £11.7m; extreme event impact of £303m.	Economic losses are premised on perfect substitutability of water (as an input to production) with capital or labour, which means that changes to water availability cause only a small (c19-20%) reduction in industrial output.

99 Akande K, Hussain S, Knox J, Hess T, Hooftman D, Stratford C, Schafer S, Acreman M and Edwards F (2013) The Impacts of Drought in England. R&D Technical Report WT0987/TR. Department for Environment, Food and Rural Affairs Water Availability Division, London

100 Not in Public Domain: A report for Thames Water, NERA, (2006) The cost of water use restrictions

101 Public First (2025) The Cost of Water Scarcity. Available at: https://www.publicfirst.co.uk/wp-content/uploads/2025/06/The-Cost-of-Water-Scarcity-by-Public-First.pdf

102 URS (2016) Annex C: The Socio-economic Impacts of Resilience of Water Resources and Water Supplies. Annex to AECOM on behalf of the Environment Agency (2016) Strategic Water Infrastructure and Resilience. Available at: Strategic water resources planning: "Strategic Water Infrastructure and Resilience" - WT1535

103 Water UK (2016) Water resources long term planning framework (2015-2065) Technical Report. Available at: https://www.water.org.uk/sites/default/files/wp/2018/11/WaterUK-WRLTPF_Final-Report_FINAL-PUBLISHED-min.pdf

104 Jenkins, K., Dobson, B., Decker, C., & Hall, J. W. (2021) . An integrated framework for risk-based analysis of economic impacts of drought and water scarcity in England and Wales. Available at: https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2020WR027715

Informal discussion with the Environment Agency, 2025	Qualitative only.	Broad agreement with the order of magnitude of economic losses.
Regular engagement with the project Stakeholder Steering Group (SSG), 2025	Qualitative only.	No record of lost hours of generation in the power sector. Industry stakeholders did not have a strong view on the losses estimated in that sector but felt that future losses would be sizeable and would imperil existing business models.

As many of the studies themselves highlight, there is a wide range of economic losses estimated across the literature. This represents a range of types of impact that are attempting to be quantified; for example, the larger impacts are linked to acute water scarcity events (e.g. droughts), as in the Water UK analysis, while estimates of chronic water scarcity impacts are typically much smaller (as in the Jenkins et al. paper), with businesses more able to adapt through changes to business models in the case of the latter. Quantitative estimates can also vary substantially depending upon the assumptions made around future economic growth – while our analysis limits growth in sectoral GVA over time. This is to be consistent with projected increases in water demand, applying long-term growth rates more consistent with historical economic growth can lead to much larger nominal economic losses (for example the AECOM study for the Environment Agency shows a 3-year drought in 2050 could lead to up to £43.5 billion of economic loss, albeit as part of a much larger UK economy than is currently the case). While most studies seek to assess losses based on existing economic structures, some also seek to quantify limits on future growth (e.g. the Public First report), which can also lead to large nominal losses based on potential future economic growth trajectories.

The economic losses calculated in this report are larger than those reported elsewhere in the literature, given the assumption of modest future economic growth and that the analysis focusses on chronic, rather than acute, water scarcity. Besides differences in the water scarcity data which feeds into the analysis, there are two key drivers of these differences, which are set out below.

While the methods used, and estimates of economic loss shown, vary substantially across the literature reviewed, the elasticities used and scale of relative economic impact seem to be broadly comparable in AECOM (2016)[102] and Water UK (2016)[103], meaning that points of difference are likely to be due to the underlying water modelling. Jenkins et al[104] use much lower water elasticities of output than in this analysis, although their assumption of perfect substitutability of water as an input to production gives much lower elasticities than seen elsewhere and runs contrary to the views solicited from industry experts in the project SSG. The calculation of economic losses requires an assumption that either water can be substituted as a factor of production by labour or capital (as in the Jenkins et al study), or that it cannot, and therefore any loss of water as an input necessarily reduces output. Based on our own expertise, and the range of views solicited from stakeholders, we have taken the approach that assuming that water cannot be substituted as a factor of production is the more robust assumption.

One key point of difference for this analysis is the estimation of substantial economic losses today. Economic analysis typically starts from a position of limited or no inefficiency in the current system and tracks how future scenarios might differ from that position, reflecting many economists' strong belief in

the efficiency of markets to deliver optimal outcomes[105]. The substantial economic losses that are being estimated for the current day suggest that there are major inefficiencies in the current system, which are discussed in more detail in the relevant results chapters that follow. This suggests that these sectors are currently structured in such a way as to manage extensive economic losses. A key question for the conclusions to draw from this study is the extent to which sectors can continue to manage existing and future greater levels of risk and economic loss. The SSG views have been that major changes to water availability would imperil existing business models, suggesting that there is not much additional flexibility.

3.1.6 Sensitivity analysis

There are substantial unknowns and simplifications incorporated within this assessment (see Chapter 2.1.6 for further information). The purpose of this sensitivity analysis is to understand the impact that these could have on the outcome of this study.

The modelling approach for England was more sophisticated than that for the devolved administrations, due to availability of existing models. The key variables tested as part of the sensitivity analysis were:

- In England, high climate hazard future (2ºC in 2030s and 2.5ºC in 2050s), no growth, higher level of Environmental Destination and future water company plans.
- In the devolved administrations, high climate hazard future (2ºC in 2030s and 2.5ºC in 2050s) and no growth.

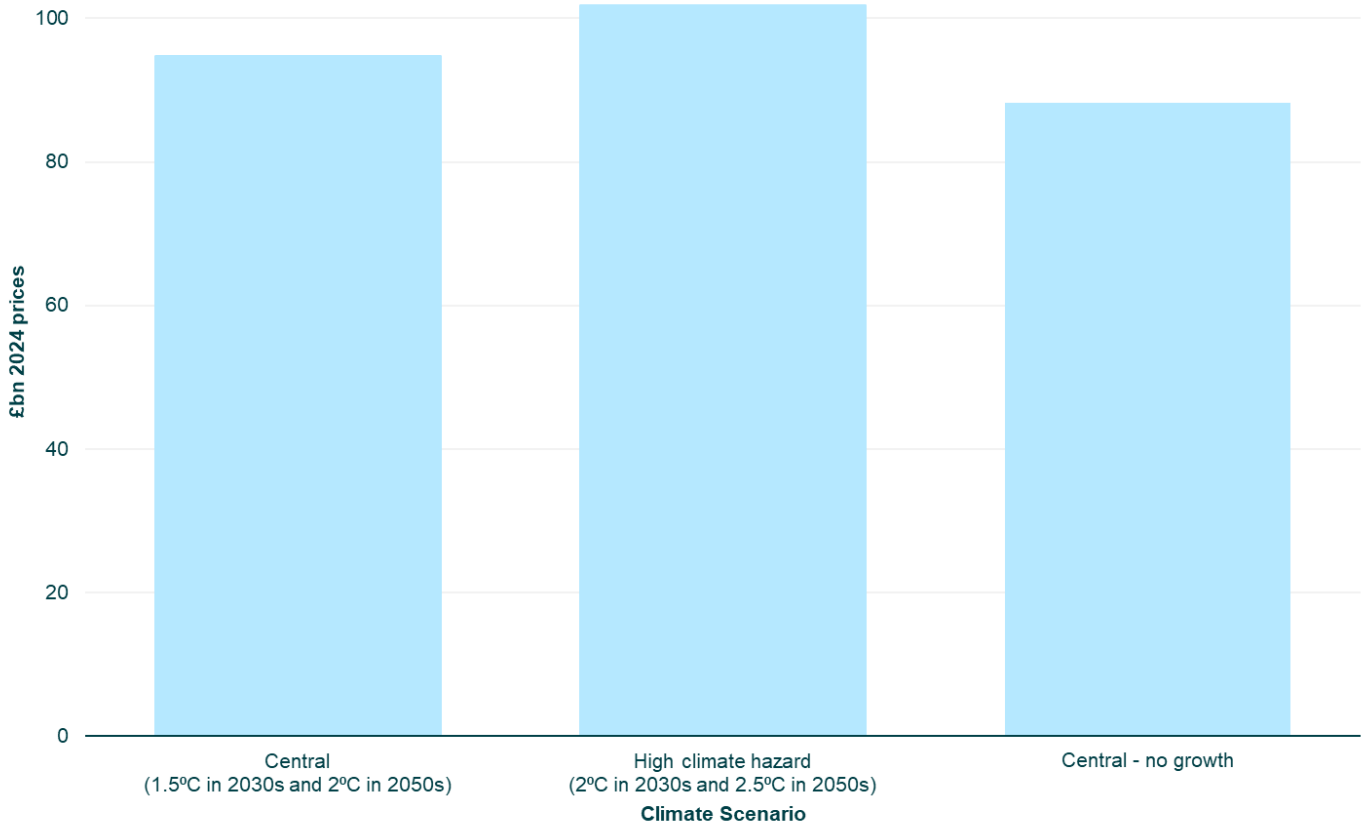
The following chapters discuss the outcomes of each variable (see Chapter 2.1.6 for description of each variable). Note, where the variable only applies to England the impact is also compared just with England.

High climate hazard scenario: As shown in Figure 3-10the high climate hazard future (2ºC in 2030s and 2.5ºC in 2050s) is calculated to increase the NPV (2024 prices) of economic losses by around 7.5% cumulatively over the period to 2059 across the UK economy. This modest increase is considered because of the large existing losses, and the relatively short timeframe of this assessment meaning that the climate future scenarios do not diverge substantially. It is likely that the difference in impacts between the future climate scenarios would be far more pronounced with a longer timeframe (such as to the 2080s).

Growth in water demand and economic activity: Growth in water demand (and economic output from these sectors) incorporated into the assessment has been based on evidence from the literature and aligned with other national studies. Figure 3-10 below indicates that if that growth is removed, the economic losses are reduced by 7% NPV (2024 prices) over 2025-29. The reduced losses are due to two factors: lower overall demand for water, and less economic output to be lost.

[105] A Dictionary of Economics (5 ed.) Nigar Hashimzade, Gareth Myles, and John Black. Oxford University Press. Publication Date: 2017. ISBN-13: 9780198759430. DOI: 10.1093/acref/9780198759430.001.0001

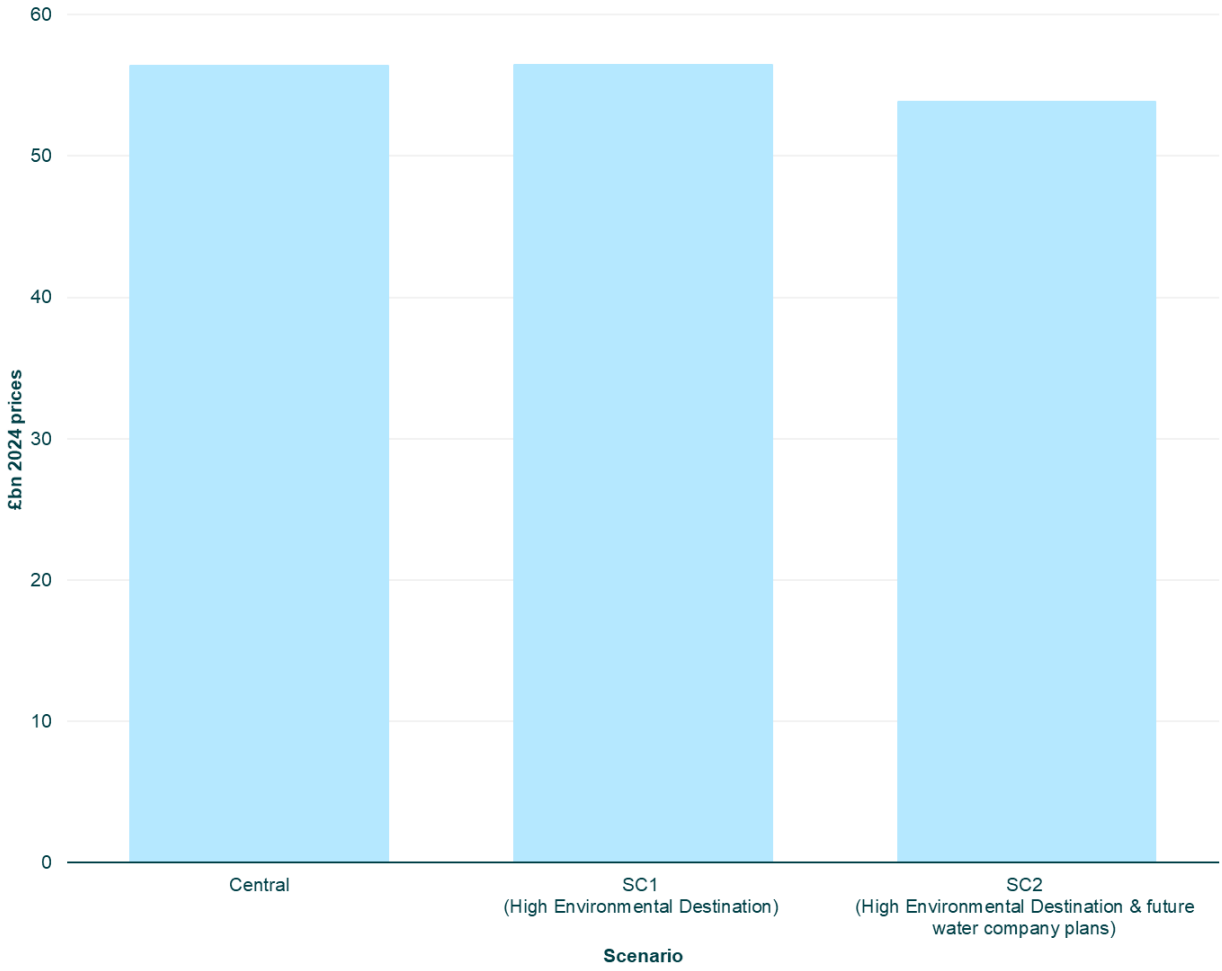
Figure 3-10 NPV (2024 prices, £ billion) of GVA losses in the UK between 2025 and 2059 in all analysed sectors by climate scenarios



Environmental Destination: Figure 3-11 SC1 indicates that greater levels of Environmental Destination (ED) ambition have a minimal impact on economic losses in England. This is predominantly due to the relatively few surface water abstraction licences in localised areas which are impacted by the policy, and because direct costs of ED reductions are not accounted for.

Future water company plans: Figure 3-11 SC2 compares the losses related to incorporating the future likely water company plans (such as major reservoirs, water transfers, etc), into the baseline. The results indicate that these plans reduce economic losses associated with future water scarcity by less than 5% over the period to 2059. The main reason for this is that whilst these plans can free up more water, they are focussed on meeting the demands of public water supply, not private abstractors. This conclusion aligns with the assumptions made around the benefits of system adaptation measures (see Chapter 2.7 for further information).

Figure 3-11 NPV (2024 prices) of GVA losses in England between 2025 and 2059 in all analysed sectors, by different pathways (central climate scenario)



3.2 Acute water stress

3.2.1 Outputs of the assessment

The chronic water stress assessment examined average modelled levels of water stress, while the acute water stress assessment considers extreme events of water stress. Different sectors and their sub-sectors may experience varying levels of exposure and vulnerability to different types of acute water stress event, even within the same geographic area, due to their specific water usage requirements. The acute water stress assessment has focussed on 'hydrological droughts', specifically the influence on flows and the impact this has on an abstractor's ability to abstract.

As noted in Chapter 2.6.6, due to the data and methodological limitations, there are substantial uncertainties which exist in the assessment of acute water stress. A key finding has been that this methodology and timeframe considered means that statistically it is difficult to distinguish between natural variation in events and climate driven worsening. For this reason, the outputs of this assessment are presented at a high-level and should be viewed as indicative. A more detailed assessment for power is provided as Box 3-3.

The river flow assessment, for which the methodology is included in Chapter 2.4, has shown a worsening of flows across England in the summer and into autumn. These are consistent with other studies that demonstrate an increase in the duration of water stress periods in the future.

Acute water stress will lead to economic losses through some of the same mechanisms as chronic water stress. Prolonged acute water stress will have major structural implications within sectors, which our established economic loss quantification methodologies are not well designed to capture.

Other studies have shown that the impacts of climate change on acute water stress impacts become far more prominent on longer timeframes (i.e. out to 2080s) than considered in this assessment[106], [107].

3.2.2 Power

Prolonged future acute drought events could lead to substantial disruption at specific freshwater cooled thermal generation plants, and additional economic losses to hydroelectric power operators. Should an acute drought span a substantial timeframe, or across Europe, it could cause substantial disruption.

Box 3-3 - Acute water stress in the power sector in the UK, an illustrative example

Acute water stress events were computed at a site level and aggregated to a regional scale. An inventory of weather events was created for each abstraction licence. These events represent periods used to compare water stress levels across scenarios. The methodology can be reviewed in Chapter 2.4.

The key findings of the assessment for power at a UK scale are:

- The greatest change in acute water stress risk for the power sector comes from assumptions about future growth in water demand. If abstractors use their full licensed volumes (rather than recent actual use), unmet demand could increase substantially, potentially tripling across the UK by the 2050s.
- While climate change (moving from 1.3°C to 2.0°C warming) does worsen summer and autumn river flows and increases the frequency and severity of water stress events, these changes are modest compared to the impact of demand growth. Natural climate variability can mask the climate change signal, and the severity of recent droughts has not surpassed those of the 1970s despite over 1°C of warming.
- Changes to abstraction licences for environmental reasons and public water supply adaptation actions have only small influences on the number and volume of unmet demand events during acute water stress at regional or national scales. Their impacts are highly localised and specific to certain sites or river reaches.
- The power sector in Water Resources East is the most severely impacted region by acute water stress as there is a relatively high concentration of thermal generators (nuclear and gas) with large cooling requirements[108]. In the baseline scenario (1.3°C warming, no growth), the mean unmet

[106] https://actuaries.blog.gov.uk/2025/01/28/uncertainty-in-climate-analysis/#:~:text=La%20Ni%C3%B1a%20events)%20%E2%80%A6-,%E2%80%A6,detect%20underlying%20longer%2Dterm%20trends.%20and%20this%20one:%20https://www.ipcc.ch/report/ar6/wg1/downloads/faqs/IPCC_AR6_WGI_FAQ_Chapter_03.pdf

[107] https://www.ipcc.ch/report/ar6/wg1/downloads/faqs/IPCC_AR6_WGI_FAQ_Chapter_03.pdf

[108] https://assets.publishing.service.gov.uk/media/660445a1f9ab41001aeea416/Location_of_major_UK_electricity_generation_capacity_since_1920.pdf

demand during the worst 3-month events reaches 10% of total demand when starting in July. The frequency of severe events also increases by a factor of 2.6 when moving from 1.3°C to 2.0°C warming.

The acute water stress analysis for power has shown only small differences in weather driven unmet demand between modelled baseline and future projections of climate. Via discussion with the SSG feedback highlighted that the actual impact of acute water stress events on abstractors is directly linked to the operational use of water, for example how water is used over a typical year, what the consumptiveness of activities are and how water is returned to the natural environment, which has not been assessed through this work. This means that the results of this assessment of acute water stress are uncertain and need further testing and corroboration with sector stakeholders.

3.2.3 Agriculture – A qualitative view

Economic losses to agricultural products from acute droughts are very dependent upon the event duration, and timing relative to the growing season. Estimates from Morris, J. et al. (1999)[109] show that, for example, a sustained drought starting in June would remove 85% of the potato yield and result in a 90% quality loss of the remaining crop, while the same event starting in August would only remove 25% of the yield and reduce quality by 10%. Acute droughts starting earlier in the growing season (i.e. April-June) could lead to almost complete crop failure, while events later in the year carry much lower economic losses. This assessment has indicated that acute droughts in April to June could increase by 2050, which would imply an increase in instances of crop failure.

3.2.4 Industry – A qualitative view

Feedback from the SSG has been clear that output losses linked to water scarcity principally occur through temporary plant shutdowns. With the increased frequency of acute events experienced in some regions, it may substantially challenge current business models for some production facilities. Other sites could face substantially higher costs as they seek to adapt to water scarcity through a combination of site-specific adaptation measures and managed closures.

[109] Morris, J., Weatherhead, EK, Mills, J, Dunderdale, J, Hess, T, Gowing, D, Sanders, C. and Knox, JW. (1999) Spray irrigation cost benefit study. EA final Report

4. An effective adaptation response

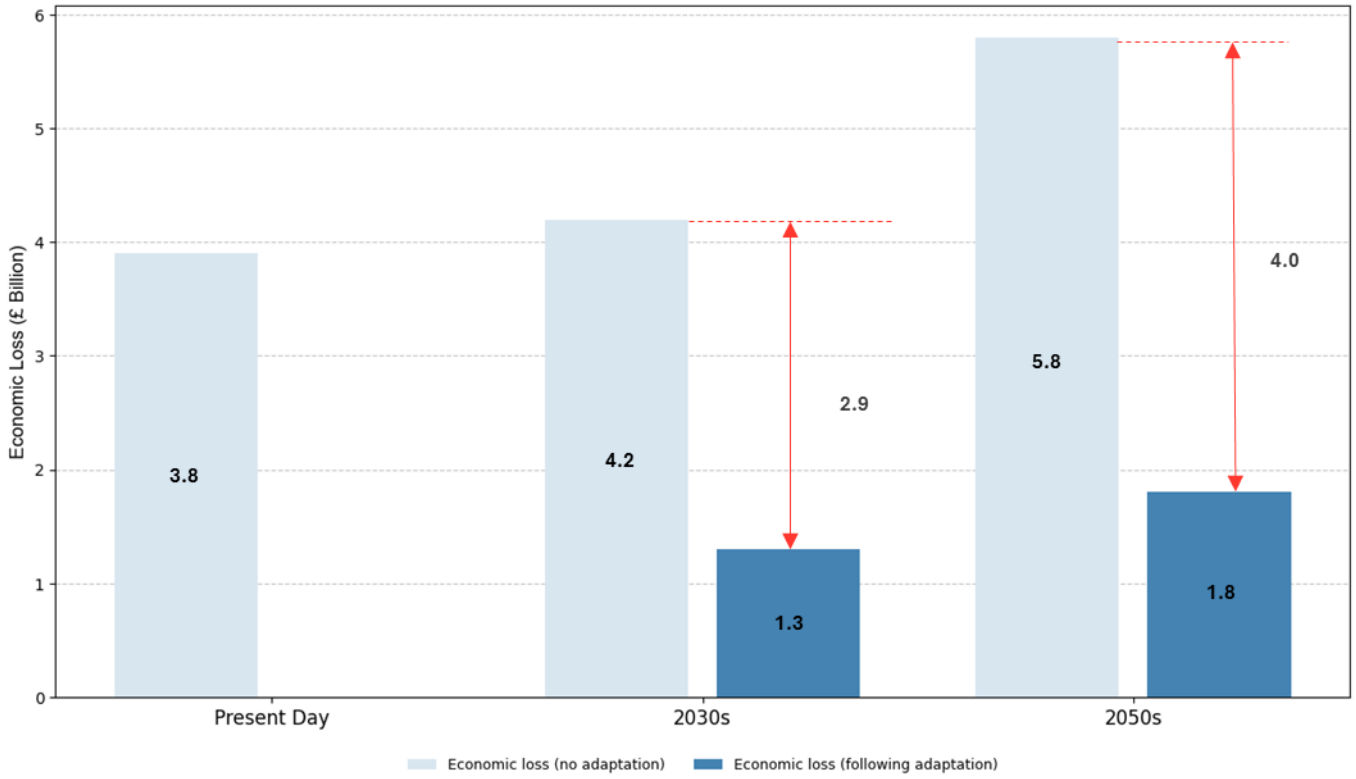
4.1 Overview

The unmet demand profiles developed for each sub-sector and region were run through the optimisation process defined in Chapter 2. This optimisation process considered the shortlisted adaptation options to meet the unmet demand (see Chapter 2.7 for a description of the process). The adaptation options considered were:

- Site and sector specific measures – such as onsite water storage, implementing precision irrigation.
- Catchment / ecosystem scale measures – such as wetlands, bank infiltration, swales and percolation basins. Such options are mainly indirect adaptation measures that would promote more infiltration into the ground (replenishing groundwater), supporting rivers during periods of drought, potentially allowing abstractions to continue longer.
- System-wide measures – these are large scale options, such as desalination plants and water transfers. They typically come at a large cost with long lead in times but yield substantial water volume. These solutions have been identified from water company and regional group plans where they have been considered but not selected. In the context of this assessment, a proportion of the water resources benefit has been assumed; as an example, by developing a strategic water transfer less water would need to be abstracted for public water supply, reducing water stress on other abstractors. The costs of this water have been factored, i.e. if 5% of the water yielded from a water transfer, the cost (CapEx and Operational Expenditure (OpEx)) would be 5% of the total.
- Institutional measures– these measures are focussed on optimising water use through practices such as water trading. Institutional measures are explored separately in Chapter 4.6 and have not been included within the assessment, due to the uncertainty and lack of available information.

The selected adaptation measures were then aggregated (measure and impact) to a sector and regional (and national) level; an example of how this works is provided in Box 4-1. The reductions in regional economic losses are then aggregated together to derive a UK national total reduction in economic losses by adaptation package application.

Figure 4-1 Avoided climate risk from a cost-optimal adaptation package (central scenario – UK combined). Presented as the economic loss with no adaptation & economic loss with adaptation (£ billion)



The results of the total economic losses from water stress for the central scenario with and without adaptation are provided in Figure 4-1. There is opportunity to substantially reduce water scarcity losses, by £2.9 billion in the 2030s and £4.0 billion in the 2050s, at the comparatively modest annual average cost of adaptation (approximately £30 million annual average ToTex over 2030s, and £100 million over the 2050s).

The residual losses identified in Figure 4-1 are due to:

- In the short term – the time taken to develop and implement adaptations (for example, a desalination plant takes 10 years, alternatively irrigation at night can happen instantaneously).
- In the longer term – some unresolvable impacts to industry where the feasible list of options / adaptations are exhausted (e.g., removal of sediment in existing reservoirs in Eastern Scotland).
- Hydropower – no details of the type of hydropower (i.e. run of river, storage) is available from the abstraction licence data. Addition or expansion of any storage to manage water stress would be highly site specific and typically combined with other facilities, such as reservoirs, so have not been included. It is considered that the catchment and institutional measures identified, which focus on replacement of water would not be cost beneficial. Therefore, the losses remain.

Table 4.1 summarises the adaptation options selected at a national level, presented as a percentage of the regions. The table illustrates that for most cases, there are several adaptation packages which could be chosen to reduce losses. Those identified are typically a combination of: benefit cost ratio, time to deployment and volume of water yielded. As an example, precision irrigation is selected over

desalination for agriculture, despite the cost effectiveness to provide the water being lower; this is predominately due to the time taken for plant deployment and the required volumes of water (desalination is not as scalable).

The table illustrates that across industry and agriculture, easily adopted and cost-effective sector specific adaptation measures are implemented rapidly, such as irrigating at night or on-site storage. These solutions decrease the existing impacts of water stress substantially. The next most cost-effective adaptations are typically at catchment and system level. This is generally because they are more cost effective than other sector specific adaptations, which are only selected when catchment or system adaptations are too slow to be implemented or exhausted. Box 4-1 presents an illustration of the pathway taken for industry.

As discussed in Chapter 2, most adaptation measures for the power sector identified focus on provision of additional water (directly or indirectly, see Chapter 2.7 for further information) to meet the demands of a particular site (in keeping with the scope of this assessment), rather than considering strategic energy network resilience (to water stress). However, there is substantial potential to reduce water demand from this sector, in combination with the journey to Net Zero, through transitioning to different technologies and coastal / estuarine water sources to essentially form adaptation for other sectors (see Chapter 5 for further discussion).

As discussed in Chapter 2, the assessment has necessarily focussed on generally applicable adaptations. Optimal adaptations will be highly process, operational and site specific. This means that there is opportunity for more cost-efficient approaches, particularly within industry, and a lesser reliance on catchment and system adaptations. The remaining system and catchment solutions would likely need to be developed and maintained by others outside of the sector themselves.

Table 4.1 Adaptation options ordered by their cost effectiveness ratio and percentage of regions selected

Adaptation types: S/S site or sector specific, C catchment, S system; *Ratio indicates the relative cost of providing water, lower the best; - indicates not relevant.

Adaptation Measure	Adaptation type	Cost effectiveness*	Approx. rank	England			Scotland			Wales			N. Ireland		
				Agriculture	Industry	Power	Agriculture	Industry	Power	Agriculture	Industry	Power	Agriculture	Industry	Power
Swap to drought-resistant and drought-tolerant crops	S/S	0.00	1	100 %	n/a	n/a	100 %	n/a	-	100 %	n/a	-	100 %	n/a	-
Irrigate at night	S/S	0.00	1	100 %	n/a	n/a	100 %	n/a	-	100 %	n/a	-	100 %	n/a	-
Tied ridging or contour ploughing	S/S	0.02	3	40%	n/a	n/a	33%	n/a	-	50%	n/a	-	0%	n/a	-
Build infrastructure for induced bank filtration	C	0.09	4	40%	40%	20%	n/a	n/a	-	0%	n/a	-	0%	n/a	-
Install wastewater (greywater) reuse units	S	0.15	5	20%	20%	40%	n/a	n/a	-	0%	50%	-	n/a	n/a	-
Install roof rainwater collectors	S	0.20	6	20%	60%	80%	33%	66%	-	0%	50%	-	0%	0%	-
Build desalination plants	S	0.34	7	0%	40%	80%	0%	66%	-	n/a	n/a	-	n/a	n/a	-
Mechanical cultivation of the subsoil (termed 'subsoiling' or 'deep ripping')	S/S	0.35	8	20%	n/a	n/a	0%	n/a	-	0%	n/a	-	0%	n/a	-
Precision irrigation (PI) and objective irrigation scheduling	S/S	0.38	9	60%	n/a	n/a	66%	n/a	-	0%	n/a	-	0%	n/a	-
Intra-basin water transfers	S	0.46	10	0%	40%	60%	n/a	n/a	-	n/a	n/a	-	0%	0%	-

(Strategic Water Transfers)															
Build on-site storage reservoirs (shared in Agriculture)	S/S	0.48	11	0%	n/a	n/a	0%	n/a	-	0%	n/a	-	0%	n/a	-
Build on-site storage reservoirs	S/S	0.53	12	0%	60%	80%	0%	100 %	-	0%	100 %	-	0%	100 %	-
Deficit irrigation	S/S	0.54	13	0%	n/a	n/a	33%	n/a	-	0%	n/a	-	0%	n/a	-
Use mulching to reduce evaporation of soil moisture and reduced or no tilling	S/S	0.68	14	0%	n/a	n/a	33%	n/a	-	0%	n/a	-	0%	n/a	-
Establish and/or restoration of riparian buffer zones	C	1.02	15	0%	n/a	n/a	0%	n/a	-	0%	n/a	-	0%	n/a	-
Soil amendments or improvers (polyacrylamides, PAM)	S/S	1.40	16	0%	n/a	n/a	0%	n/a	-	0%	n/a	-	0%	n/a	-
Remove accumulated sediment in reservoirs	S	1.77	17	0%	100 %	80%	0%	0%	-	0%	100 %	-d	0%	0%	-
Create inland wetlands	C	2.52	18	0%	40%	80%	0%	33%	-	0%	50%	-	0%	0%	-
Alter sowing and harvest dates	S/S	4.04	19	0%	n/a	n/a	0%	n/a	-	0%	n/a	-	0%	n/a	-
Install swales (depressions to capture water)	C	6.41	20	0%	60%	80%	0%	0%	-	0%	50%	-	0%	0%	-
Build percolation basins	C	10.44	21	0%	40%	80%	0%	33%	-	0%	0%	-d	0%	0%	-

Box 4-1- Example of adaptation pathway for industry

The figure below presents the calculated adaptation pathway to meet the unmet demand in the industry sector in the Water Resources South East region of England. Each region and sector has its own profile – this is being used for illustration purposes.

The unmet demand line (orange) shows an existing volume of under 4Ml/d until just after 2034, then it linearly increases through to over 8Ml/d in 2059.

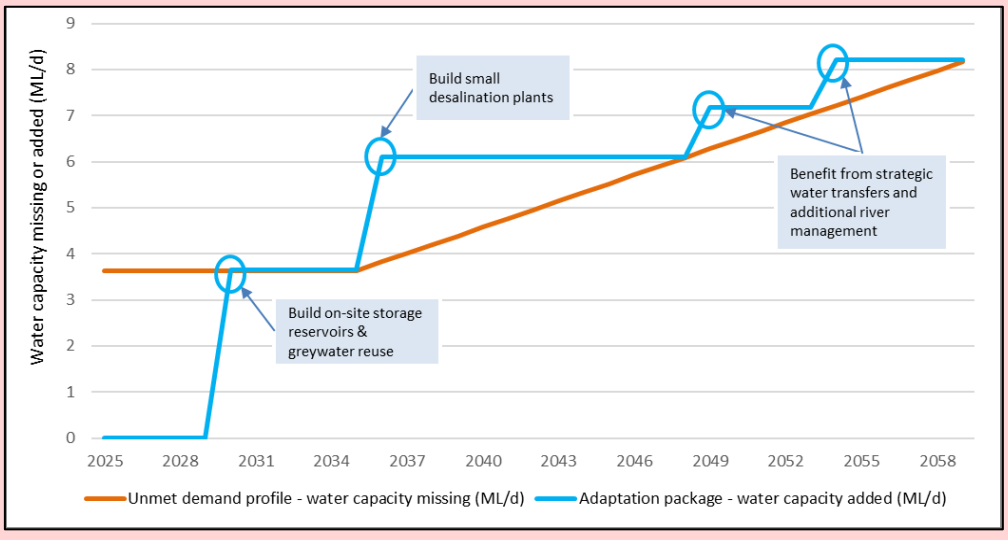
The first cost effective measures applied are onsite storage and greywater solutions to meet the existing unmet demand – this selection is a combination of cost and the ability to be rapidly deployed.

The next cost-effective measure is small desalination plants (system measure, provided by the public water supplier), which provide a capacity of water which is sufficient to meet the unmet demand requirements through to approximately 2049. Desalination plants need an extended time to design and implement, but there is enough time to plan and implement them before the water is required. As with other system options, this option has been taken from the water companies' list of water resources options not taken forward in the last planning cycle (i.e. those published in 2024). It is therefore an option for water supply but would be delivered by water companies rather than the industry sector.

Following this, a strategic resource option (water transfer) is selected, which would again be delivered by the water company. As with desalination plants, water transfers require a long time to implement, but is sufficiently far into the future to plan, design and build ahead of its requirement. Following this, the catchment option of bank infiltration is chosen.

This pathway shows how the adaptations are selected and ordered to meet the unmet demand in a conservative way (i.e. the water is provided ahead of when it is needed), according to cost.

Figure 4-2 Projected unmet demand profile for industry in Water Resources South East region of England- Central Scenario - and the adaptation package optimised to meet it



4.2 Agriculture

Full adaptation pathways are presented in Appendix K. The key packages of adaptation are:

Now: all regions select lower-cost and easily implementable measures, such as:

- Increasing the current uptake of irrigating at night to reduce the impacts of evapotranspiration and wind on non-uniformity. Following best practice[110] many growers already irrigate at night due to the rotational requirements of mobile irrigation equipment, with fields being irrigated according to a defined schedule requiring a high utilisation rate of the equipment moving sequentially from field to field. Irrigating at night offers benefits in terms of reduced evapotranspiration rates and lower wind speeds, reducing non-beneficial water losses (from wind drift resulting in irrigation of non-cropped areas) and higher irrigation efficiencies. There are challenges in irrigating at night including health and safety issues linked to moving equipment and raising humidity levels in some crops leading to elevated disease risk, but there are still modest opportunities to encourage wider adoption of night-time irrigation.
- Switching to more drought resistant / tolerant crops, where feasible, recognising that plant breeding does not currently prioritise these genetic traits for UK crops.
- Additional measures in East Scotland and England, for example, implementing precision irrigation technologies to improve water efficiency and increase water productivity.

Precision irrigation (PI) involves applying water in a differential manner considering temporal and spatial variations in soil moisture and crop growth, and matching irrigation requirements with changing crop needs using objective scheduling techniques. PI offers opportunities to increase crop yields and quality, to minimise water, energy and environmental impacts (nutrient leaching risks)[111]. PI techniques are being implemented internationally in arid and semi-arid environments, mainly in response to water scarcity. In the UK uptake has been more gradual but rising costs for fertilisers and energy are likely to increase awareness of PI benefits and drive faster adoption, particularly in high-value horticultural crops[112].

2030s: Limited additional measures are necessary, except typically medium cost-effective catchment and system measures for some regions – particularly East Scotland and England, such as:

- Building infrastructure to induce increased soil water infiltration (catchment measures).
- Rainwater collectors and wastewater reuse (system measures).

2050s: Implementation of medium cost-effective catchment and system measures like the 2030s across more regions of England, particularly the North. Intensification of measures in East Scotland as the capacity of the 2030s measures are exhausted.

Initially the low-cost site-specific measures that involve behavioural changes to increase uptake rates are selected, for all nations, to save water in the short term. Through the 2030s and into the 2050s adaptation measures increase to catchment and system measures and less cost-effective site-specific measures as required, particularly in East Scotland and South East regions of England.

[110] Defra & ADAS. Irrigation Best Practice – A Water Management Tool Kit

[111] González Perea, R, Daccache, A, Rodríguez Díaz, JA, Camacho Poyato, E, Knox, JW (2017) Modelling impacts of precision irrigation on crop yield and in-field water management. *Precision Agriculture 19(5): 1-16.*

[112] Monaghan, J.M., Daccache, A., Vickers, L., Hess, T.M., Weatherhead, E.K., Grove, I.G., Knox, J.W. (2013). More'crop per drop' – constraints and opportunities for precision irrigation in European agriculture. *Journal of the Science of Food and Agriculture* 93(5):977-80

Many on-farm storage reservoirs already exist, for example, recent research by Knox et al[113] estimated 1,300 reservoirs in Eastern England. However, these are predominantly single use (irrigation only) and provide water for a single business. Effective adaptation could be achieved by utilising these reservoirs in a collaborative manner, increasing their connectivity to provide access to stored water for small groups of adjacent or neighbouring farming businesses. For example, recent research in the Lark catchment[113][114]identified opportunities for more effective shared reservoir management to improve resource efficiency and to manage irrigation deficits during droughts. Early-stage feasibility investigations and appraisal of this approach for collaborative water sharing using existing reservoirs are currently being undertaken in Suffolk (Lark catchment) and in Shropshire (Strine). Utilising existing reservoirs more effectively for drought risk management through such collaborative ventures would also reduce the need substantial investment in new reservoirs.

Box 4-2 - Alternative water sources for agriculture

Growing in polytunnels means that Place UK, a soft fruit grower based in Norfolk, relies entirely on irrigation. However, several of their legacy abstractions were deemed to be having a negative impact on local SSSIs, and their licences were therefore revoked by the regulator.

The business therefore needed a solution to provide an alternative supply while remaining economically viable. They decided on rainwater harvesting; this is not considered a reliable source as it is weather dependent, so most growers only use it to supplement licensed abstraction. However, Place UK had limited alternatives, so they devised an innovative system that captures 100% of runoff from their tunnels, even when the plastic sheeting is partially rolled up for ventilation. They also regraded the land surface to encourage gravity flow across the farm and built a 150,000m³ reservoir, large enough to store water for at least two dry years to ensure they have sufficient water for drought periods. A bonus was the improved water quality using rainwater and that the business now uses less fertiliser and produces higher quality fruit[115].

This case study provides an excellent example of how switching water sources has taken place out of necessity, and the adaptation measures (including source diversification to rainwater harvesting and storage) have allowed business continuity. However, the substantial costs (>£1 million) incurred for this adaptation response do need to be recognised.

4.3 Industry

Full adaptation pathways are presented in Appendix KK. The key packages of adaptation selected are:

Now: all nations and most regions implement small on-site storage reservoirs for highly cost-effective back-up sources of water. South-East and West England and Eastern Scotland are shown to require additional measures, like other regions in the 2030s, mainly until more substantial infrastructure can be brought in (middle 2030s).

[113] Knox, J., Holman, I., Momblanch, A., Simms, D., Panigrahi, N., Mwanza, M., (2024) Assessing drought and regulatory risks facing irrigated agriculture in Eastern England. Final Technical Report.

[114] Project-REPORT_-WfT-Lark-CamEO-Local-Project.pdf

[115] How Place UK is revolutionising fruit farming with agri-tech and automation

2030s: Across most of England, Eastern Scotland and Wales, medium catchment and system measures are selected, such as greywater reuse, percolation basins, removal of sediment in existing reservoirs or installation of swales, etc. In West and South East of England, East and North Scotland desalination plants and water transfers are brought in to meet demands in the 2030s.

2050s: Eastern Wales and most regions of England require additional catchment and system measures.

Substantial water scarcity is associated with East Scotland by the 2050s, largely connected to the large-scale food & drink industries in this area often sited on sensitive river catchments. However, most substantial economic losses are associated to parts of West and South-East England where water scarcity to the mineral production and large manufacturing industries results in large economic losses due to the higher levels of GVA associated with the sub-sector. While the food & drink sub-sector is more water-intensive than the mineral production and large manufacturing industries, because of the absolute economic size of the latter, economic losses from water scarcity are still substantive.

Other water scarcity at-risk regions and sectors include large-scale mineral production sites in West Wales, as well as multiple paper & pulp and chemical & petrochemical sites in the West and South-East of England.

Several desalination plant options have been selected, in East and North Scotland, and in South East and West of England, where heavy industry is located. These options would rely upon the water companies selecting and installing these from their plans or require collaboration between industrial facilities rather than being driven by individual sites.

As discussed in Chapter 2, this assessment has focussed on generally applicable adaptations. Optimal adaptations will be highly process, operational and site specific, particularly for industry. For example, water recycling and reuse would be more complex in food & drink or paper & pulp where the water is directly used as a feedstock (and quality requirements are stringent) in comparison to applications where water is used for quenching or cleaning (e.g. in the steel, mining sectors). There are potential differences in the design (and associated cost) of the same measure. This means that there is opportunity for more cost-efficient approaches, particularly within industry, and a lesser reliance on catchment and system adaptations (such as desalination plants).

Box 4-3 - Desalination

Desalination has become an increasingly vital tool in addressing water scarcity, particularly for industrial and agricultural applications in arid and drought-prone regions. By converting saline or brackish water into freshwater, desalination offers a dependable supply where traditional sources are insufficient or unreliable. Globally, 30.2% of desalinated water produced is used for industrial applications, 4.8% for power, and 1.8% for irrigation[116].

Reverse osmosis (RO) is the most widely adopted technology, accounting for over 60% of global desalination capacity. It has proven effective in delivering high-quality water for irrigation and industrial cooling, especially in regions with limited rainfall or overexploited aquifers. In Australia, the Kwinana desalination plant supplies water for industrial use in Perth's southern corridor, supporting manufacturing and mining operations. Similarly, in Spain's Murcia region, desalinated water has been

[116] Jones, E., Qadir, M., Van Vliet, M.T., Smakhtin, V. and Kang, S.M., (2019). The state of desalination and brine production: A global outlook. *Science of the total environment*, *657*, pp.1343-1356.

instrumental in sustaining high-value horticulture in semi-arid zones, with the Águilas-Guadalentín Desalination Plant providing capacity to irrigate 16,000 hectares of agricultural land[117].

Cost-effectiveness varies by context. While capital and operational costs are high, driven largely by energy consumption, technological advances such as reverse osmosis and energy recovery systems have substantially reduced costs. This has enabled the deployment of smaller-scale, private plants in water scarce areas such as Campo de Cartagena in Spain. There is estimated to be over 1,000 small desalination utilities in this region[118]. Associated costs are capital costs and operational costs, with individual cost-effectiveness dependent on the production (e.g. kg/ha for agriculture) and the price of services or products. Therefore, research into the cost effectiveness of site-specific, small desalination plants is not well defined and is often constrained to certain crops such as citrus[121].

Desalination's energy intensity remains a trade-off. Most large plants rely on fossil fuels, raising concerns about carbon emissions and freshwater consumption for cooling. Some regions are managing this through renewable integration; the Al Khafji plant in Saudi Arabia is powered entirely by solar energy, supplying water for agricultural use in desert farming initiatives[119]. Powering desalination plants with renewable energy also has the benefit of decreasing operational costs over time, evidenced by modelling for small (<600m³/day supply) desalination plants decreasing the cost of water when connected to renewable energy sources[120].

Environmental impacts include brine disposal and marine ecosystem disruption. Yet, innovations in brine management and intake design are improving sustainability. In China's Tianjin region, desalinated water supports industrial zones while employing advanced brine dilution techniques to minimise ecological harm[121].

4.4 Power

As discussed in Chapter 2, most adaptation measures identified for the power sector focus on provision of additional water (directly or indirectly, see Chapter 2.7 for further information) to meet the demands of a particular site (in keeping with the scope of this assessment), rather than considering strategic energy network resilience to water stress. The power sector, in combination with the journey to net zero, offers substantial potential for reducing current water demands, essentially forming adaptation for other sectors (see Chapter 5 for further discussion).

As previously stated, hydropower can come in several forms; run of river and storage operate very differently and have very different water scarcity risks and adaptation requirements. Due to this site-specific nature of their requirements, few of the adaptations identified are relevant and cost beneficial (in the form of providing more water). Run of river hydropower stations are expected to lower and raise their operational levels during the year based on river flow levels, and alternative (more expensive) available energy sources are often utilised during these low flow periods.

[117] Sacyr S,A, (date unknown) Águilas-Guadalentín Desalination Plant: quality water for high yield agriculture. Available at: Desaladora Águilas
[118] Aparicio, J., Candela, L., Alfranca, O. and García-Aróstegui, J.L., 2017. Economic evaluation of small desalination plants from brackish aquifers. Application to Campo de Cartagena (SE Spain). *Desalination*, *411*, pp.38-44.
[119] Saudi Vision 2030 (date unknown) AlKhafji Desalination Plant. Available at: https://www.vision2030.gov.sa/en/explore/projects/alkhafji-desalination-plant
[120] Kariman, H., Shafieian, A. and Khiadani, M., (2023). Small scale desalination technologies: A comprehensive review. *Desalination*, *567*, p.116985.
[121] China's Largest Dual-Membrane Seawater Desalination Project Fully Operational

Surface water cooled thermal power stations, i.e. fossil fuel plants, are only located in England. Scotland, Wales and Northern Ireland all have sea-cooled thermal power stations only. Therefore, adaptation requirements have only been identified for England.

Substantial adaptation would be required (full details in Appendix KK), with selected actions focussed on:

Now: A range of catchment and system measures to meet immediate demands.

2030s: Mid-level new infrastructure, such as bank filtration, desalination plants and storage reservoirs.

2050s: Further selection of catchment and system measures adding modest amounts of water as water stress increases. Measures include wetlands, permeable drainage features promoting infiltration into the ground (swales and percolation basins) as well as wastewater reuse (system measure implemented by water companies).

In many cases across the power sector, actual adaptation would likely involve the operator switching to a source of energy which uses less / no water or is coastally fed (see Box 3-2 for further information).

Box 4-4 - Institutional option – water trading, *an illustrative appraisal*

The assessment of adaptation measures included an illustrative appraisal of an institutional measure entailing water trading. The aim of this option was to explore the efficiency in distributing licences between different businesses in different regions (with no changes to overall total water availability). It is noted that this is a highly simplified exercise produced for illustrative purposes only and assumed that the market design does not cost businesses anything. Therefore, this measure has not been included within the adaptation response.

The benefits of this approach would require a detailed assessment, incorporating the true constraints around water trading, such as relative location of abstractions along a waterbody. The purpose of this exercise is not to develop this market trading governance, but to explore the hypothetical potential the measure holds in adapting to water stress at a national level.

As per the methodology, the direct economic value of water (GVA divided by total sub-sector demand) by sub-sector by country has been determined. National variances between the sub-sectors are apparent, but generally the most valuable use (direct only) is industry, followed by agriculture and power. The lowest value of water is for hydropower. As mentioned in previous chapters, the licence data does not indicate if these systems are consumptive (i.e. with storage) or run of river (i.e. non-consumptive). This is clearly a very important factor in understanding the potential to reallocate their licence value. The full results are presented in Appendix II.

The results of the assessment are summarised in the table below. It is re-iterated that this is an illustrative appraisal, and these results should not be used for any other purpose.

Table 4.2 Illustrative water trading results

Country	Sector	Sub sector	Ml/d water traded	Benefit-Cost Ratio*
England	Industry	Paper & Pulp	10.2	1.13
	Agriculture	Agriculture - Irrigated production	16.3	1.07
	Power	Fossil Fuels	78.8	1.02
	Industry	Chemicals & Petrochemicals	6.2	1.01
	Industry	Mineral Products, Extractives & Other Large Manufacturing	3.4	1.01
	Industry	Food & Drink	0.7	1.01
	Power	Waste / Biomass	0.7	1.00
	Power	Hydropower	-116.4 (0.6% of sector's water demand)	1.00
Wales	Industry	Food & Drink	0.7	1.29
	Industry	Chemicals & Petrochemicals	0.2	1.08
	Agriculture	Agriculture - Irrigated production	0.2	1.05
	Industry	Mineral Products, Extractives & Other Large Manufacturing	0.5	1.00
	Power	Hydropower	-1.5	1

			(0.02% of sector's water demand)	
Scotland	Industry	Food & Drink	48.3	1.12
	Industry	Paper & Pulp	19.9	1.06
	Agriculture	Agriculture - Irrigated production	1.3	1.03
	Industry	Mineral Products, Extractives & Other Large Manufacturing	1.3	1.03
	Industry	Chemicals & Petrochemicals	0.00	1.00
	Power	Hydropower	-70.8 (0.1% of sector's water demand)	1
Northern Ireland	Industry	Mineral Products, Extractives & Other Large Manufacturing	0.1	1.03
	Power	Hydropower	-0.1 (0.01% of sector's water demand)	1

*This is the ratio of the traded water i.e. the receiving subsector water value / the losing subsector water value

When comparing the total water use to the unmet demand, the unmet demand is a small percentage. Therefore, the hypothetical reallocation of existing water permits to industry and agriculture from the power sector would constitute a very small proportion of the overall sectoral water demand, i.e. between 0.01% (Northern Ireland) and 0.56% (England). It is noted that while a substantial share of water abstraction in the hydropower subsector is non-consumptive, the volume of water reallocated to other sectors would comfortably fall within the subsector's consumptive use.

Current economic value (annual average) of abstracted water for all sub-sectors in all countries is approximately £1,070 billion. Optimisation of the met demand value by reallocating water to the most valuable uses (without changing available water quantity) would increase annual value obtained from the same water to £1,089 billion - an increase of 1.7% or £18.5 billion per year on average. This additional value is obtained by simply re-allocating it to sub-sectors which obtain a higher GVA from the same water. Only a fraction of this would be achievable due to trading constraints, such as location.

Overall, this illustrative exercise has shown that there is the potential to deliver additional value from the available water, through reallocation. However, this was a hypothetical illustration, and detailed assessments would be required to confirm this conclusion and highly complex and mature governance would be required to ensure that the measure promotes positive outcomes at a catchment and watercourse reach level.

4.5 Co-benefits

The positive co-benefits of adaptation options results and quantification parameters are presented in Appendix J. Due to the nature of the co-benefits, the only adaptation options which provide them are the catchment measures for biodiversity and climate change. These benefits have been quantified, and the results are summarised in the table below; adaptation for agriculture did not include any options with co-benefits so is not included within the table.

Table 4.3 Co-benefits of adaptation options – total annual benefits (£million, NPV, central scenario)

	Industry		Power	
	Inland wetlands	Percolation basins	Inland wetlands	Percolation basins
England				
Biodiversity	5	0	5	0
Climate change	15	15	10	0
Scotland				
Biodiversity	5	0	N/A	N/A
Climate change	10	10	N/A	N/A
Northern Ireland				
Biodiversity	N/A	N/A	N/A	N/A
Climate change	N/A	N/A	N/A	N/A
Wales				
Biodiversity	0	N/A	N/A	N/A
Climate change	5	N/A	N/A	N/A
Total	45	25	15	0

*Note, inland wetlands and percolation basins were not selected for agricultural adaptation, are not included within this table

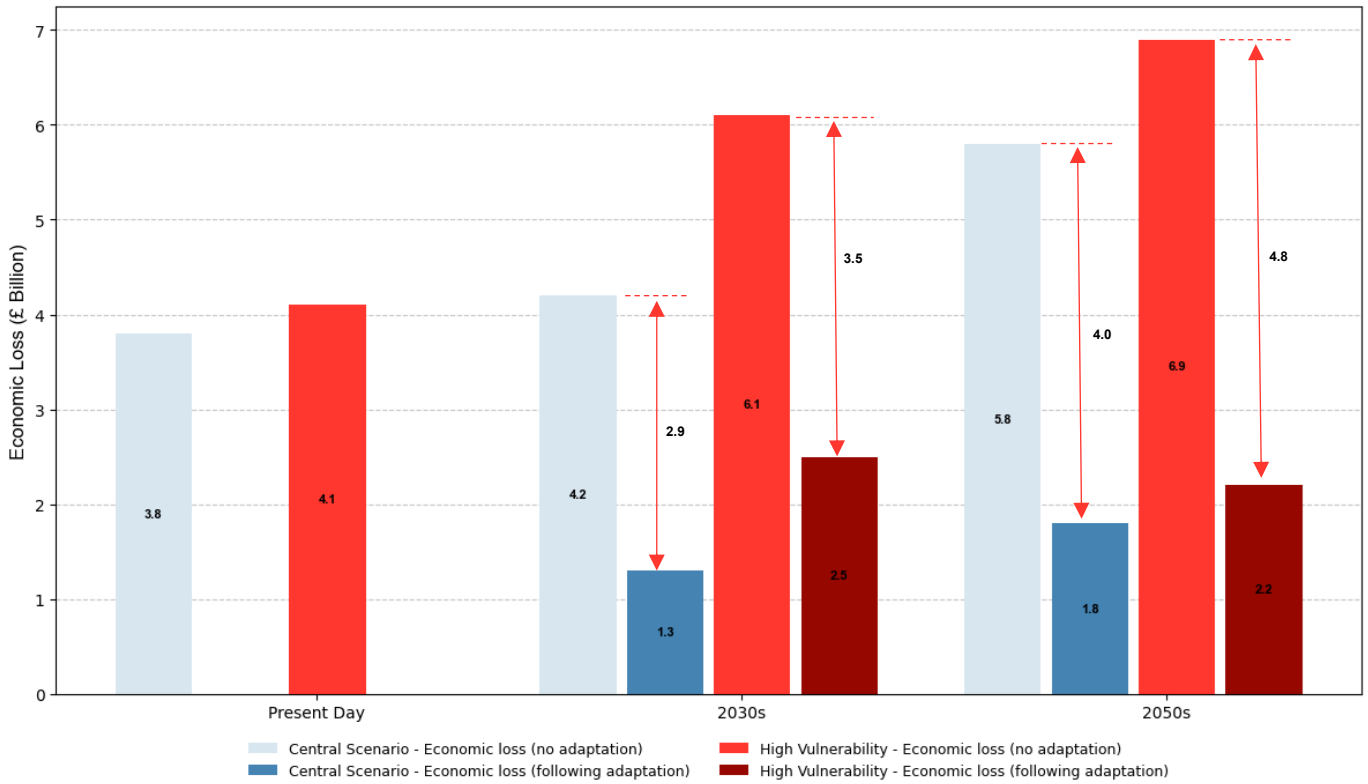
Total co-benefits (biodiversity and climate change mitigation) of adaptation options are included in the cost-optimal package presented in Figure 4-1, totalling approximately £85 million (NPV). As previously noted, the associated disbenefits of these measures (such as embedded carbon) have not been determined.

4.6 Sensitivity analysis

As presented in Figure 4-3, the central and high climate hazard scenarios increase in economic losses through the 2030s and 2050s, with the high climate hazard scenario increasing more rapidly. Swift deployment and implementation of adaptation measures in the 2030s materially reduces the losses. Through to the 2050s, more substantial and less cost-effective adaptation measures are required. This leads to a higher proportion of adaptation costs and reduced avoided damages. Due to the exhaustion of quick implementation adaptation measures early on, and the time taken to implement longer term engineering solutions, losses following adaptation in the 2030s are higher.

Adaptation, particularly for industry, requires the implementation of long lead-in infrastructure, such as water transfers (15 years) and desalination plants (10 years). The high climate hazard scenario would require an acceleration of these measures to be adopted.

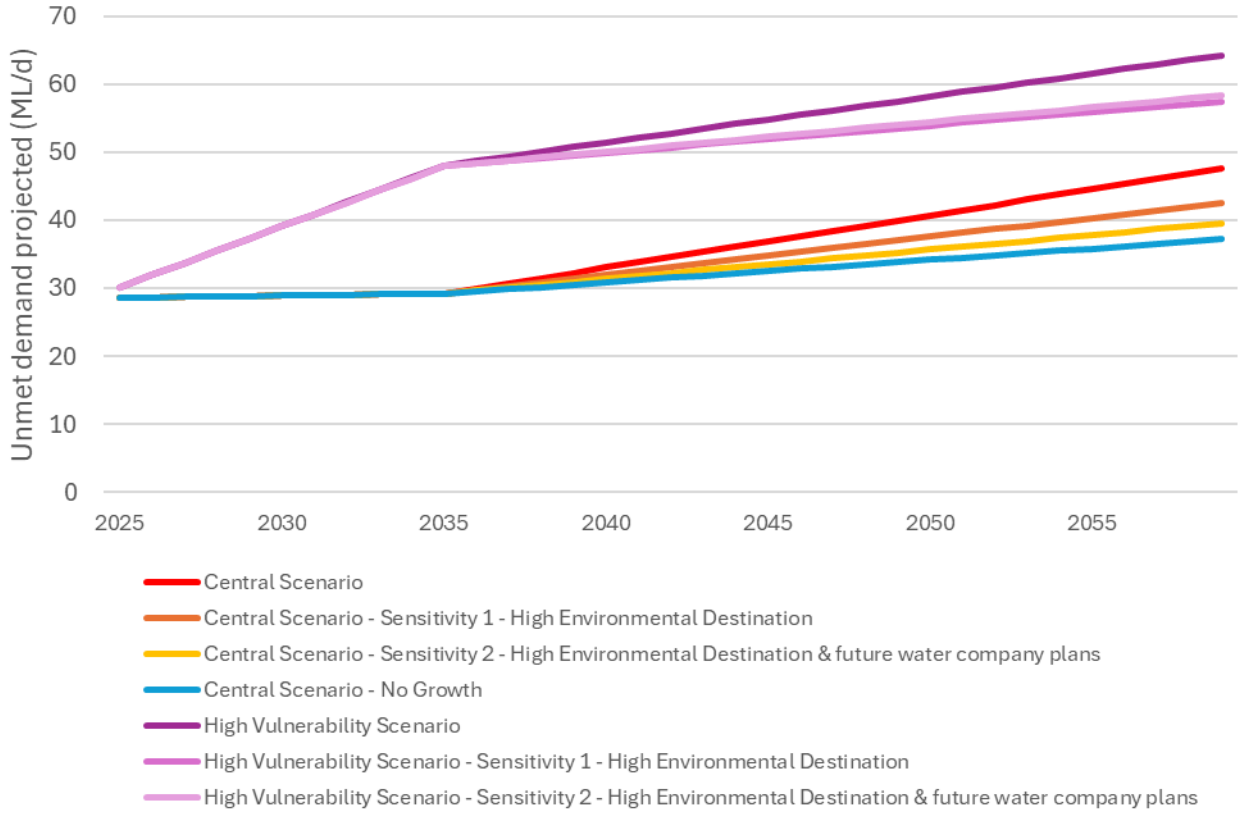
Figure 4-3 Avoided climate risk (£bn) from a cost-optimal adaptation package (high climate hazard scenario vs central scenario – UK combined)



Due to a more sophisticated base model available for England, additional sensitivity scenarios were possible and assessed the impact of: high Environmental Destination ambition (sensitivity 1) and future water company plans (sensitivity 2). A central scenario with no growth applied out to 2050 is also examined (scenario: No Growth), with the difference between this and the central scenario indicating the impact of growth on unmet demand and thus also on economic losses.

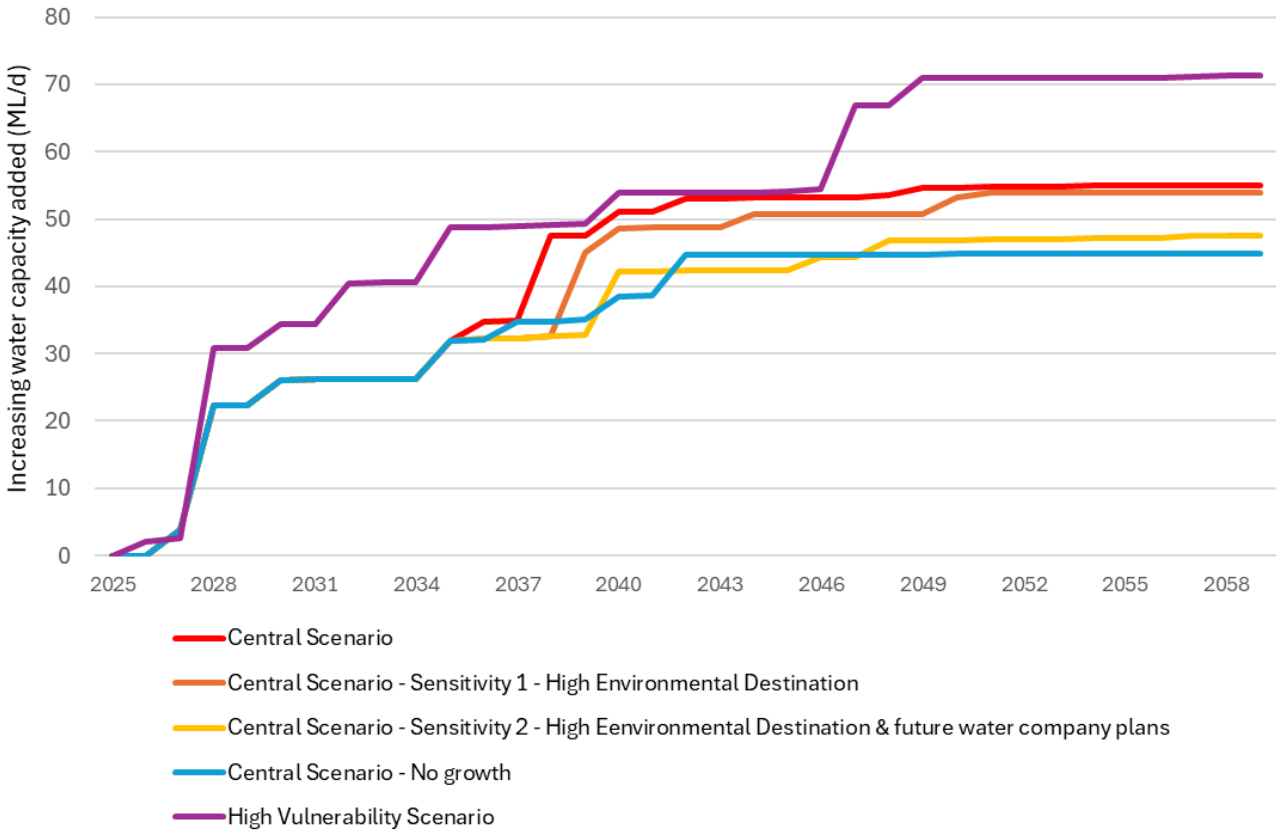
The unmet demand profiles generated across the different sensitivity scenarios for the combined sectors of industry and agriculture across England are shown in Figure 4-4. This shows how the scenarios with the higher Environmental Destination ambition applied have a reduced profile of unmet demand registered, caused by the abstraction reductions already being applied in these scenarios due to Environmental Destination. These profiles are further reduced by the inclusion of the future water company plans, which provide additional supply in the summer dry periods in isolated areas. The no growth central scenario shows the lowest unmet demand registered against the base central scenario.

Figure 4-4 Variation in unmet demand (megalitres per day) across the sensitivity scenarios in England for industry and agriculture combined



The cost-optimal adaptation packages 'water capacity added' for each of the scenarios are presented in Figure 4-5. Whilst each of these pathways have important differences, the key outcome for this study is that the sensitivity analysis pathways sit below the high climate hazard, with the central scenario sitting approximately in the middle.

Figure 4-5 Variation in adaptation packages 'water capacity added (megalitre per day)' pathways across the sensitivity scenarios in England for industry and agriculture combined



5. Transition to Net Zero

5.1 Context

The CCC's advice on CB7 sets a recommendation to cap greenhouse gas emissions at 535 $MtCO_2e$ for the period 2038–2042. Achieving this target would represent an 87% reduction relative to 1990 levels by 2040, increasing to approximately 90% when excluding international aviation and shipping. The advice outlines 'balanced decarbonisation pathways' across key sectors:

- **Power:** Expansion of renewable energy sources, enhanced grid flexibility, and increased electricity storage capacity.
- **Industry:** Transition through electrification, CCS, hydrogen adoption, and efficiency enhancements.
- **Agriculture & land use:** Emissions mitigation via improved land management and livestock practices.

This chapter evaluates and outlines the risks and opportunities associated with changes in sectoral water demand resulting from the net zero transition. The focus is on technologies expected to be implemented in the power and industrial sectors, since many emissions mitigation measures associated with agriculture and land use changes also serve as adaptation options included in the previously discussed optimised adaptation strategy in Chapter 4.

For power generation, this assessment estimates the projected energy mix in the CCC's advice on CB7 for 2040-2050, measured in megalitres per day (Ml/d) per terawatt hour (TWh) generated. For the industrial balanced pathway, water intensities are given in Ml/d per tonne of CO_2 captured by CCS and per kilogram of hydrogen produced (KgH_2). Appendix L lists the adopted water intensity factors and their sources.

5.2 Power sector decarbonisation

The power sector 'Balanced Pathway' set out in the CCC's advice on CB7 requires substantial changes to the energy system. These changes involve a major shift towards renewable energy sources, primarily offshore and onshore wind and solar photovoltaics (PV), utilisation of low-carbon fuels such as hydrogen and biomass, and the deployment of CCS to new or retrofitted thermal generation plants. The deployment of these technologies differs by location, and they are integrated to provide capacity, storage, and dispatchable power to the grid. This approach is designed to maintain grid flexibility and stability with the aim of achieving an 87% reduction in emissions from 1990 levels by 2040.

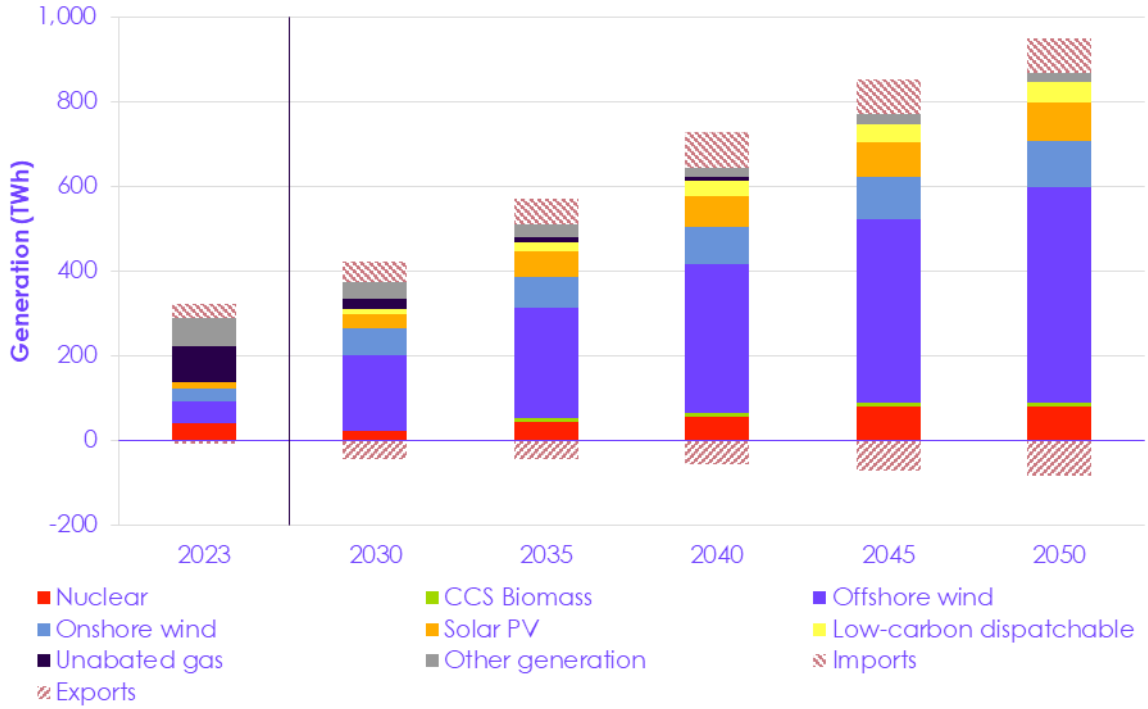
Figure 5-1 shows that the CCC's Balanced Pathway anticipates a six-fold increase in offshore wind capacity (to 88 Giga Watts (GW)), a doubling of onshore wind (to 32 GW), and a rise in solar PV to 82 GW by 2040. These technologies operate without thermal cycles, requiring minimal water. They may involve minor water use for panel cleaning or dust suppression, but this is likely to be negligible in the UK context.

Nuclear power remains a key dispatchable low-carbon source in the CCC's Balanced Pathway in 2040. Whilst nuclear plants are among the most water-intensive technologies, as they use large volumes of water for cooling, all those currently existing and planned are located with access to coastal or brackish water (estuarine locations).

Of the remaining technologies, the following are somewhat dependent on inland surface water sources referred to as freshwater in this chapter:

- **Low carbon dispatchable technologies**: Including:
  - Hydrogen – both as a fuel for generation and a store for capacity.
  - Existing and new thermal (gas) generation typically as Combined Cycle Gas Turbine (CCGT) with CCS or CCGT with hydrogen.
- **CCS bioenergy:** Also known as BECCS.
- **Unabated gas:** Natural gas typically as CCGT.
- **Other**: Including energy from waste, energy from waste as Combined Heat and Power (CHP), Gas CHP and biomass.

Figure 5-1 Power generation mix for the CCC's Balanced Pathway (TWh, 7th Carbon Budget)



The possible freshwater demand for each power generation and hydrogen production technology considered in the CCC's advice on CB7 is discussed further below, Appendix L provides a full list of the water intensity factors used along with their source. It must be noted however, that the intensity of freshwater demand varies considerably, depending on both the specific technology and the type of cooling process employed. In most cases, the most substantial portion of water demand is attributed to cooling processes. For this analysis, the highest reported water intensity values from the literature have been adopted to provide an indication as to the worst case. These upper range values are typically

linked to once-through cooling methods, which can increase water demand by up to ten times when compared with closed-loop and hybrid cooling systems.[122] [123] [124].

5.2.1 Thermal generation

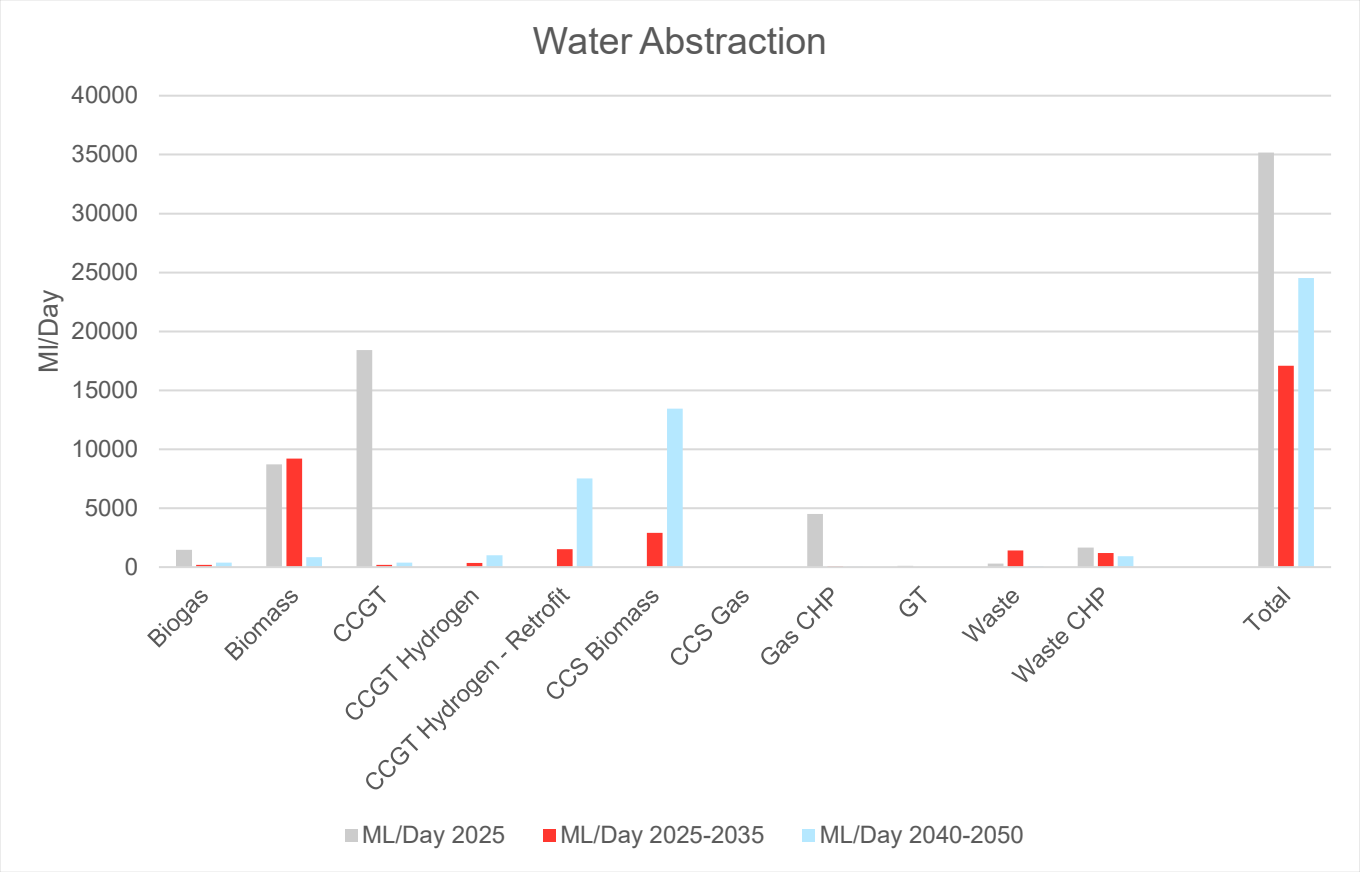
In the CCC's Balanced Pathway, projections indicate that unabated fossil fuels will be fully phased out by 2050. Some unabated gas-fired generation may continue in the short term to support system balancing and could remain part of the generation mix into the 2040s, with thermal generation transitioning toward CCS. CCS is an essential mechanism for enabling low-carbon, dispatchable power within the CCC's Balanced Pathway. Its primary application is in fossil fuel-based thermal power generation, specifically natural gas, allowing continued energy production while mitigating associated carbon dioxide emissions.

Figure 5-2 presents the average estimated freshwater demand for the near term and long term, across the thermal generating technologies compared to the reference year of 2025. Although power generation is projected to increase from around 300 TWh to approximately 800 TWh by 2050, it is estimated that for thermal power generation the freshwater intensity will drop in the near-term (2025-2035) when compared to the baseline year of 2025, by approximately 51% from the water intensity of 35,172Ml/d to 17,080 Ml/d as production shifts toward renewables.

Within the CCC's Balanced Pathway, gas with CCS is positioned as a transitional, dispatchable resource. While its significance declines toward the end of 2040's, it remains a major contributor to the providing the extra generation required for electrification, and hence overall water demand during this period, requiring more than 24,532Ml/d on average (see Figure 5-2). Whilst it should be noted that this estimate is likely conservative as it has been based on the presumption of once-through cooling systems, CCS facilities do have substantial water requirements for processes such as solvent regeneration, cooling, and carbon dioxide compression and transport.

[122] https://www.energy-uk.org.uk/wp-content/uploads/2023/03/Report_JEP21WT02_V1.pdf
[123] Electricity generation and cooling water use: UK pathways to 2050 - ScienceDirect
[124] Environment Agency. National Framework for Water Resources – Water & Energy AECOM Jan 2024

Figure 5-2 Estimated Present day (2025) freshwater demand compared to near-term (2025 -2035) and long-term (2040-2050) for power generation in megalitres per day (Ml/d)



In addition to natural gas, both new and retrofitted CCGT using hydrogen as a fuel are projected to play a substantial part in the transition toward Net Zero. Water used for hydrogen production is discussed below. The water consumption of CCGT primarily depends on the type of cooling system implemented. Once-through cooling systems generally result in higher water abstraction than evaporative cooling systems (cooling towers); however, most of the water withdrawn by once-through systems is non-consumptive and is returned to the original surface water source[125].See Figure 5-2.**Error! Reference s ource not found.** shows that both new and retrofitted hydrogen CCGT could require up to on average 550 ml/d in the 2040-2050 period.

Biomass is allocated for BECCS to provide negative emissions and for flexible generation capacity to maintain grid stability. Fresh water use related to biomass includes irrigation of energy crops (when sourced domestically), and water required for processing and cooling in combustion or gasification plants. Research by Wu et al. (2021)[126] found that water consumption during the biomass production stage constituted 98% of total water usage throughout the life cycle in a dedicated biomass-to-power pathway. In the baseline risk assessment discussed in Chapter 3, the agriculture sector already incorporates projected growth factors for future water needs; therefore, the production stage is not further examined here. However, water demand has been calculated based on the possible water requirements of CCS and adopting the assumption of once through cooling. Figure 5-2**Error! Reference s**

[125] JEP21WT07 A Review of Water Use For Hydrogen Production - Energy UK
[126] Consumptive life cycle water use of biomass-to-power plants with carbon capture and sequestration - ScienceDirect

ource not found. shows that the relative freshwater demand of biomass with CCS increases to over 7,500Ml/d, but this increased water demand is offset by the phasing out of unabated biomass.

5.2.2 Hydrogen production

Hydrogen's energy density relative to its weight and its storage characteristics are relevant for the UK's transition to net zero. In the CCC's Balanced Pathway, hydrogen plays a small but key role as a long-term energy storage solution to support grid stability alongside variable renewables. The effects on abstraction rates from inland surface waters strongly depend on the hydrogen production method and their location. The CCC's Balanced Pathway considers four different hydrogen production technologies:

- Autothermal Reforming (ATR).
- ATR with CCS.
- Biomass Gasification with CCS.
- Electrolysis.

These methods of hydrogen production all consume different amounts of water. Water is both used as a feedstock and as a reactant. It also supports many of the processes for hydrogen generation such as cooling.

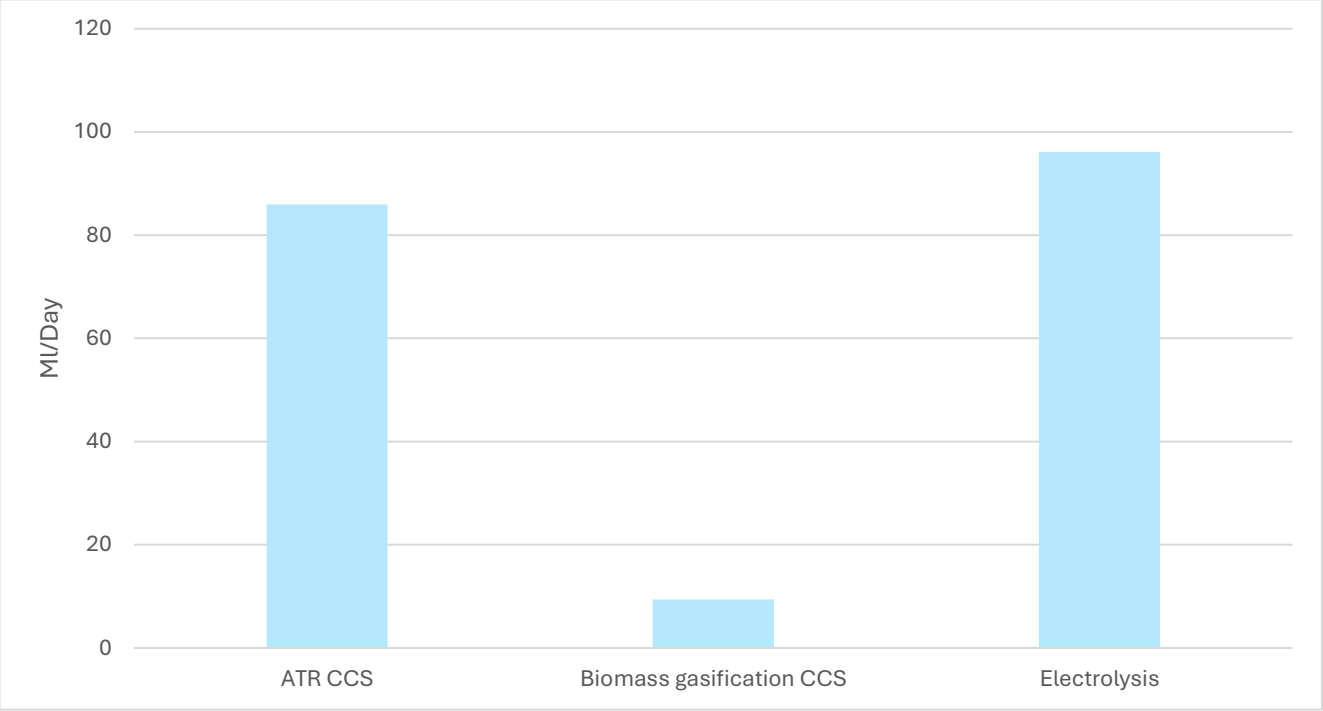
Thermochemical methods, including Steam Methane Reforming and ATR, combine steam reforming with partial oxidation. These processes involve reacting natural gas (methane) with steam and oxygen at elevated temperatures to yield synthesis gas (syngas) and so require water as an input for steam generation but also require water for cooling. The rate of cooling water abstraction per unit of power generated (t/MWh) is highly dependent on the type of cooling system utilised: once through cooling systems result in far higher abstraction rates than evaporative cooling systems[127].

Green hydrogen (produced via electrolysis) uses pure water (deionised or distilled) as a process input, since electrolysers are sensitive to impurities such as salts. While seawater can be utilised for hydrogen production, it currently requires desalination, although new membrane-based technologies are in development.

Biomass gasification for hydrogen production is a mature technology pathway that uses a controlled process involving heat, steam, and oxygen to convert biomass to hydrogen and other products, without combustion. Because growing biomass removes carbon dioxide from the atmosphere, the net carbon emissions of this method can be low, especially coupled with CCUS in the long term. Appendix L provides researched water intensities in L/KgH_2 with reference to the source data. Figure 5-3 shows average daily future estimates of water consumption for 2040-2050. At present, short-term comparative data cannot be provided because hydrogen has not been deployed during this timeframe. The average water intensity across hydrogen production technologies is about 191 million litres per day (Ml/d). When this is compared to the water intensity of thermal generation for the same period, it is notably lower than current levels.

[127] JEP21WT07 A Review Of Water Use For Hydrogen Production - Energy UK

Figure 5-3 Estimate of average freshwater demand for Hydrogen production for power in megalitres per day (Ml/d) for 2040-2050



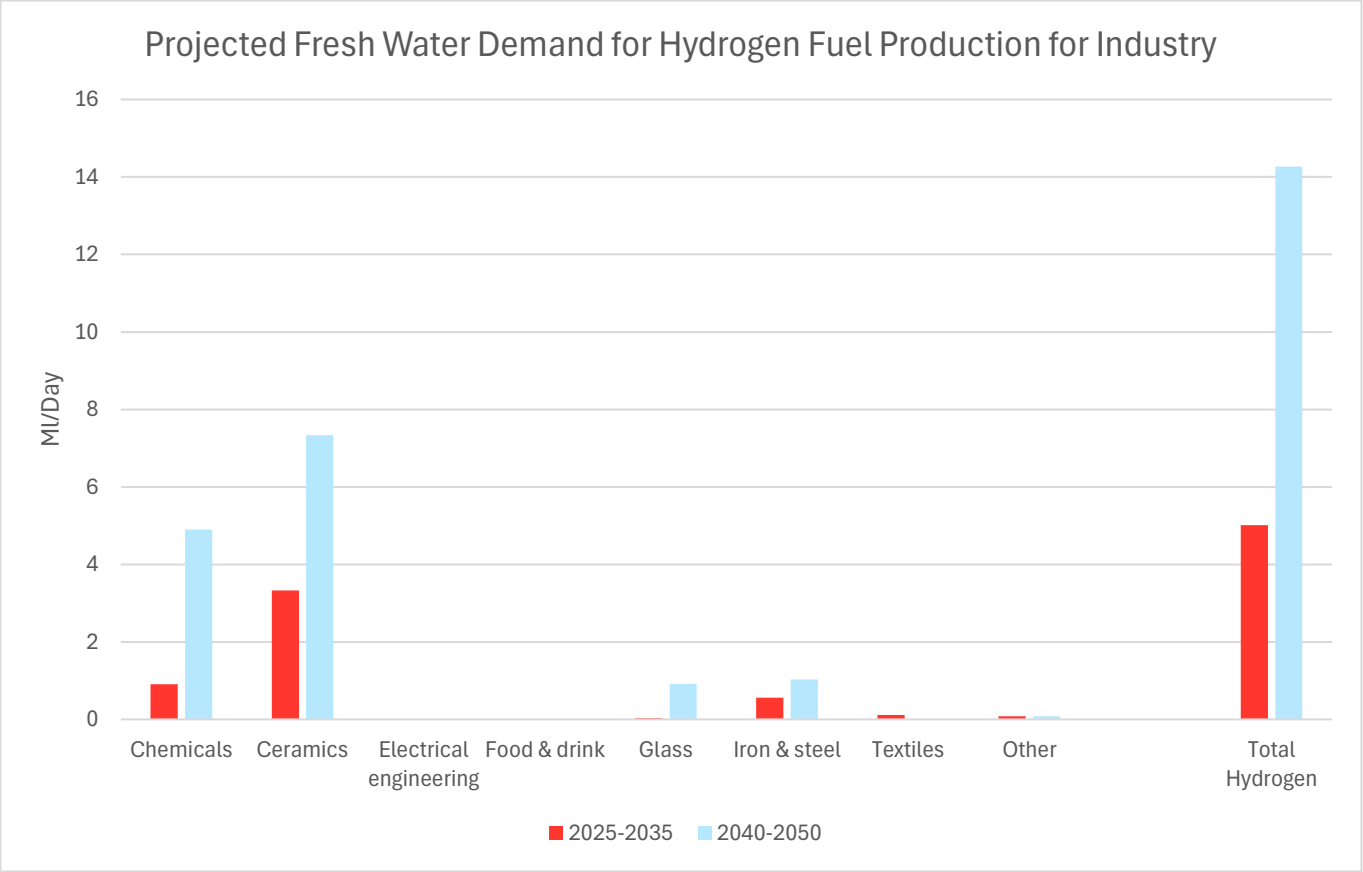
5.3 Industry sector decarbonisation

The UK industry sector's decarbonisation pathway in the CCC's advice on CB7 involves mainly electrification, with a smaller role for low-carbon fuels such as hydrogen, CCS, and demand-side efficiency measures. By 2040, electricity is expected to account for 61% of industrial energy consumption, an increase from approximately 26% in 2023. Key technologies contributing to this transition include electric boilers, electric furnaces (such as those used in glass manufacturing), and electric heat pumps. Electrification allows industries to utilise the UK's lower-carbon electricity grid. To avoid double-counting in this assessment, all industry power is assumed to come from the grid, as freshwater demand for power generation has already been considered. However, this may underestimate total usage because some industrial sites use local generation technologies that also need freshwater.

Even in the long-term there will remain some industries that are hard to electrify, especially those sub-sectors that require very high heat processing such as some steel, glass and ceramic production, as well as some chemical and petrochemical production. In these cases, green and blue hydrogen will play a niche but important role as a viable lower carbon alternative fuel which will require some freshwater. Figure 5-4 shows estimated freshwater demand for the key industry sub-sectors where hydrogen is likely to be used a fuel generated locally to key industrial clusters.

Freshwater demand rises from an average of just over 5Ml/day in the short-term (2025-2035) to an average of 14.3Ml/day by the 2050s.

Figure 5-4 Estimate of freshwater demand (in megalitres per day (Ml/d)) associated with local hydrogen generation to be provide as a fuel to industry sub-sectors



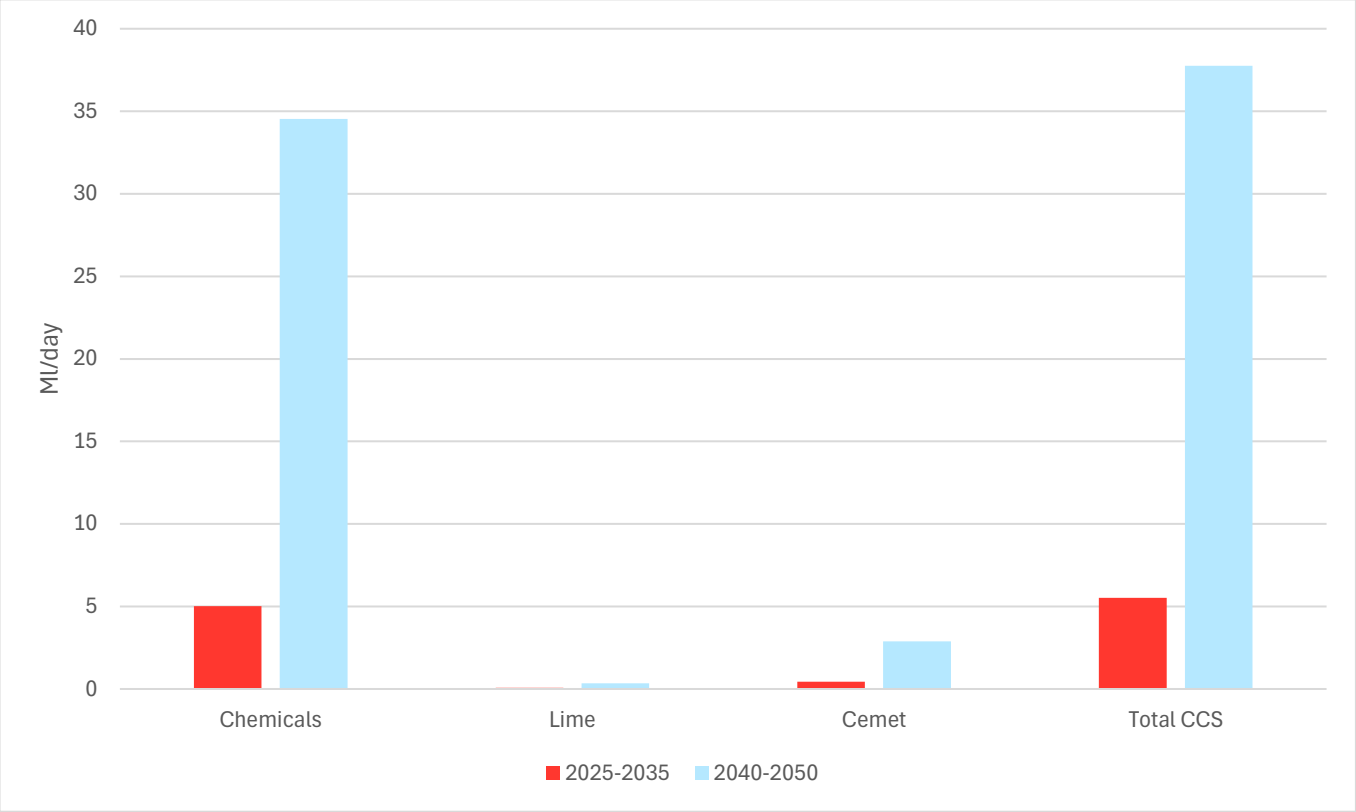
5.3.1 Carbon Capture and Storage for Industry

CCS is another essential technology for process emissions abatement in sectors that are hard to electrify. The CCC's advice on CB7 highlights chemicals, cement and lime specifically as sub-sectors that will require deployment of CCS technologies to aid CO_2 removals. Under the CCC's Balanced Pathway for industry a total of ~9.4mtCO_2e across these sectors are removed by CCS technologies. Water demand varies considerably with CCS technology used. Rosa et al (2021)[128] estimated a possible range of 0.74 to 575m^3 H_2O/tonne CO_2 across the whole life cycle, with the higher end estimate associated with BECCS and water used as part of irrigation making up a substantial proportion of this. A narrower range of 0.5 – 3m^3 H_2O/tonne CO_2 is also provided for point-source capture from fossil sources. The Environment Agency's Environmental Capacity in Industrial Clusters Project (2025)[129] strongly emphasises how site and technology specific water consumption is regarding CCS but identifies 2.6m^3 /tCO_2 as the highest water intensity of the cooling technologies considered. Given post combustion point-source CCS with an open loop cooling system (which would typically be deployed in these industrial settings) would have a comparatively large water demand, 2.6m^3 /tCO_2 was used in this assessment.

Figure 5-5 shows how the increasing deployment of CCS for the hard to electrify sectors in the medium term is estimated to increase water demand in the short-term from 5.5Ml/d to approximately 38Ml/d.

[128] The water footprint of carbon capture and storage technologies - ScienceDirect
[129] Environmental capacity for industrial clusters - GOV.UK

Figure 5-5 Projected freshwater demand short-term (2025-2035) and medium-term (2040-2050) for industrial CCS in Megalitres per day (Ml/d)



5.4 Water resources in strategic planning

Figure 5-6 shows the estimated water demand for CCS and hydrogen fuel at each of the industrial clusters by 2050 as scaled radials. These have been placed on a map of projected water availability in 2050 that accounts for present-day levels of freshwater demand see Figure 5-6. The base map shows which UK catchments are projected to have a water surplus or deficit by the 2050s under the Central Scenario, as defined under CCRA4. Red areas mark regions facing summer deficits where abstraction must be reduced to restore sustainable flows, making them unsuitable for further abstraction and targeted for abstraction licence reductions. Regions highlighted in light blue, where water availability is either non-existent or limited (less than 25%), may be classified as areas of elevated risk for high-consumption technologies such as hydrogen production or abstraction processes requiring continuous year-round supply, such as CCS for industrial use. It is anticipated that some freshwater resources may become available as the power sector transitions to net zero. However, there could be local freshwater resource impacts in some already water-stressed catchments if the industry transition is not manged in a strategic way with full consideration of the possible implications of the environment. Spatial tools such as those shown in Figure 5-6 are powerful for quickly, and visually, showing where water resource issues are likely to occur – Humberside and Medway for example.

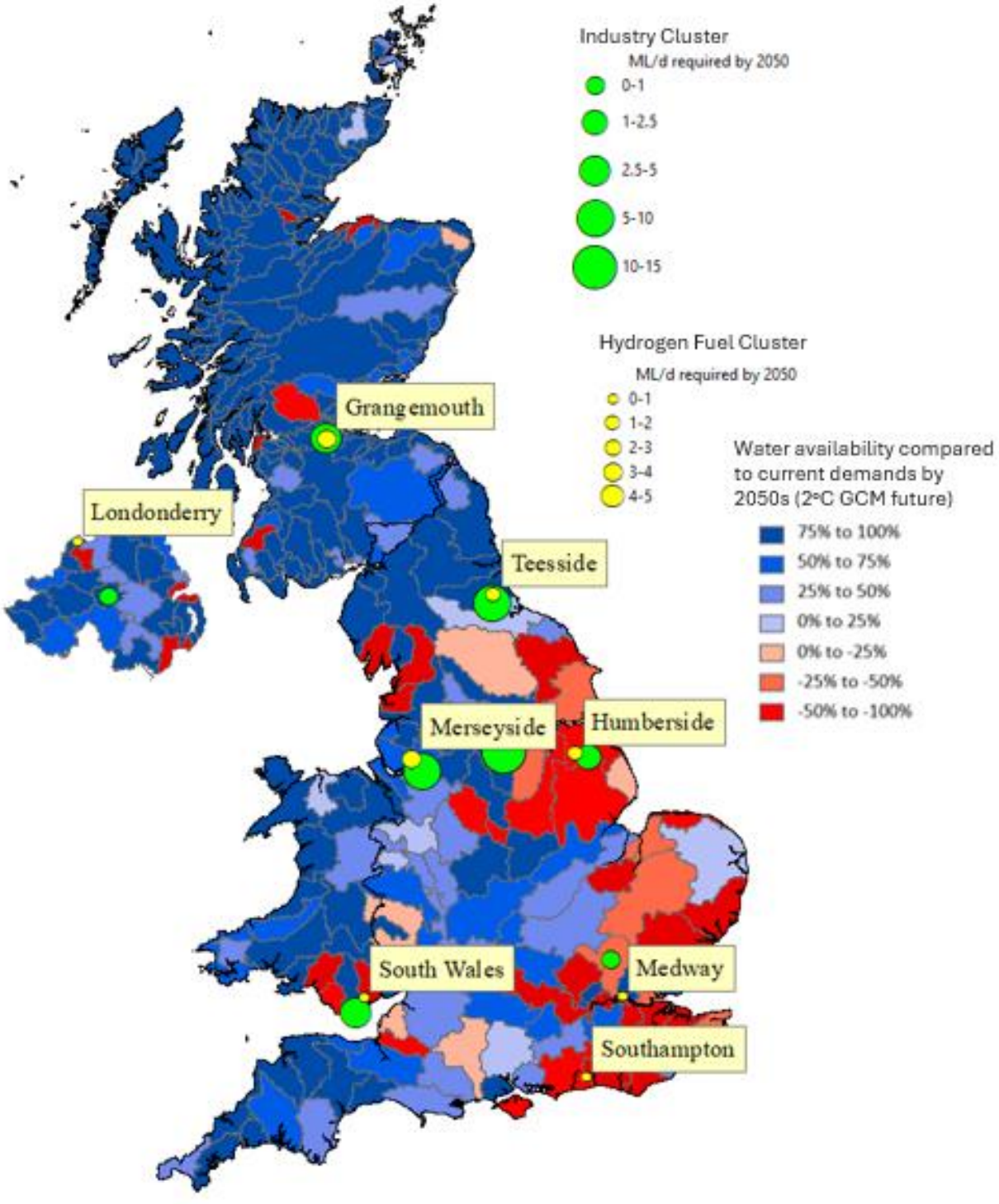


Figure 5-6 Location of industrial clusters show estimated water demand for CCS and Hydrogen fuel generation (Megalitres per day by 2050) against a surplus-deficit map of UK showing water availability regions, in 2050s in the Central scenario*[130]

[130] **Adapted from CCRA3: "Updated projection of future water availability for third UK Climate Change Risk Assessment" HR Wallingford, 2020[130]. MAR6025-RT002-R05-00*

By integrating these spatial insights into catchment-level planning, policymakers and land managers can align water resource management with climate mitigation and adaptation goals, ensuring that investments in new technologies and land management practices are both environmentally sustainable and resilient to future water stress.

The Environment Agency's Environmental Capacity in Industrial Clusters Project (2025)[129] concludes that, 'growth in industrial clusters will be unlocked with better strategic planning at a 'cluster-scale', where the focus goes beyond the individual net zero projects and includes the environmental capacity needed and the associated water infrastructure to support them'. National Energy System Operator (NESO) is taking the required broadscale and 'whole-system view' to steer the transition to greener energy sources. NESO's stated goal for the Strategic Spatial Energy Plan (SSEP)[131] is to provide a pathway for electricity and hydrogen generation and storage types, locations, capacities, and timings. This will be optimised for cost across demand and high-level network needs, as well as environmental, societal, and other spatial interests, to support the energy transition efficiently and securely. The SSEP has now completed its supporting Strategic Environment Assessment (SEA) scoping report, which is an important step toward ensuring that environmental issues are fully integrated and addressed with water being a key consideration in this assessment. Similar SEA's could be completed for industry at the 'cluster-scale' to help ensure the environment outcomes are maximised and water resources fully considered.

The figures in Ml/day presented as part of the assessment described in this chapter can only be taken as high-level and conservative estimates. The assessment has shown that water demand is highly context specific, demanding detailed information on industrial process, site scale and cooling methods used. This leads to the recommendation that the industry sub-sectors could do more to provide credible, transparent forecasts for freshwater demand.

5.5 Summary

The CCC's Balanced Pathway for Power offers a net reduction in freshwater demand for power generation, primarily due to the displacement of thermal fossil generation by renewables. The generation of electricity to the grid is anticipated to increase by over 50%, from the baseline average in 2025-2035 of 386 TWh to an average of 763 TWh over the 2040-2050 period. This increase meets the demand as the UK switches to low carbon electrical technologies. Through to the 2050s, although power generation is projected to increase, the proportion produced by technologies that depend on freshwater will be approximately 30% less than today's level, as production shifts toward renewables with lower freshwater intensity.

However, the emergence of hydrogen and CCS for thermal power introduces new, localised water demands, particularly in generation clusters. Equally, some regions facing water stress may see lower demands from power because of decarbonisation – for example, if there are heavy demands for cooling thermal generation that is no longer needed, or for cooling fossil-fuelled industrial plant that is electrified. Strategic planning must ensure that water resource availability is integrated into energy infrastructure development, especially in regions vulnerable to water stress, such as Humberside.

The decarbonisation of the UK's industrial sector will drive substantial changes in both energy and water use, with electrification, CCS, and hydrogen adoption presenting new patterns of demand. While these

[131] Strategic Spatial Energy Plan Methodology

technologies offer substantial carbon reduction benefits, they could also bring some localised challenges for water resource management, particularly where the hard-to-abate sectors reliant on hydrogen and CCS are located together in water stressed regions. Growth in this sector will be enabled by the effective integration of water, energy and industrial strategies whilst also ensuring industry decarbonisation remains both environmentally sustainable and resilient in the face of future water constraints.

Strategic planning and adopting a system-wide perspective are crucial for managing water stress during the UK's decarbonisation journey because they enable policymakers and industry leaders to anticipate and address the complex interplay between energy, water, and environmental objectives. As new technologies such as hydrogen and CCS are deployed, particularly in industrial clusters, localised water demands could increase, this could pose risks to the environment if this deployment takes place in regions already facing water scarcity. By integrating spatial insights and environmental capacity assessments into cluster-level and catchment-level planning, decision-makers can ensure that investments in infrastructure and new technologies are both sustainable and resilient to future water stress.

Coherent and coordinated policy approaches are essential to ensure that environmental protection, energy resilience, and equitable water availability are all balanced. This requires alignment between water resource management, energy transition strategies, and broader environmental objectives. Policies must be designed to support both the decarbonisation of the energy system and the sustainable management of water resources, considering the projected intensification of water stress driven by climate change, economic growth, and abstraction reforms. Only through such integrated planning and governance can the UK address the risks of water scarcity, support economic growth, and achieve its net zero ambitions while protecting the environment for future generations

6. Conclusions

6.1 Context

This assessment has developed an understanding at the national level of chronic and acute drought risks, the associated economic losses and potential adaptation measures. To achieve this, this assessment has necessarily incorporated many assumptions, limitations and simplifications which must be borne in mind alongside these conclusions. Further details on these are provided through the methodology, see Chapter 2.

6.2 Baseline current and future water stress risks

Total GVA losses from water stress across the sub-sectors has been calculated to be approximately £3.8 billion per year today. Whilst these impacts have been compared to other contemporary modelling studies, historic losses and evidence gathered via engagement, the scale of these impacts remains highly uncertain. These estimates are thought to be at the higher end of the range of other present-day economic loss estimates in comparable studies. Given these results are modelled values rather than actual historic losses they are therefore best thought of as production that goes unrealised in industries that are largely built to deal with current levels of water stress.

The assessment indicates that the drivers of future change, climate and economic growth are projected to intensify future water stress. The findings suggest that all sectors reliant on abstraction will likely encounter increased unmet water demand moving forward. The economic losses are estimated to increase by a further £2 billion, reaching £5.8 billion per year by the middle of the 2050s. It should be noted that these are direct losses only; indirect losses, such as lost production resulting from power shortages are likely to be substantial.

Losses from industry sub-sectors dominate the economic losses in absolute terms. There are two principal reasons for this. First, these sub-sectors are a much larger part of the UK economy than agriculture or power generation, meaning that there are more people employed, and GVA generated, by these sub-sectors that could be placed at risk by water stress. Second, industry sub-sectors (and agriculture) are expected to remain heavily dependent on extracted water. Taking a closer look at the sub-sectors within industry, agriculture and power in turn:

- In the industry sector, economic losses in the paper & pulp and chemicals sub-sectors are much smaller in absolute terms. However, paper & pulp is by far the most vulnerable sub-sector in relative terms, with more than 11% of GVA lost due to water stress by the 2050s. This is because all stages in the production process are water intensive, from pulping and bleaching to paper formation and cooling. This underscores the dependency of this sector on a stable freshwater supply. The food & drink sector also shows a relatively high-level of vulnerability, with economic losses reaching 4% of total sector GVA by the same period. Vulnerability is particularly prominent for food & drink industries such as bottled water, brewing and distilling where the source of water can be an intrinsic part of the product identity. Losses in chemicals and minerals, extractives & large manufacturing are only around 1% of GVA across all modelled years.

- For the agricultural sub-sectors, strawberries see the largest calculated relative losses across the agriculture sector (more than 6% of output by the middle of the 2050s). Impacts are also substantive across the other products assessed (carrots, potatoes and onions will all experience losses of 2-3% by mid-century). In absolute terms, strawberries and potatoes will experience the largest economic losses. Strawberries are completely reliant upon abstracted water in the UK and are a high value crop characterised by both a high and time critical water demand. Even short periods of water stress can result in loss and reduced quality of yield. It is both the overall value and vulnerability of this crop which results in the largest losses in both relative and absolute terms. Potatoes are one of the biggest volume crops in the UK in value terms, despite a lower unit value than strawberries, meaning that a smaller relative loss translates to a larger loss in absolute value terms.
- In the power sector, total economic losses are higher in Scotland and Wales when compared to other UK nations. This distribution reflects the greater hydroelectric capacity in Scotland and Wales compared to England and Northern Ireland. While gas-fired generation experiences a lower percentage of losses, the absolute economic impact exceeds £100 million per year in the 2050s. This outcome is linked to the anticipated future role of gas-fired plants, often paired with carbon capture and storage technology, and their position within the merit order cost curve, which results in replacement by imported electricity and a corresponding loss of generation value to the UK. Whilst there are economic losses associated with water stress, feedback gathered through engagement with the Sector Steering Group and other studies, has highlighted that the current energy system is resilient to periods of low water availability, even when combined with simultaneous periods of high energy demand. No substantial disruption to power supply via the national grid can be attributed to drought periods in living memory. Through triangulation with other studies (e.g. Energy Systems Catapult) it seems that the power sector is broadly resilient to water stress under climate change through to 2050. Grid resilience is generally managed through using more power from sites abstracting from estuarine/coastal water, using less-intensive cooling methods and more renewable generation. There is however an increasing cost in providing this energy.

Considering relative impacts across the nations, agricultural subsector losses are largest in England but are a much lower percentage than industry. The economic losses by industry subsector are disproportionate across nations, with important impacts in Wales from chemicals and food & drink, Scotland with food & drink and England for paper & pulp. In Northern Ireland, the only impacts observed in industry are in the minerals and large manufacturing sub-sector: these are higher than the impacts for all other nations, except for Scotland in the 2050s. For power, the relative losses present a similar picture to the absolute values.

Acute water stress events are difficult to define because different sectors and their sub-sectors may experience varying levels of exposure and vulnerability to different types of acute water stress event, even within the same geographic area, due to their specific water usage requirements. Due to the data and methodological limitations, there are substantial uncertainties which exist in the assessment of acute water stress. A key finding has been that this methodology and timeframe considered means that statistically it is difficult to distinguish between natural variation in events and climate driven worsening. For this reason, the outputs of this assessment are presented at a high-level and should be viewed as indicative.

The assessment has shown that climate change worsens river flows across England in summer and into autumn. These reductions in river flows in turn increase the frequency and severity of acute water stress

events. This indicates that water usage, particularly water consumption patterns across a year, may be the biggest driver of acute water stress in the future.

The analysis suggests that the strategies outlined by water companies, both present as part of the current investment cycle and planned future cycles, are likely to deliver only modest reductions in economic losses, estimated at less than 5%. This limited impact to agriculture, industry and power is because the water company plans are focused on provision of public water supply and not wider benefits to other sectors.

The assessment also found that for power, the severity of recent droughts had not surpassed the droughts observed in the 1970s. In the power sector, the current system has proven resilient to acute water stress events. Resilience of the system in the future is likely to remain high as water demand decreases as the energy system shifts toward less water intensive renewable generation.

The future resilience of agriculture and industry without any further adaptation is substantial remaining question. As water stress increases in the future, is not clear the extent to which exposed and vulnerable sectors (such as pulp & paper and food & drink), or agricultural products (most notably strawberries) can adapt their business models to continue to accommodate ever-increasing economic losses. High levels of chronic water stress (and increasing acute water stress) will ultimately challenge the existing resilience measures that businesses and regulators have put in place – most notably, acute water stress events can devastate entire crops and halt production if relevant adaptations are not implemented. However, this analysis finds that cost optimal adaptation options are available in these sectors, as summarised in the next section.

6.3 Cost optimal adaptation

The assessment indicates that there is opportunity to substantially reduce water scarcity losses with the implementation of adaptation measures both immediately and into the future. The adaptations identified for each sector can meet the water demand identified in most of the current and future scenarios assessed across the UK, thus reducing economic losses. The economic losses could be reduced by more than the cost of adaptation, with avoided losses in the order of £2.8 billion in the 2030s and £3.0 billion in the 2050s, after the costs of adaptation actions have been considered.

The assessment identified an immediate opportunity in both industry and agriculture for adoption of cost-effective, sector-specific adaptation measures, such as objective-based irrigation (during night-time hours for example) and increased on-site water storage. These approaches can reduce water demand and enhance water availability, which can substantially reduce associated losses. The subsequent adaptation measures are generally at the catchment and system levels (i.e. providing indirect benefits), and several cost beneficial options exist to meet adaptation requirements through to the 2050s.

Several system measures with long lead-in times, such as desalination plants and water transfers, are identified as adaptation options for industry in West and South East of England, East and North Scotland. Due to their long lead-in times, work would need to commence rapidly for them to be implemented in time. Despite this, these measures are cost effective and can benefit multiple abstractors through a single investment. It is worth noting that system and catchment measures may need to be promoted, developed and maintained by regulators, agencies and network operators outside of the individual sectors.

In the power sector, most of the adaptation measures shortlisted via the options appraisal process and therefore used during the optimisation process involve providing additional water to meet operational demands, either through on-site storage in the near term or catchment/system-level approaches such as small-scale desalination. These adaptation options should work in combination with other highly site-specific adaptation options to modify or adopt new cooling technologies. Work completed for the Energy System Catapult[9898] evaluated retrofitting or modifying cooling technologies, demonstrating that there is a trade-off between water requirements, consumptiveness, and costs for thermal technology cooling methods. This work highlighted that for new power generation sites, the main adaptation action is to strategically site them to use water from coastal and estuarine sources for cooling.

The assessment has necessarily focussed on generally applicable adaptations. Optimal adaptations will be highly process, operational and site specific. They can require substantial process and operational changes and typically occur alongside investment lifecycles in the operational infrastructure. This means that there is opportunity for more cost-efficient approaches, particularly within industry, and a lesser reliance on catchment and system adaptations.

6.4 Transition to Net Zero

The CCC's Balanced Pathway in its advice on CB7 would imply a reduction in freshwater demand for power generation by replacing fossil fuels with renewables. Despite the power provided to the grid more than doubling by 2050, the percentage of this generation from technologies that are reliant on freshwater is estimated to be 30% less in the 2050's as generation shifts toward low water intensity renewables. However, the emergence of hydrogen and CCS for thermal power introduces new, but highly localised water demands, particularly for the Humber and Medway Clusters.

Decarbonising UK industry through electrification and hydrogen will shift energy and water usage patterns, potentially heightening risks in areas where hard-to-abate sectors cluster together in already water-stressed catchments, while also potentially reducing risk where water demands for fossil fuel generation in water-stressed catchments are no longer needed. Strategic, system-wide, cluster and catchment-level planning are essential to anticipate and manage these changes. Integrating spatial and environmental capacity assessments into infrastructure and technology investment decisions will help ensure that water efficiency is considered by design and sustainable and resilient to future water scarcity.

6.5 Recommendations for further work

The methodological limitations of this study are numerous and the uncertainty in subsequent estimates of economic damages and unmet water demand across the sectors are large (and difficult to quantify). The recommendations for further work therefore seek to address these challenges. The following areas should be considered.

- **Test and pilot new approaches to separate the effects of natural flow variability from climate change signals in river systems**: Distinguishing the anthropogenic climate change signal from natural variability is generally challenging over the short to medium term (up to 2050) but is further complicated in the UK, where weather patterns are strongly influenced by the North Atlantic

Oscillation, storm tracks and high-pressure blocking events[132]. This can lead to particularly large biases in some regions and may also result in the models not being able to simulate dynamical patterns and weather regimes key to the formation of droughts[133]. Large climate model ensembles used to drive hydrological models have now been shown to characterise internal atmospheric circulation variability with some skill[134].

- **Improve understanding of sector specific water stress vulnerabilities:** Future research should focus on identifying which types of droughts the three different economic sectors are most vulnerable to, including the timing, duration, and severity of water needs. This will help clarify sector-specific risks and inform more targeted adaptation strategies. This could build on existing research to develop coherent drought storylines[135], including the impact pathways developed in this project, and be further strengthened with research to understand possible adaptation behaviours.
- **Improve understanding and quantify indirect costs of water stress:** This analysis focusses on direct economic costs of water stress in particularly vulnerable sectors. However, the economy is an interconnected system, and impacts on one sector cascade into others through supply chain linkages. Changes to the power sector (whether because of losses or arising from adaptation measures in the sector) could lead to changes in electricity prices which will have a much larger impact at the macro level than the losses incurred directly within the power sector. Future analysis should seek to understand and quantify these impacts, including follow-on induced effects that arise from changes to employment, wages and consumer spending power across the economy.
- **Evaluate and leverage Adaptation Reporting Power:** ARP reports vary widely in depth and format, making cross-sector comparison difficult. Some standardisation of specific indicators of exposure and vulnerability should be explored to enhance ongoing risk assessments and sector resilience which could facilitating monitoring of sectoral vulnerabilities.

[132] Climate change and water in the UK – past changes and future prospects
[133] Sillmann, J., Thorarinsdottir, T., Keenlyside, N., Schaller, N., Alexander, L.V., Hegerl, G., Seneviratne, S.I., Vautard, R., Zhang, X. and Zwiers, F.W., Understanding, modeling and predicting weather and climate extremes: Challenges and opportunities, Weather and climate extremes, 18, pp.65-74 (2017)
[134] Climate variability conceals emerging hydrological trends across Great Britain - ScienceDirect
[135] NHESS - Added value of seasonal hindcasts to create UK hydrological drought storylines

Appendix A

Sectoral growth

Appendix A – Sectoral growth

Appendix B

Environmental Destination

Appendix B – Environmental Destination

Appendix C

Scenarios

Appendix C – Scenarios

Appendix D

Unmet demand results

Appendix D – Unmet demand results

Appendix E

Acute drought detailed results

Appendix E – Acute drought detailed results

Appendix F

Summary of economic loss from water scarcity evidence reviewed

Appendix F – Calculation of economic losses

Appendix G – Summary of economic loss from water scarcity evidence reviewed

Appendix H

Adaptation appraisal

Appendix H – Adaptation appraisal

Appendix I

Institutional measures

Appendix I – Institutional measures

Appendix J

Co-benefits

Appendix J – Co-benefits

Appendix K

Full-list of optimisation runs, and adaptation packages selected

APPENDIX K – Full-list of optimisation runs, and adaptation packages selected

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Appendix L – Water Intensity Factors for Decarbonisation Technologies