

# UK water-energy nexus under climate change



## Key Issues and Priorities

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The Whole System Energy Modelling Consortium (WholeSEM) is a ground breaking, multi-institution initiative to develop, integrate and apply state-of-the-art energy models. Our aim is to employ extensive integration mechanisms to link and apply interdisciplinary models to key energy problems.

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This report presents the outcome of the wholeSEM UK Water - energy workshop held at the University of Cambridge on the 24 - 25th September, 2015. The workshop brought together 30 stakeholders involved in water and energy systems management from industry, academia, non-governmental organisations and government agencies.

## Authors

Dennis Konadu (University of Cambridge), Richard Fenner (University of Cambridge), Keith Richards (University of Cambridge) and Julian Allwood (University of Cambridge)

With contributions from: David Butler (Exeter University), Chris Kilsby (University of Newcastle); Jim Hall (Oxford University); Andrew Mason (Environment Agency); Ugo Gasparino (RWE Generation, UK); Keith Colquhoun (Thames Water); Adrian Johnson (MWH Global); Philip Davies (Aston University); Edward Byers (IIASA, Austria); Rob Ward (BGS); Simon De Stercke (Imperial College, London); Yadira Bajón Fernández (Cranfield University); David Riley (Anglian Water); Simon Spooner (Atkins Global); Geoff Darch (Atkins Global); Michael Osborne (Arup); Roger Street (UKCIP, Oxford); Sarah Mukherjee (Water UK); Alona Armstrong (Lancaster University); and Richard Williams (CEH, Wallingford)

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# Executive Summary

This report discusses key issues and potential future challenges associated with water and energy system interdependencies in the UK, and highlights opportunities for a low-carbon future, and priorities for research and modelling. The UK's energy policy, which is underpinned by the Climate Change Act (2008), seeks to provide a balance between greenhouse gas (GHG) emissions reduction, costs and security of supply. However, energy and water systems are intricately interdependent. Thus, meeting the emissions reduction target, and ensuring security of supply of energy and water would depend, among other factors, on the availability of water resources, which are directly influenced by factors such as population, climate and economic growth.

As the UK's population increases, along with urbanisation and industrial growth, and the potential ramifications of climate change, the demand for both water and energy are also likely to increase. This could lead to increased competition for water and resource stress, particularly in resource-poor regions, and this would limit power generation and risk security of supply. These notwithstanding, water systems also present some opportunities for harnessing and utilising low-carbon energy that could contribute to decarbonising the water industry.

Addressing these issues requires concerted collaborative efforts from all stakeholders, which reflect the interdependencies and the potential consequential challenges, risks and uncertainties, as well as opportunities. This collaboration was the main rationale for the stakeholder workshop, the outcomes of which is presented in this report, and are summarised as follows:

- Future/new power stations in the UK face freshwater availability issues with the reducing availability of new coastal sites;
- The impacts of extreme hydro-meteorological events and dynamics – floods, heatwaves and drought could have a significant impact on the UK energy system, and raise uncertainties about the deployment of some low-carbon technologies, particularly CCS and Nuclear power;
- The impact of onshore hydrocarbon exploration and exploitation on UK water systems, particularly groundwater, remains highly uncertain;
- Although water sector energy consumption is relatively small compared to other industrial sectors, energy management in the water sector constitutes a significant cost component to the water service providers;
- Emerging low-carbon technologies and innovations could help reduce energy consumption from the grid by the water industry; however, there are significant scaling-up barriers associated with these technologies;

- A National Infrastructure Systems perspective is valuable in addressing the nexus interdependencies, not only for looking cross-sectorally, but also for thinking across scales, and for challenging decision-making where there is a lack of ownership in government circles of critical system interdependencies;
- Whilst many of the challenges associated with the water-energy nexus play out at a national or regional scale, many of the solutions are likely to be small-scale systems associated with single households and individual behaviours.

A summary of the recommendations following the key issues outlined above include:

- Analysis of the effects of climate change on severe flood events arising from contemporaneous coastal surge, riverine, groundwater, and urban flash flooding that together impact on critical infrastructure, and on flood response systems;
- Modelling spatially distributed changes in land use in order to assess (a) how runoff source areas can be managed in order to reduce flood magnitudes (by including Sustainable Urban Drainage Systems - SUDS - in built-up areas, and conservation agriculture in rural); (b) and how floodplain storage can be an effective contribution to flood risk management;
- Increased emphasis on baseline monitoring and modelling of the effects of possible future fracking on groundwater storage, flow and quality, and better understanding of the costs and benefits of fracking;
- Research into psychological and social influences on citizen/consumer behavioural changes that might lead to reduction in demand for water, and especially reduce the tendency for a 'rebound effect' in which efficiency gains release resources that simply lead to new forms of consumption.
- Nexus analysis of the water-energy system needs to include evaluation of changing carbon emissions as a performance indicator of alternative approaches to water supply delivery, and carbon accounting needs to be embedded and refined in the water industry;
- Institutional reform at all levels - in research, disciplinary structures, organizations, administration and regulation - to enable multi-disciplinary approaches to research and management questions ("nexus" or "system of system" approaches), and to institutionalise a process of testing single-discipline decision-making across the boundaries of multiple other disciplines.

# 1 UK water and energy futures – policies, opportunities and challenges

Energy and water systems are intricately interdependent, and are directly influenced by factors such as population, climate and economic growth. Water is required in the energy delivery value-chain, particularly for the extraction of fossil fuels, fuel production, hydropower, thermal power plant cooling and heat transfer in domestic and district heating, and increasingly in the irrigation of bioenergy crop production. In parallel, energy is required in the pumping, transportation, treatment and distribution of fresh, saline and waste water. Thus sustainable joint provision of energy and water is fundamental to every country's economy, for the health and well-being of its populace, and to meet the requirement of aquatic and riparian ecosystems for environmental flows.

As population increases, along with urbanisation and industrial growth, the demand for both water and energy are also likely to increase, leading to increased competition for available water resources, particularly in resource-poor regions. Additionally, potential ramifications of climate change could lead to regionally variable freshwater resource scarcity, which could exacerbate this competition for available resources. Meeting the water demand of all sectors of the economy and the essential provision of a potable water supply under these circumstances could result in significant changes in the water industry, including development of trans-regional bulk water transfers and building of more desalination plants, which are both energy and GHG intensive. However, within the water industry, energy use remains the highest operational cost (excluding employee cost), thus a further increase in energy intensity of water provision would be an additional burden.

On the back of increasing demand for energy and water resources is the need to reduce greenhouse gas (GHG) emissions, and to protect aquatic environments. These are underlined by UK and EU legislations, in particular the Climate Change Act (2008) and the Water Framework Directive (WFD), which enjoin the water and energy industry to internalise the environmental cost of their operations – including GHG emissions and water quality. The ultimate goals are to mitigate climate change impacts and potential risks to the wider economy, as well as ensure public health and safety from the increasing frequency of extreme events (both flood and drought). Among the suggested measures in this regard are demand management, resource use efficiency and the decarbonisation of major industrial systems, particularly energy (and water) production. Notwithstanding the potential future challenges associated with water resources and energy provision, opportunities also exist for innovative approaches to recovering energy from water, aside from conventional hydropower. These include scaling up of anaerobic digestion

from wastewater treatment, in-pipe power generation, water-based heat-pumps and thermal recovery from wastewater – all of which could be harnessed to augment conventional low-carbon energy systems.

In the UK, the Climate Change Act (2008) has set binding GHG emission reduction targets (80% of 1990 levels), stipulating that a greater portion of the energy system should be decarbonised by 2050 (HM Government, 2008). This legislation led to the development of the UK Carbon Plan 2050, which mainly sets out how the UK will achieve decarbonisation within the wider energy policy framework – in a transition to a low carbon economy, while maintaining energy security, and minimising costs to consumers. The transition to a highly decarbonised economy demands significant changes in the UK energy system, and suggests a significant change in the current level of natural resource use for energy provision - in particular water, but also land (which is the subject of another report in this series; Konadu et al., 2016).

The impact of climate change uncertainties on water resources, coupled with future increased demand for water by other sectors of the economy, and the increasing need to improve the quality of aquatic environments have all led to the development of various long-term national water resource strategies across the devolved UK administrations. Principal among these are the Water Strategy for England (DEFRA, 2009) and the Water Strategy for Wales (Welsh Government, 2015), which seek to address and respond to the potential impact of climate change on water resources – particularly droughts and floods – mainly aimed at improving the ecological status of surface water resources for people, wildlife and recreation; providing fair, affordable and cost-reflective charges for customers; and reducing GHG emissions from the water industry.

Even though these policies and strategies are predicated on avoiding the challenges associated with climate change, neither adequately addresses the main interactions and interdependencies of water and energy systems. For example, the water strategies acknowledge the water requirement for the energy system, but do not provide detailed future management strategies for meeting energy generation demands. The Carbon Plan on the other hand gives no indication of the potential water demand associated with the projected changes in the energy systems. However, some of the suggested low-carbon energy technologies for meeting the decarbonisation targets, including Carbon Capture and Storage (CCS) and Nuclear Energy are water intensive, and could increase the current pressure on available resources if deployed at the projected scale.

These issues raise potential future challenges of increased competition for water resources between energy, public supply, industry and the maintenance of ecosystem services. Additionally, the impact of extreme hydro-meteorological events (floods and drought), driven by climate change, on energy generation and critical infrastructure are not addressed adequately in either policy. Furthermore the potential ramifications of unconventional primary fossil fuel exploitation (of shale oil and gas) on the quality of groundwater resources need to be addressed in terms of the impact this activity may have on reducing the quantity of available groundwater resources.

Addressing the above issues and harnessing the opportunities associated with water and energy interactions require the concerted collaborative effort of all stakeholders in the water and energy industry. Such efforts must, however, focus on an integrated, multidisciplinary approach to framing policies on water and energy systems that reflects the interdependencies and the potential consequential challenges, risks and uncertainties, as well as opportunities.

Of critical importance in this regard is the role of research and modelling, which is fundamental to comprehensive policy development, implementation and efficient resource management.

This report therefore discusses some of the main issues associated with water-energy interdependencies in the UK, and highlights the key priorities for research and modelling. It focuses on three main areas of the water-energy nexus:

1. The spatial and temporal dynamics of water resources in the UK – availability, distribution and the potential risks and uncertainties of water resources for energy and water services under climate change;
2. The interdependencies between water and energy systems in a low-carbon energy future and the implications of climate change and extreme weather conditions; and
3. The strategies and innovations for a low-carbon water industry - GHG emission reduction, and opportunities for harnessing low-carbon energy in the water industry.



## 2 Spatial and temporal dynamics of UK water resources

The total UK annual long-term renewable freshwater resource, based on the difference between the total annual precipitation and evapotranspiration, is estimated at 164,300 million cubic metres (Eurostat, 2015). However, the geographical distribution of water resource availability in space and time across the UK is highly variable. Some regions have an abundance of rainfall, whilst others experience scarcities as a result of low rainfall levels. The spatial distribution of the seasonal rainfall across the UK shows that higher land in the North and West receive higher rainfall than in the South and East. Conversely, the North has a comparatively lower population density and lower public water demand, whilst the relatively drier South is highly populated with higher public water demand (see figure 1). These dynamics of water resource availability thus inform the abstraction licensing regime in the UK (see BOX 1).

However, not all abstracted water is consumed in the utilisation process. Water abstraction and use is therefore classified as either consumptive or non-consumptive. Consumptive abstractions include those in which water removed for use is not returned to its source. Non-consumptive abstractions on the other hand imply abstracted water does not substantially change in quality, with almost all of it returning to the system after use. Within the energy sector, water abstraction for hydropower generation is mainly non-consumptive, and this water is immediately returned, mainly to rivers in almost the same volume and quality, and can be immediately re-used. Nevertheless, part of the water abstracted for thermal cooling in electricity generation is consumed through evaporation. Water abstractions for

public use are mainly non-consumptive, but may require substantial treatment before they are returned to the system, usually lower down a catchment. Re-use of this return flow is therefore possible, and such recycling augments the available supply.

In addition to the impact of population, differences in water demand across UK regions are dictated by industrial, commercial and recreational needs. Figure 2 presents the water abstraction by source and use for Environment Agency regions in England and Wales. This shows that most of the freshwater (groundwater and tidal water) used in the UK comes from surface water sources - mainly rivers and lakes. Water abstraction for public supply is the highest amongst all major licensed abstractors, constituting ~45% of all abstractions in England and Wales. Energy supply is the second highest overall water abstraction sector representing 35%, followed by industry and fish farming and amenity ponds with ~9% of all licensed abstractions respectively. The agricultural sector, including irrigation as well as private and other minor water abstractors constitutes only ~1% of all abstractions, and are these mainly required during the growing season. So most agriculture in the UK is rainfed, using "green"<sup>1</sup> water and relatively little "blue"<sup>2</sup> water, although this varies regionally.

In terms of regional abstraction levels, Wales has the highest overall abstraction, dominated by hydropower and pumped storage electricity generation operation. The South East (including London) has the highest overall abstraction in England, which is mainly for public supply.

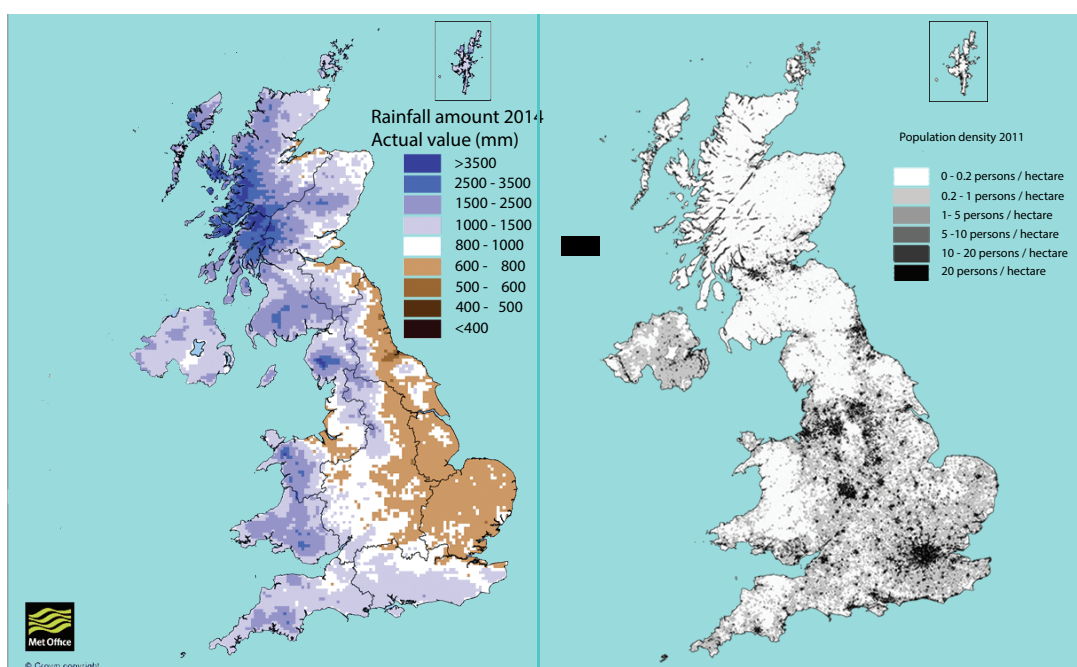


Figure 1: Comparison of the (a) spatial distribution of the 2014 annual rainfall (Met office) and (b) the 2011 population density distribution of the UK (ONS)

## Box 1: Abstraction licensing and regulation

The environment, people and business need water, and there are increasing pressures from population growth and climate change. It is the Environment Agency's job, working with external partners, to balance these needs through its permitting and planning activities. In doing so, the Environment Agency needs to meet its environmental obligations set out in domestic and European legislation - the Habitats Directive and the Water Framework Directive are particularly relevant to water resources regulation and management.

The Current licensing system was established in the mid-1960s

- It has evolved over time but its focus now on protecting the environment and dealing with historic sustainability problems.
- The Environment Agency needs to secure the proper use of water resources and protect existing rights and privileges
- Most abstractions and impoundments require a license from the Environment Agency.
- Some notable exemptions include navigation, quarry de-watering and trickle irrigation
- There are currently around 20,000 abstraction licences in England authorised to take some 60,000 Ml/d, but a large proportion of this water is returned to the environment after use.
- The Government is proposing to reform the abstraction system in England to make it more flexible and better able to respond to changing environmental conditions and demands for water.

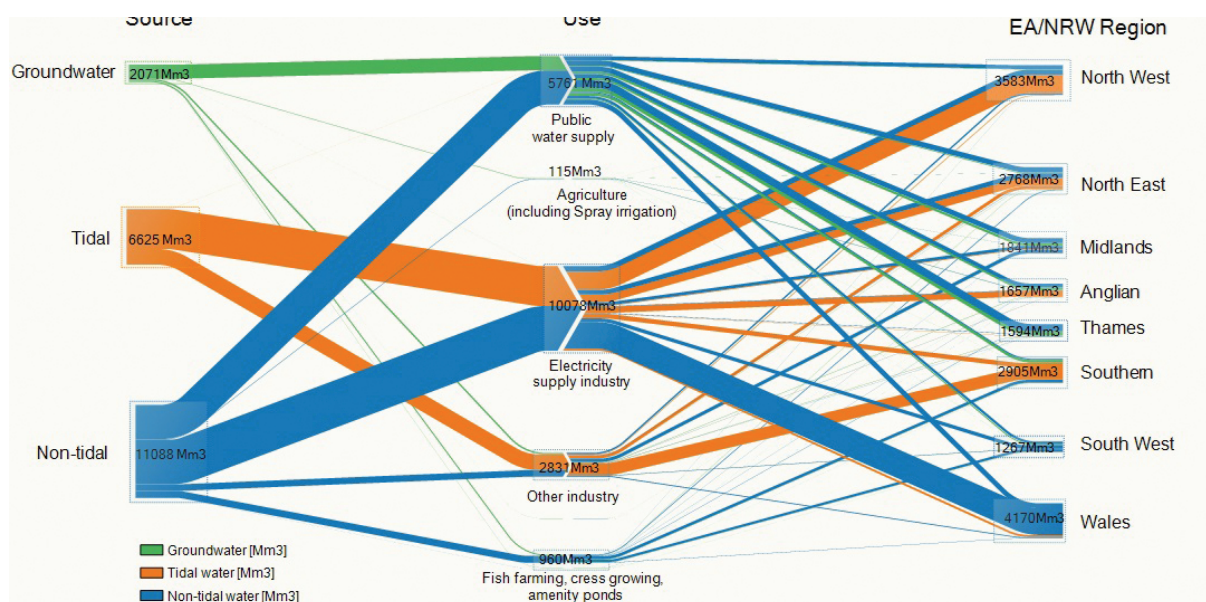


Figure 2: Water abstraction by source and final use in England and Wales (2014) (data for Scotland and Northern Ireland were not readily available at the time of this review)

Besides rainfall and water resource distribution and demand, climate variability and unusual hydro-meteorological conditions and extreme weather events across the UK also pose potential risks and uncertainty for water availability and the functioning of energy systems. These potential risks and uncertainties are mainly associated with variability in precipitation, droughts and extreme flood events. Detail discussion of these risks are presented in the next two subsections.

## 2.1 Climate variability and impact on UK water resource

The climate of the UK is characterised by natural variability (spatially and temporally), but also by change. This is particularly evident in the precipitation the UK receives, with droughts and floods influencing the way water resources are managed and used. Historical climate records and recent events clearly show this variability in precipitation which is reflected in the nature of water stress<sup>3</sup> across the UK. For example: the south east of England is already seriously 'water stressed' with London's water resources already over-abstracted, or over-licensed; in a dry year, Thames Water forecasts that current demand is 80Ml/day greater than available supply (Thames Water, 2013).

The output of the UKCP09<sup>4</sup> analysis projects that precipitation will continue to be variable, but also that the UK will see drier summers and wetter winters as a result of changing climate. There is also evidence suggesting that there will be longer dry periods, but also episodes of more intense rainfall. This intensification of precipitation extremes with climate change is of key importance to business and society, as a result of the increased impact of flooding. Observations show that heavy rainfall is increasing on daily timescales in many regions of the UK, but how these changes will manifest themselves on sub-daily timescales remains highly uncertain. Recent research (e.g. Kendon et al., 2014) has shown a future intensification of short-duration rain in summer, with significantly more events exceeding the high thresholds indicative of serious flash flooding, implying a reduction in the return period of floods of a given magnitude.

Understanding and managing the risk and opportunities to our water resources in the context of changes to the climate is complicated by interdependencies within the water and other sectors, including the energy sector. These include:

- multiple demands for water – from natural and human systems that rely on water with cross-system dependencies;
- policy and regulatory issues – both synergistic and conflicting;
- connectivity of water systems – between geographic regions and also infrastructure;
- socio-economic and political factors influencing investment in infrastructure to meet changing demand; and
- multiple drivers of change – socio-economic, demographic, environmental and political together with the different dimensions of climate change.

As a result of this complexity, decision-making and the business of water management will need to consider interdependencies both within the sector and between dependent sectors. The challenge is that at present, activities both between sectors and between scales, and the collaborations that are fundamental to addressing these risks effectively (amongst industry, policy and science) are fragmented. Addressing this challenge requires effective and efficient decision-making and investment, and innovations in technical, economic and governance areas. and into dependent sectors. The challenge is that at present, activities both between sectors and between scales, and the collaborations that are fundamental to addressing these risks effectively (industry, policy and science), are fragmented. Addressing this challenge requires effective and efficient decision-making and investment, and innovations in the technical, economic and governance areas.

## 2.2 Hydro-meteorological risk to energy system infrastructure

Severe floods and droughts seem to occur with increasing frequency, and records established during the instrumental period are now being broken with regularity. To date at least, however, it has always been possible to find evidence of more severe events that have occurred in past decades and centuries, recorded informally or inferred from proxies. The water and energy sectors have developed and operated over centuries within a very broad envelope of risk. An example is the record-breaking Tyne flood of Dec 2015, which nevertheless still fell short of the great flood of 1771. What is less clear, of course, is whether earlier extreme events were of the same return period as similar events today. Similar evidence of greater earlier extremes can still be found for convective (thunderstorm) generated floods, and indeed for severe droughts; although statements about extreme event magnitudes require return period estimates as well.

This is of little concern to water and energy engineers, however, for at least two reasons. Firstly, even if the hazards are not yet greater than previous historic events, the risk is often greater, as our population and its dependence on energy and water infrastructure is demonstrably larger than ever before. This dependence is not just because of the general societal reliance on critical infrastructure, but is also because of the increasing inter-dependence of energy and water networks. Secondly, climate change projections for the UK (Glenis et al., 2015) extend this already substantial envelope of risk by introducing the prospect of new and increased levels of both flood and drought, with enhanced seasonality and gradients of rainfall across the UK. The risks to both energy and water critical infrastructure arise at several scales and from various sources, as the following illustrations will show.

### 2.2.1 National scale flood risk

The impact of simultaneous flooding at multiple locations is important in terms of collective damage (relevant to re-insurance) as well as in terms of impairment of the overall performance of infrastructure networks (e.g. power transmission and distribution, water treatment facilities, pumping stations etc.) when multiple nodes are affected. The case of widespread fluvial flooding has been addressed by the ITRC consortium<sup>5</sup>, where a spatial rainfall model (Serinaldi and Kilsby, 2014) was used to provide the spatially-dependent drivers to a hydrological model to generate flooding scenarios to “attack” infrastructure networks where assets are vulnerable to flooding (e.g. the water treatment plant at Mythe, Tewkesbury, close to the River Severn). Regional impacts are readily observed in floods generated by widespread frontal rainfall, but more serious risks can be posed by national scale events where severe flooding affects many points on the network simultaneously, and where rainfall flooding incides with coastal flooding (caused, for example, by storm surges).

### 2.2.2 City scale flood risk

Energy and water infrastructure assets are concentrated in urban areas, so surface water flooding generated by convective rainfall is important for assessing overall and local network reliability under climate change. Increases in convective rainfall are likely in a warming world, as has been demonstrated by Kendon et al. (2014), who show that summer precipitation intensities are expected to increase by 30-40% for short duration heavy events.

Such increases in short duration rainfall pose a threat to cities with sewer networks first designed and built in the 19th century and now their capacity are substantially exceeded due to both increased populations, and impervious areas contributing to storm runoff. The impact of such storms has been assessed using the CityCAT hydrodynamic model (Guerreiro et al., 2017) to generate detailed flood inundation maps of cities (e.g. Figure 3), capable of realistic assessment of vulnerability of assets in complex urban environments. This modelling approach allows risk to be assessed and also, more importantly, strategies for protection to be trialled safely and effectively in silico, as severe storms are of course infrequent and isolated and critical networks are not suitable for a trial and error testing approach.

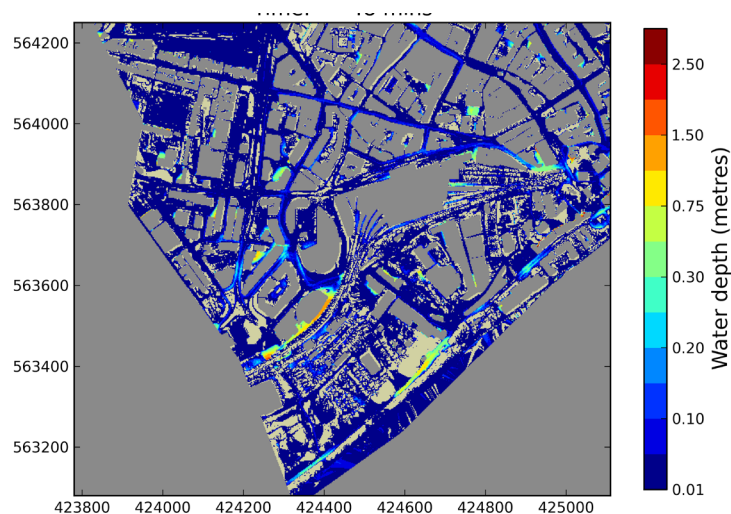


Figure 3: Modelled flood depth map (2m resolution) for a severe short duration rainfall event in Newcastle. Detailed information on flow paths and flood depths can be obtained for design of asset protection.

## 2.3 Key Issues and Priorities for Modelling and Research

Although quantitative uncertainties about the future hydro-climatology of the UK remain, qualitatively it is likely that the spatial imbalance in water supply and demand will increase, and those extreme events, both flood and drought, will be more frequent and intense. These offer several challenges for research, modelling and the policies that these will inform. Increasing spatial variation in the demand-supply imbalance could be addressed by infrastructure investments that deliver excess supply from the north and west to the deficit south-east. However, residual uncertainty, together with the political inertia that confronts planning for such long-term development, are likely to favour deferral of decision-making.

An alternative would therefore be to manage demand, both at the end user scale, and through regional policies that redistribute economic growth across all UK regions.

The spatial and temporal dimensions of hydro-climatic change could make agriculture more dependent on irrigation ('blue' water), both because of increasing seasonality of rainfall in the south-east, and because of more frequent droughts. This will add to the agricultural sector's demand for both water and energy-for-water, and water-for-energy will also enter the equation as bioenergy crops compete for agricultural land. Reducing the impacts of these trends could be aided by emphasis on improved land-and-water management through conservation agriculture - that would increase the infiltration of heavier rainfall, enhance soil moisture ('green' water), and also thereby reduce flood risk, and therefore the scale of investment required in flood defence. This will require 'end-to-end' flood models with sub-models of the cascade from rainstorm-runoff-flood routing-inundation, capable of experimenting with the consequences of land cover and channel capacity changes (Macmillan and Brasington, 2008).

There will be a need, therefore, to evaluate the nature and scope of both the risks of, and adaptation responses to, future hydro-climates in terms of dependencies amongst the water, energy and food sectors as an integrated 'nexus' rather than as a set of separate entities. In this nexus, each element may constrain the others. This necessity for integrated resource analysis may have wide-ranging implications for governance structures and policy initiatives, regulation and incentives, and research priorities; the breakdown of silos in all these areas may be increasingly necessary.

These issues suggest that important areas for further research and modelling include:

- Analysis of the effects of climate change on severe flood events arising from contemporaneous coastal surge, riverine, groundwater, and urban flash flooding that together impact on critical infrastructure, and on flood response systems;
- Modelling spatially distributed changes in land use in order to assess (a) how runoff source areas can be managed in order to reduce flood magnitudes (by including Sustainable Urban Drainage Systems - SUDS - in built-up areas, and conservation agriculture in rural); (b) and how floodplain storage can be an effective contribution to flood risk management;
- Developing tools to support decision-making at different spatial scales that reflect regional variations in resource availability, demand and potential stress, particularly given the regional variation of climate change impacts across the UK, and different frameworks and drivers in different sectors.

### 3 Water implications of Low-carbon energy - interdependencies and risks

Currently, water demand for energy provision in the UK is mainly associated with hydro/pumped storage generation, located in the uplands; and cooling in thermal electricity generation systems, located along coastal/estuaries and inland reaches of major rivers. In 2014, hydropower generation contributed a total of 5.9TWh of electricity to the UK grid, representing 1.3% of the total UK power generation, and 9% of all renewable energy (DECC, 2015). This generation relies on large dams and pumped storage systems, and requires large volumes of water. However, the water used in this case is non-consumptive, except in the sense that the water held in storage is maintained for exclusive use.

Thermal electricity generation systems (including nuclear), which constitute approximately 85% of the UK's overall grid electricity, require relatively less water in their operations than hydropower generation. However, a proportion of the abstracted water is consumed through evaporation. The level of consumption is dependent on the cooling technology deployed and the primary fuel used for generation. Moreover, the volume of freshwater abstracted and the thermal quality and volume of the water returned to the source usually varies significantly.

Water resources may experience significantly increased stress in the future as the UK transitions to a low-carbon energy system. This is because, some of the technologies that could be deployed in electricity generation require more water to operate (Byers et al, 2014; Konadu et al., 2015), and increasing demands for energy are anticipated. Moreover, prospects of future onshore hydrocarbon exploitation in the UK, in particular fracking for shale gas, could have impacts on groundwater resources (see Section 3.1). In addition to the future demand for water by the energy sector, is the need to maintain environmentally acceptable flows and quality levels in riverine and groundwater systems (See box 2). Thus the critical question here is, "are future energy pathways that are "no-regrets" options with respect to carbon emissions also "no-regrets" option with respect to UK water resources?"

#### 3.1 Decarbonisation, low carbon technologies and water use

As discussed in Section 1, future changes in electricity generation are essential in meeting economy-wide carbon emissions targets. The Climate Change Act describes a range of factors – including affordability, competitiveness, the public finances, energy policy, technological progress, international and EU circumstances, scientific knowledge about climate change and the differences between the devolved administrations – that must be balanced to determine how

best to reduce carbon emissions to the level required by 2050. Consequently, alternative decarbonisation routes have been investigated (including their impacts on competitiveness, affordability and energy security), aiming at the identification of possible 'optimal' pathways (e.g. DECC 2050 Calculator). The implications for water resources of the decarbonisation of electricity production will depend on the assumed pathway and on the details of its implementation.

In some UK regions, less freshwater might be available in the future for consumptive use because of the combined effects of climate change and a growing population (Brown et al., 2016; Konadu and Fenner, 2017). This may be exacerbated by the requirements, under the Water Framework Directive, to improve water bodies not at good status (See Box 2). As a backdrop to development of various strands of environmental regulation and policy, and in particular water resource allocation reform, Defra and the Environment Agency have also been working with a number of sectors (such as the water industry, agriculture and electricity producers) to forecast their future demand for water. The implemented approach relies on the use of a set of future scenarios designed to include plausible future water demand (EA, 2014).

The Joint Environmental Programme (JEP), is a programme of research into the environmental impacts of electricity generation funded by nine of the leading producers in the UK. It has developed an independent model for the estimation of the uncertainty and 'central case' development of future water 'gross usage' (water intake, mainly for cooling purposes) and 'consumption' (difference between the water intake and water discharge) by thermal Power Stations. This is based on power station capacity and energy production scenarios specified within the DECC 2050 pathways (JEP, 2013). The approach relies on the following steps:

- select a set of 'DECC 2050 Pathways' (capacity, generation, load factor), used to 'envelope' future electricity demand; and initialise the generating fleet in 2010;
- evolve the fleet step-wise by partitioning the projected output in MWh across the fleet using a Monte Carlo approach subject to rules for closures, openings (capacity, location, river-basin), type (fuel, cooling); and
- evaluate the associated (consumptive and gross) water demands (based on Energy-UK water use  $\text{m}^3/\text{MWh}$  indicative ranges), for the following water source classes: Freshwater; Riverine/Tidal and Saltwater; Estuarine/ Coastal.

## Box 2: Environmental flows, water quality and abstraction licensing for energy

The Environment Agency uses its 'Environmental flow indicator' (EFI) to assess whether river flows are sufficient to support a healthy ecology. The EFI is the percentage deviation from the natural river flow represented by a flow duration curve. This percentage deviation is different at different flows, and is dependent on the ecological sensitivity of the river to changes in flow. The Agency also uses information from its monitoring network to assess the current and past water and ecological situation. It routinely gathers information on rainfall, river level and flows, groundwater levels and ecology. At the start of a resource assessment, the EA calculates a water balance for each catchment area. The elements of the water balance calculation are river flows, groundwater recharge, abstractions, discharges, and a resource allocation for the environment and any other water uses or features that require protection.

For surface waters the impact of pressures on the water resource is measured against natural flow conditions as described by the EFI. (Natural flow is the flow that would occur if no artificial influences - abstractions, discharges, and flow regulation - existed). For compliance with the Water Framework Directive (WFD) surface waters are assessed to be of High, Good, Moderate, Poor or Bad Ecological Status. At High Ecological Status (HES) the water body must show virtually undisturbed conditions. Water bodies in this category have no significant artificial influences and have a high biological quality; any pressures on the water body are minimal, and hydrological, morphological, ecological and chemical states are all close to natural. At HES the hydrological element helps to define this near-natural status. Water bodies of High status must be maintained at HES and not be allowed to deteriorate. Where the pressures on surface water bodies result in the quality state being assessed as worse than Good, measures have to be identified that will restore the quality to Good status. The overall status of a water body is defined by the status of the worst of the quality indicators. Restoration of Good quality requires Programmes of Measures for this reinstatement.

Some water bodies have been designated 'artificial' or 'heavily modified' because they are in use for a specific purpose (such as water supply or power generation) or because of physical alterations, and they cannot be restored to Good Ecological Status (GES) without compromising the specified use – in this case the WFD objective is Good Ecological Potential (GEP). The WFD sets a target of GES or GEP, unless an alternative objective can be justified. At GES the hydrological regime is a supporting element, which means that the biological quality of the water body must not be compromised by the flow. Practically, this means that flows must adequately support the river biology.

Where water bodies do not meet GES or GEP, or may not reach this quality unless action is taken, the measures required to achieve good status are set out in the relevant River Basin Management Plan. The EA must also take action to prevent water bodies deteriorating in status -actions may include making changes to existing licences, placing restrictions on the granting of new licences, or a combination of these.

The modelling exercise indicates the necessity of approaching the issue of future water demand by the electricity sector in a probabilistic way (as opposed to a deterministic one) and highlights the requirement to conduct comprehensive uncertainty and sensitivity analysis before any 'robust' conclusions are drawn. The main sources of uncertainty for future water 'gross usage' and 'consumption' by thermal Power Stations are found to be associated with:

- the assumed future energy scenario;
- uncertainty in actor choices on plant closures, and new plant capacity, type and location;
- variation in partitioning projected generation across individual plant in the 'fleet of the time'; and
- variation in year on year water use ( $\text{m}^3/\text{MWh}$ ) at a given plant (in response to changing operation).

A typical example of model output is illustrated in Figure 4.

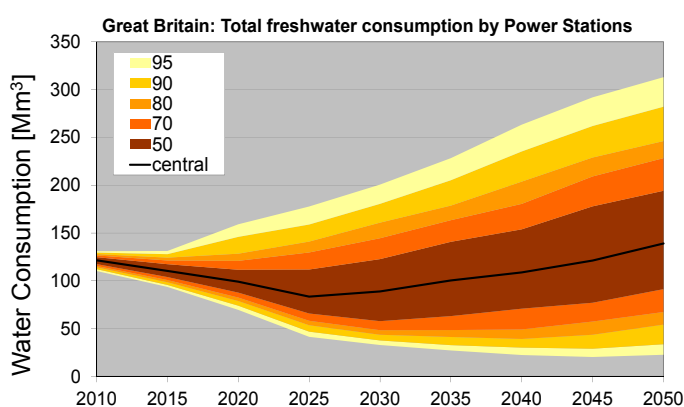


Figure 4: The chart reports GB freshwater consumption under a "DECC 2050 Pathway", where electricity generation is dominated by nuclear plants. The chart shows the 'central case' development (black curve) and the associated uncertainty range (expressed as percentiles: shaded area). Similar charts can be produced for different "DECC 2050 Pathways", water classes and spatial resolutions (up to single river basin districts)

The future development of water requirements by the Power Sector can only be assessed with a very substantial level of uncertainty. This is due to the variability of the gross water use and consumption rates associated with the different available cooling technologies, and uncertainties in the timings of closure of existing plant and opening and location of new plants. This holds even under the assumptions of a well-defined energy scenario, where future activity by different classes of generators

### 3.2 Water for energy under extreme weather conditions

A changing climate requires renewed attention to the way that power stations are both designed and operated. This approach must take into account both long term gradual changes in climate, such as marginally higher mean air and water temperatures, and also the impacts of climate change on weather events, such as more frequent flooding, hotter and more frequent heatwaves, and prolonged drought. Failure to account for climate impacts increases the risk of poor economic performance, economic damage and loss, and impacts on supply security. Various assessments in the UK synthesise the risks of climate change to the electricity sector (McColl et al. 2012, Energy UK 2015, Byers et al. 2015a, Byers et al. 2015b). However, the large majority of this work has been

done on an asset-by-asset basis, as opposed to with a systems-of-systems perspective (Thacker et al. 2014). Of the many climate impacts and risks to the energy sector (for examples see McColl et al. 2012; Byers et al. 2015b), key water-related climate impacts, effects and risks to thermal power plants are summarised in Table 1.

For inland thermal power plants, cooling system choice is a particularly important consideration. Wet tower cooling systems require water and thus leave the plants vulnerable to low flows, droughts and elevated water temperatures. Dry air-cooled systems greatly reduce the risk of water shortages, but have higher capital and operational costs. Dry systems perform less efficiently, particularly in high air temperatures, resulting in higher fuel input and GHG emissions, power output reductions and even the possibility of shutdown.

The higher efficiencies of combined cycle gas turbines (CCGT) results in cooling and subsequent water requirements that are approximately half those of coal-fired steam cycle plants. Thus 'fuel switching' capacity for more CCGT is widely considered as one of the most effective ways of reducing emissions and saving water in the sector (Grubert et al. 2012; Scanlon et al. 2013). The use of carbon capture is also a promising technology for reducing emissions, but due to parasitic loads, results in water requirements between 40-90% higher than

Climate change impact	Effects	Risks
<b>Chronic</b> – changes slowly over time with effects that are felt over long timescales. Slight changes in process efficiency can subsequently change the quantity of fuel use, GHG emissions power output and profitability.		
Higher mean air temperatures	Variety of marginal impacts on efficiency of steam turbines (↑), gas turbines (↓), wet tower cooling (↓) and dry air cooling (↓), as well as higher cooling water temperatures.	Changing temperature distributions have slight effects of efficiency of power production
Higher mean water temperatures (both fresh and saline sources), used for cooling water	Marginally reduces the efficiency of cooling	Changing temperature distributions have slight effects of efficiency of power production
Higher humidity	Variety of marginal impacts on efficiency of gas turbines (↓), wet tower cooling (↓) and dry air cooling (↓).	Changing temperature distributions have slight effects of efficiency of power production
<b>Episodic</b> – occurs on an occasional basis with variable frequency and intensity. Plant operates in conditions close to the extreme of or outside original design parameters. May result in inefficient production, increased wear and tear, increased risk of component failure		
Low flows and drought	Less water reliably available for cooling; competition with other users; increased water treatment plant use	Reduced output or even shutdown required; higher water costs; higher water treatment costs
Heatwaves (high air temperatures)	Reduced efficiency of production; possibility of unit-tripping	More fuel input, lower output, higher emissions and subsequently higher operating costs; risk of forced shutdown if cooling is severely impacted
High rainfall, coastal processes and sea level rise	Flooding of facilities, transport links, co-dependent infrastructure and supply chain impacts	Economic losses, damages and repairs; partial or complete shutdown

Table 1: Water-related climate change impacts on thermo-electric power stations.

conventional unabated plant per unit of electricity generated (Parsons Brinckerhoff 2012). Combined with the fact that plants with carbon capture are likely to be 'clustered' to reduce infrastructure costs, this means that these higher water demands may be spatially concentrated, further increasing their vulnerability to low flows, droughts and heatwaves (Byers et al. 2014). Other low carbon pathways, such as those with more nuclear or renewables, offer a range of different environmental challenges, notably increased competition for land, for example when pathways include bioenergy cropping (Konadu et al., 2015a, b).

### 3.3 Urban Energy and Water Systems Interactions

Cities are centres of human capital in which demand for services is highly concentrated. Many of these services require water and energy to function, and these need to be provided along supply chains that stretch far beyond the city's borders. Water and energy systems are linked at all levels. For example, this occurs on the supply side through cooling of thermoelectric electricity generation and through moving the water to the city's consumers. On the demand or end-use side, energy is required for pumping water locally and heating it e.g. for cooking, hygiene and comfort, and where conversely water can be used as an energy vector.

An analysis of London (see Box 3) indicates that the linkages between the water and energy systems are greatest at the end-use. Service-level conservation can save more water in conjunction with energy than was used to generate or process that energy.

Whereas the end-use nexus, in terms of quantity, is the most important for cities, models for energy and water planning do not represent demand in a way that fully recognises these linkages. This is a consequence of the two systems being largely separate in terms of planning.

The water-energy 'nexus' from an urban perspective constitutes a complex system of systems (of water, electricity and fuels) with several possible feedbacks, which may change the overall behaviour over time. One of those feedbacks may be that water for electricity generation reduces water available for potable urban supply, necessitating more energy intensive water supply expansion. Another feedback may be that hikes in energy prices both increase the operational costs for the water sector, as well as inducing hot water conservation by consumers, bringing down revenues from metered users and putting pressure on the budget available for preventive measures such as pipe replacement or upgrading. Under conditions of increasingly stringent water availability and energy-related goals, the interactions between the several feedback processes may lead to outcomes other than those expected under a business-as-usual approach. Hence, it is important to map all of these processes into a dynamic systems model to elucidate the unexpected problems, which

may arise, as well as the actions, which lead to comprehensive solutions (De Sterke et al., 2015). (The opportunity to recover some of this energy from wastewater streams is addressed later in Section 4.3)

### 3.4 Groundwater resource implications of shale gas extraction

The UK government has committed to supporting the exploitation of unconventional domestic hydrocarbons, in particular shale gas. Its objective is to be less reliant on imports of natural gas in a drive to achieve greater energy security. Without new domestic sources of gas it is expected that the UK will need to import around 70% of the gas needed by 2025. At the same time the Government has also committed to an 80% reduction in greenhouse gas emissions by 2050, so it considers shale gas to be a bridge to a lower carbon future.

Interest in shale gas has arisen as a result of considerable success in exploiting the gas in North America where it now accounts for almost 50% of domestic gas production. The rise in the importance of shale gas has been made possible by the development of new technology, which includes horizontal drilling, and hydraulic fracturing (fracking). This combination has allowed the 'shale' rock that contains the gas to be accessed and economically mined.

Potential shale gas source rocks occur in many areas of the UK, including the Midland Valley of Scotland, across Northern England and in the Wessex and Weald Basins of southern England. There is considerable variation in the depth and thickness of each of the shale formations and their full extent is not yet known. The first of a series of detailed shale gas resource estimates for UK shales was published in 2013 (BGS, 2013), and suggested a median resource figure of 1329 trillion cubic feet of gas. Exploration is still at an early stage, and it will be some time before it is known how much gas can be economically exploited and what this will mean for UK gas supplies.

#### 3.4.1 Extracting shale gas and the need for water

The process of extracting shale gas involves drilling a well vertically towards the shale rock and then orientating the direction of the drilling so that the well extends horizontally within the layers of shale (Figure 6). Restrictions recently imposed in the UK by the Infrastructure Act (2015) mean that exploitation of shale gas by hydraulic fracturing will not be allowed at depths of less than 1 km. However it is likely that production of shale gas in the UK, if it goes ahead, will require the drilling of wells of up to 5 km in depth with horizontal sections nearly as long. Once the well has been drilled the horizontal section is progressively hydraulically fractured (or stimulated) in a controlled way by pumping water that contains around 5% sand and some chemical additives. The fluid is injected at high pressure to fracture the shale rock. The creation of fissures and interconnected cracks significantly



### Box 3: London

London, with a population of over 8 million people, is one of the world's megacities. Most of the water supply to its industries, commercial facilities and households is derived from surface water (the River Thames), and has generally been sufficient to support the city's activities. Nonetheless, in recent years some drought risk has materialised, resulting in the construction of a desalination plant in Beckton on the Thames estuary to supplement water supply in emergency situations (see also Box 4). With a growing population requiring more water, water supply will need to be expanded even in wet years, and the impacts of drought will be more severe.

In terms of energy, London has set itself an ambitious target: to reduce energy-related greenhouse gas emissions by 60% against 1990 levels by 2025 (Mayor of London, 2014). This will require strong reductions in energy demand. London's domestic sector accounts for more than half of the non-transport total final energy use, and 2/3 of London's natural gas use (DECC, 2013). Around 20% of this final energy serves water-related purposes (Kemper Gubetich, 2015). This is an important linkage which can be leveraged for both energy as well as water savings at the end-use and upstream.

Figure 5 shows estimates of the magnitude of the connections between the water and energy systems for London. On the left is the volume of water related to energy use in various sectors, and broken down by stage in the energy chain. The right side shows the estimated energy related to water use by households and commercial/industrial users, identified by urban water cycle component.

Compared to the linkages at the end-use, the energy intensity of water supply in London is significantly smaller, by an order of magnitude as can be seen from the estimates in Figure 5 for 2010. However, this will not necessarily remain so - future water supply expansion and stricter environmental regulations, requiring treatment of wastewater to higher standards, may both considerably increase the energy intensity of water supply and treatment. A focus on the end-use of water is hence necessary from the perspective of the linkages with the energy system.

In London competition for water between the water supply and electricity sectors - a concern elsewhere - is minor. Whereas the Thames and its tributaries were important for electricity generation through the twentieth century, providing both cooling water as well as water supply, water-intensive power generation has been moving out of the Thames basin in recent decades, reducing future competition for water between the electricity sector and the water sector in this region.

The relationships between the water and energy systems are not fixed but change over time, adding to the complexity of London's resource-use dynamics. It is important that they be further studied and taken into account in the planning for a sustainable and prosperous future for the city.

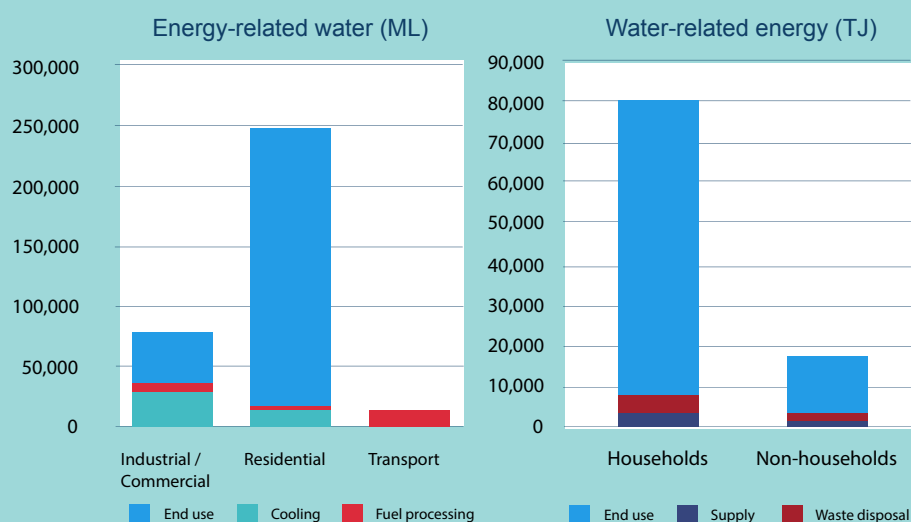


Figure 5: Water-energy linkages for London in 2010. Left: water related to energy use, by user and energy chain component. Right: primary energy related to water consumption, by user type and urban water cycle component. (Mijic et al. 2014)

increases the permeability of the shale. The chemical additives help to optimise the hydraulic fracturing process, e.g. acting as friction reducers and scale inhibitors, and the sand (proppant) holds the fractures open once they have been formed. As a result, gas trapped in the shale is released and can flow into the well and then to the surface.

The drilling of shale gas wells requires significant volumes of water for lubrication and cooling of the drill bit, to return the cuttings to the surface and to overcome hydrostatic pressure. A larger volume of water is then needed for the hydraulic fracturing process. It is not yet known how much water will be required to support a fully-operational industry in the UK, for two reasons. Firstly there is significant uncertainty about how the industry may develop, and secondly, the amount of water the operation will require in the UK is unknown, given that there has only been exploratory drilling and very few small unrepresentative hydraulic fracturing operations to date. A review of the water usage in the United States shows large variations in the amount of water used, reflecting variations in the complexity of drilling, the geological conditions encountered, the total depth/length of the well and the number of hydraulic fracturing stages carried out. These factors will also apply in the UK.

If the higher values from the United States were to be considered representative and 100 wells were to be drilled and hydraulically fractured every year in the UK, this would mean a requirement of around 2.4 million cubic metres of water/year. When compared to the total amount of freshwater licensed for abstraction in England and Wales in 2014 – 13,160 million cubic metres of water/year (Defra, 2015) – this demand represents less than 0.02% of this total.

However, although the water requirements for the industry may be modest at a national scale, the demand will not be distributed evenly due to the location of the shale gas resources, and there may therefore be local pressures on water resources. The Environment Agency manages water resources and abstraction licences (see Boxes 1 and 2), and produce maps of water resource availability, which show that in some parts of the country prospective shale gas areas coincide with areas of limited water resource availability, particularly in the south of England.

Given the potential limits on local water resource availability, the industry will need to consider how it can meet its requirements through discussion with the Environment Agency and the water companies (as potential suppliers). It also needs to consider how to reduce its demand for freshwater by maximising the potential for recycling and re-use of water. A further pressure may arise as a result of climate change if this leads to the increasing occurrence of droughts. Significant droughts leading to water shortages have been experienced in parts of the UK, and are likely to increase in frequency in the future (see section 2.1), and so this additional factor may impact on the industry.

### 3.4.2 Shale gas and pollution

Shale gas operations involve the use and/or generation of chemicals and materials that are potentially harmful to human health and/or the environment. The risks associated with these hazards therefore need to be assessed and managed effectively. The hazards arise from drilling, the use of hydraulic fracturing chemicals and the shale gas and waste water produced during the operation.

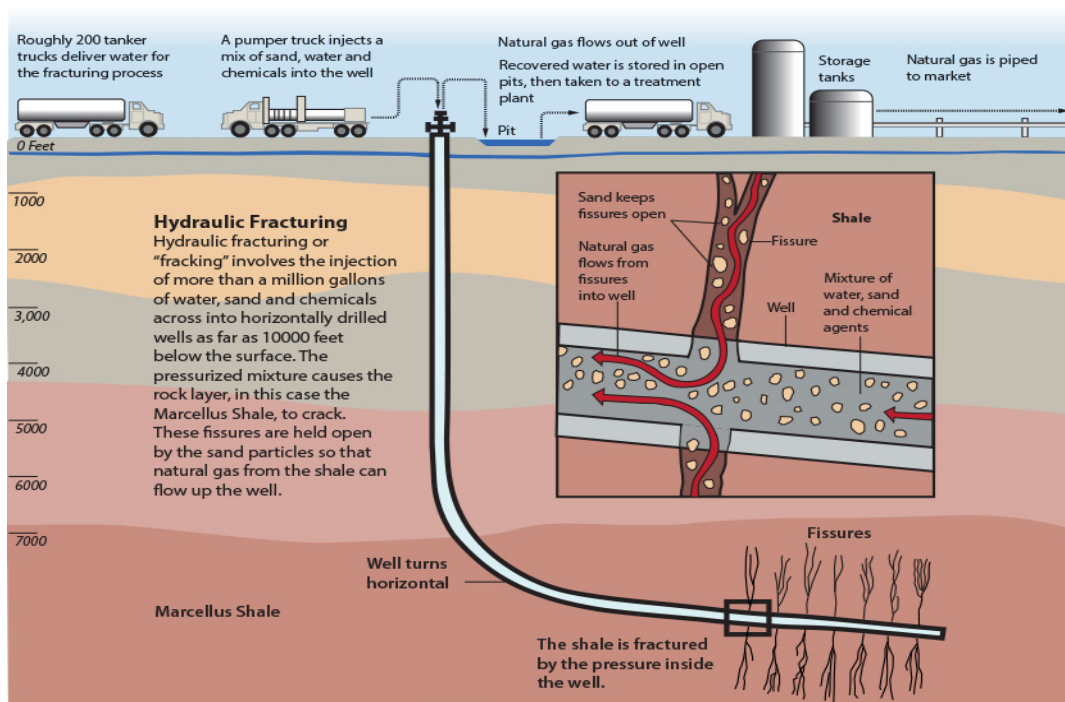


Figure 6: Illustration of shale gas hydraulic fracturing and gas extraction process. Note that in the UK recovered water will be stored in closed tanks and not in open pits. Graphic by Al Granberg, ProPublica.

Environmental risk assessment procedures are well-established in the UK especially with respect to groundwater and surface water protection. However, shale gas exploitation is a new industry in the UK and presents new challenges that need to be considered and managed, especially as many of the shale gas resources underlie some of our most important drinking water supply aquifers. The various potential pollution sources, the pathways and the receptors at risk are illustrated in Figure 7. All combinations of source-pathway-receptor need to be considered but some potentially pose a greater risk than others. One concern is the potential for contamination of shallow drinking water aquifers by the upward movement of natural gas (methane), chemical additives and other pollutants along fractures induced by fracking. Whilst the generation of fractures that extend from a kilometre or more below ground to the surface is highly unlikely (Davies et al., 2012), the British Geological Survey (BGS) has mapped the 3D distribution of shales and the principal aquifers across England and Wales (BGS, 2011) to show where aquifers overlie the shales and how great the separation is between them. Figure 8 shows an example where three shale oil/gas rock types, the Kimmeridge Clay, the Oxford Clay and the Lias, which are considered to have hydrocarbon potential, lie below the Chalk aquifer of the South Downs. As a result of public environmental and safety concerns the UK Government has introduced amendments to the Infrastructure Act (2015) that restrict hydraulic fracturing to greater than 1000m depth and 1200m below drinking water source protection zones. It is generally recognised that the most significant sub-surface risks arise from the hydrocarbon well. Although strict criteria apply for well design and installation, there is limited experience of the long-term integrity of shale gas wells. There is a growing number of cases of well integrity failure in the United States some

of which appear to have led to contamination of drinking water supplies (Llewellyn et al. 2015). This is a controversial topic because it is often unclear whether there was already a problem before shale gas operations started, in the absence of pre-operational environmental baseline monitoring. In the UK at least 12 months baseline monitoring will be required (Infrastructure Act, 2015), and additionally programmes of independent baseline monitoring have been initiated by the BGS to measure concentrations (and temporal variability) of a wide range of chemicals, including dissolved methane, and other indicators (e.g. isotopes) in groundwater and surface water (BGS website). This information will be critical for informing risk assessments and establishing the baseline against which any future change(s) arising from shale gas operations can be detected.

### 3.5 Key Issues and Priorities for Modelling and Research

DECC's alternative energy pathways towards the 2050 goal requiring an 80% reduction of GHG emissions all involve a more diversified energy mix than the present, implying a larger range of issues to understand concerning the inter-dependence of resources, notably energy with water. These are fraught with uncertainty. At the plant scale, there are uncertainties about the frequency with which future hydrological extremes (notably low flows, droughts and their effects on cooling) will prejudice generation, which scale up to the implications of this uncertainty for the number, technology and spatial distribution of power stations across the whole energy production landscape. These system uncertainties lead to very wide confidence intervals in the trends of future water needs in the energy sector, and research is needed to reduce these uncertainties to support modelling

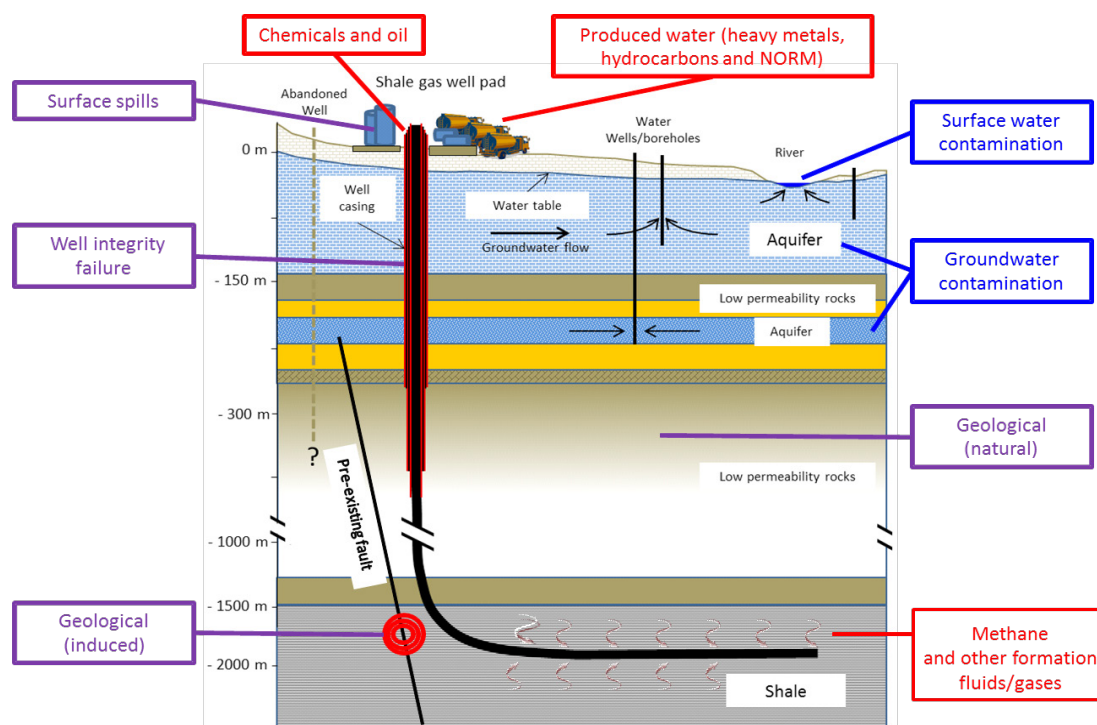


Figure 7: Potential pollution sources (red), pathways (purple) and receptors (blue) that need to be considered as part of a risk assessment for shale gas.

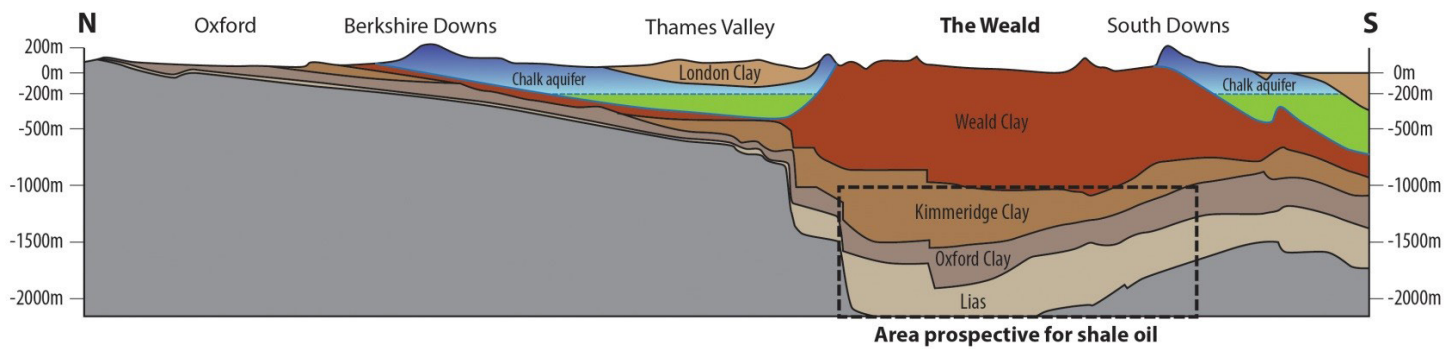


Figure 8: Geological cross- section extending from the south coast of England to the Midlands showing selected shale rock types and areas where they are considered to contain oil and/or gas, and the Chalk aquifer, one of the most important sources of public water supply.

and rational planning of the mix of technologies and plant locations.

These uncertainties are presently rendered all the more problematic because the regulatory regime for environmental flow maintenance is underpinned by the transposition into UK law of the European Water Framework Directive. After the UK leaves the European Union and unpicks the environmental regulations that it has pioneered, there will be added uncertainty about what might replace them, and whether low flow maintenance for ecological reasons will continue to constrain abstraction in the same way. Research will be needed into the likely consequences of this.

In a future where decarbonisation is required, shale gas exploitation may seem to be taking a wrong turn, although there is an argument supporting using it to substitute for risk-laden imports in the period of transition to a low carbon economy. The economics will depend on the period for which this holds sway, on the strength of the regulatory framework for preventing pollution, and on the creation of rigorous monitoring procedures, all of which will require research. The short-term imposition on local water resources, in terms of both quantity extracted and quality disposed, may prove to be a limiting factor in the UK hydro-geological context, with its less extensive and consistent geological units and smaller surface water catchments than in the USA.

New technologies (to the UK) also have a part to play in the future energy-water nexus, and this chapter has identified two; carbon capture and storage, and desalination (Box 4). Both have the potential to be “negative emissions technologies”, but the former is likely to increase the risk of over-use of water especially if clusters of power plants are necessary for each carbon capture facility. The latter is an example of how the UK could resolve water-energy nexus problems by using estuarine water resources to a greater degree, although again there are environmental impacts that will require research. Most emphasis continues to be on upstream supply-side technologies, however. There is much potential for research into the end-user, and in downstream technologies and other demand management strategies, in relation to water and energy separately and jointly. As noted in section 3.3, there are risks of feedbacks from interventions at the end-user level that have unintended consequences,

triggering behavioural changes that are counter-productive. This opens up a large area for social, psychological and behavioural research, and agent-based modelling, to understand how consumers respond to incentives of various kinds. Areas for further research and modelling suggested by the above discussion include:

- Analysis of the effects of different future energy technology mixtures on spatially distributed demand for water in the energy sector; and of the effects of extremes of water availability (floods and droughts) on energy production of these technologies, as well as the identification of critical thresholds beyond which services can't be maintained;
- Improving methods for defining seasonal ecological requirements for river flow (environmental flows), and analysis of the impacts of alternative energy technologies on the capacity to maintain environmental flows (an area of significant uncertainty given the UK's impending withdrawal from the EU);
- Enhancing emergent integrated assessment models to gain better insights into spatial and temporal variations in the dynamics of the water-land-energy nexus under climate change;
- Increased emphasis on baseline monitoring and modelling of the effects of possible future fracking on groundwater storage, flow and quality, and better understanding of the costs and benefits of fracking;
- Modelling and assessment of water usage in the power sector must provide probabilistic rather than apparently deterministic conclusions about potential long-term stress that the sector may impose on UK water resources, with on-going research to reduce the various uncertainties associated with this modelling and how best to convey risk;
- Research into psychological and social influences on citizen/consumer behavioural changes that might lead to reduction in demand for water, and especially reduce the tendency for a 'rebound effect' in which efficiency gains release resources that simply lead to new forms of consumption.

## Box 4: Energy usage of desalination

Population growth in the world's arid and semi-arid regions is the main driver behind the increasing use of desalination to provide freshwater. Several Middle Eastern states now depend heavily on desalination. Kuwait, for example, is entirely reliant on seawater desalination to meet its water needs. While filling the gap in freshwater demand, desalination introduces problems of brine discharge, energy consumption and associated carbon emissions. It tends to shift a water problem into an energy problem.

Desalination has to use significant amounts of energy for thermodynamic reasons. To desalinate seawater requires a theoretical minimum specific energy consumption of about 1 kWh per m<sup>3</sup> of water produced. This minimum is not fixed, however, but is proportional to the concentration of salt in the feed water. Thus the UK's only municipal desalination plant at Beckton takes advantage of estuarine water to achieve lower energy consumption than would be possible with seawater.

The theoretical minimum is not achieved in practice – real desalination plants consume 2 to 10 times as much energy, even using state-of-the-art technology (Davies and Orfi, 2014). Reverse osmosis has emerged as the most efficient and cost effective desalination technology in recent years, and accounts for most new plant installations. It uses far less energy than the thermal technologies it is gradually replacing. Nonetheless, energy still accounts for more than half the cost of the water produced by reverse osmosis plants.

To reduce the gap between the actual and theoretical minimum energy consumption, R&D efforts focus on the various losses that occur in the reverse osmosis process. The largest single loss arises from the need to operate the systems at higher pressures than theoretically required. The theoretical minimum pressure is 26 bar, corresponding to the osmotic pressure of the feed seawater. But high-pressure pumps in reverse osmosis plants typically operate at around 60 bar. This can be overcome using very thin membranes, provided the properties of salt retention are maintained. New materials have been put forward to achieve this goal, such as zeolitic imidazolate frameworks, and graphene oxide paper (Gupta et al., 2015; Nair et al. 2012). While such innovations remain at an early stage, incremental improvements in conventional polyamide-type membranes are also yielding gradual decreases in energy consumption. For example, using the latest commercial membranes, a specific energy consumption of only 2.1 kWh/m<sup>3</sup> was reported in the Canary Islands (Salgado et al., 2015)

A full range of efforts to address energy consumption was adopted by the recent Japanese Mega-ton Water System project – a government-led initiative involving several research institutions. Besides improved membranes, efforts by the Japanese researchers addressed seawater intake technology, assembly of the membranes into larger modules, improved pipework design, optimisation to the system configuration, and recovery of energy from the discharged brines. They reported a specific energy consumption of 2.8 kWh/m<sup>3</sup> – an excellent result considering that it was at a recovery ratio of 60% (Kishizawa et al., 2015). The recovery ratio refers to the fraction of seawater that gets converted to freshwater and is typically only around 45% in seawater desalination. Operation at a higher value of 60% helps to reduce the volume of brine discharged by desalination plants. Brine discharge is the other environmental downside of desalination, besides high energy consumption.

Further ahead, it is possible that desalination could become a 'negative emissions technology'. This is because the seawater brine, though normally considered a pollutant, also has potential to absorb carbon dioxide from the environment. Processes have been put forward that convert the substantial amount of magnesium chloride present in the brine into oxide, hydroxide, carbonate and bicarbonate (Ferrini et al., 2009; Davies, 2015). Conversion of desalination plants to a negative emissions technology could be an interesting alternative for arid countries that have insufficient water resources to implement bioenergy with carbon capture and storage (BECCS), which is currently the most prominent option among such technologies.



## 4 Achieving a low-carbon water industry

The water industry is a relatively small contributor to overall greenhouse gas emissions, at under 1% of the UK total. Nonetheless the water industry is a major user of energy, being the fourth most energy intensive industry in the UK (CST, 2009). The energy intensity of the water industry relates largely to the heavy nature of energy use when pumping is required, and to the requirement to treat water, particularly the treatment of wastewater. Energy consumption has risen in relation to higher treatment standards. Greenhouse gas emissions are primarily related to the consumption of grid electricity, although there are emissions from wastewater treatment works, biosolids used in agriculture, and from transport (CIWEM, 2013). The industry has no formal target for emissions reductions, but companies have set themselves targets for reducing embedded and operational carbon emissions in their 5 year investment plans, some of which are ambitious. A large number of options are possible for reducing greenhouse gas emissions. Electricity grid decarbonisation would offer the simplest option, but beyond that it is possible to reduce consumption of electricity e.g. by minimising treatment needs through catchment measures such as improved land management, or through optimisation of activated sludge control; and to reduce direct emissions for example through transport fleet management. Electricity can be produced by anaerobic digestion or co-digestion, hydropower, or through use of wind turbines or solar panels. Furthermore, companies have an active role in reducing the demand for hot water: domestic heating of water represents a much larger 4 to 5% of UK emissions (CIWEM, 2013). The focus of this section is therefore to highlight GHG emissions accounting and reduction and management, and physical innovations and strategies for carbon reduction in the UK water industry.

### 4.1 Energy usage in water and wastewater treatment

Treating water and wastewater and their distribution is an energy intensive activity. A report produced by the Environmental Knowledge Transfer Network (2008) showed the UK Water Industry was using a total of 7,703 GWh/year in energy, with 634 kWh to treat 1Ml of sewage (10 billion litres of sewage per day), and 586 kWh to treat 1 M litres of water. The energy used on clean water production may decrease in the future in response to leakage and demand reduction, although this may be offset if alternative forms of treatment such as desalination are widely introduced (see Box 4).

Conversely wastewater treatment is likely to show a significant increase as a consequence of increasingly stringent water quality discharge regulations. The report suggested energy efficiency could be achieved by developing an understanding of the process inefficiencies, introduction of best practice, novel processes, automated control and more efficient mixing, aeration, and pumping technologies.

### 4.2 GHG emissions accounting and reduction in the water industry

#### 4.2.1 Background to carbon accounting in the UK water industry and reporting

The UK water industry contributes approximately 0.7% of UK GHG emissions from its operational activities (Ofwat, 2010), excluding the emissions arising from new infrastructure investment. Historically there has been a trend of increasing emissions from the sector, primarily on account of the substantial capital investment in new energy-intensive assets since privatisation to address requirements such as those in the Urban Wastewater Directive (EEC, 1991).

The water industry began its effort to assess its GHG emissions in 2005 with the first 'Carbon Accounting Workbook' published by UKWIR (see Figure 9). The workbook enabled water companies to report the emissions from their operational activities in a consistent manner. The majority of operational emissions arise from the use of electricity and gas, although process emissions are also significant. Since 2005, the industry has progressively improved its assessment and reporting of both operational and embodied emissions.

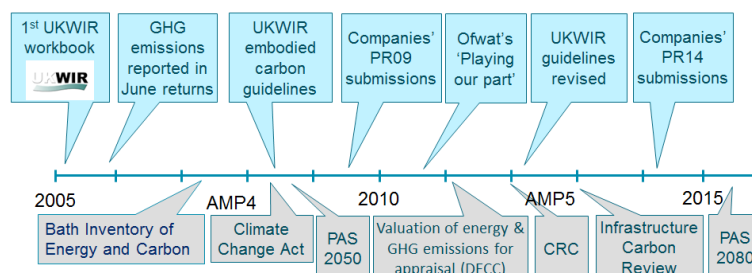


Figure 9: Timeline of carbon accounting in the UK water industry.

Reporting by water companies using the standard approach in the Carbon Accounting Workbook has enabled comparison of operational emissions using a common functional unit – kgCO<sub>2</sub>e/ML of water supplied or wastewater treated (see Figure 10). This is more useful at organisation level than at project level.

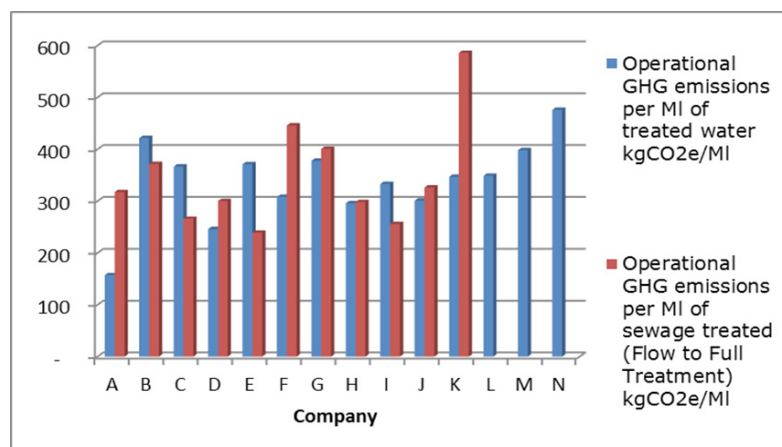


Figure 10: UKWIR workbook has enabled comparison in terms of a common functional unit

## 4.2.2 'Embodied' and 'whole life' carbon accounting

Increasingly, carbon accounting is being used by water companies to assist their decision-making. The UKWIR framework (2012) provides a standard methodology for estimating the embodied carbon arising from the construction and maintenance of capital assets, and for carrying out whole life carbon accounting for project appraisal and investment selection.

Based on the principles of lifecycle analysis, embodied carbon accounting takes into account the emissions from extraction and processing of raw materials, product manufacture, transport to site and construction activity on site, as well as waste disposal. The framework requires careful definition of boundaries to include those emissions within company control but also those it can influence, particularly those that differentiate alternative options in project appraisal.

The functional units used depend on the information available when the assessment is carried out. For example kgCO<sub>2</sub>e

emitted per m<sup>3</sup> treated may be used to develop a top-down estimate early on in project or programme development, whereas kgCO<sub>2</sub>e emitted per kg of material used is used to give more accurate results during detailed design and construction.

## 4.2.3 Outstanding issues

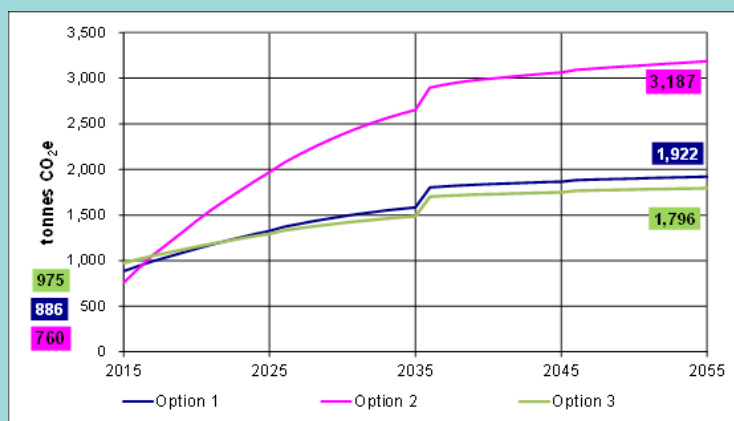
There are a number of outstanding issues for carbon accounting in the water industry:

- **Forecasting emissions vs. actual emissions:** Although the assessment of operational emissions is reliably based on actual use of energy and other consumables, assessment of embodied emissions is primarily focused on deriving forecasts during the planning and design stages of projects. Although data on actual materials and energy use are increasingly being collected during construction, there is some work to do before actual embodied emissions are routinely used to improve forecasts.
- **Relative vs. absolute measurement:** Given the differing provenance of the emission factors used in the assessment of embodied carbon, it is difficult to forecast absolute emissions from capital investment with high certainty. However, given that the primary purpose of whole life carbon accounting is to inform decision-making, it is more important to ensure that the accounting methodology used is consistent so that the relative differences in the whole life emissions of alternative options can be compared with high confidence (for example, see Box 5).
- **Materiality vs. accuracy:** Given the difficulty in obtaining accurate results in absolute terms and the potential for generating a large number of carbon calculations for any engineering project, it is important to remain focused on those components which are material to the decision being made. Setting accounting boundaries carefully and consistently will help ensure comparisons between alternatives are valid, particularly where these differ in category (rather than just size). (See Box 6)
- **GHG emissions performance vs. other performance measures:** Whilst carbon accounting is increasingly being used to inform investment decision-making in the water sector, the increasing focus on delivering better outcomes for customers and the environment means that GHG emissions are only one performance measure amongst others considered in individual decisions. Effort should be focused on integrating carbon into a multi-criteria approach such that the best solutions are those that maximise customer benefits for lowest whole life cost and carbon emissions.

### BOX 5: Example of how carbon accounting can help in decision-making in the water industry

In this simple example, three alternative approaches to developing a new pumping station and rising main are compared, specifically using three different diameters for the 1km rising main: 700mm (Option 1); 500mm (Option 2); and 900mm (Option 3). The carbon emissions from the construction and subsequent operation of the rising main are the dominant factors in the calculation.

As the chart shows, Option 2 has the lowest embodied carbon emissions from construction and Option 3 the highest. However, because Option 2 has larger hydraulic losses during operation, its operational carbon emissions over time, and hence its whole life carbon emissions, are very much larger than both Option 1 and Option 3. This simple example serves to illustrate the importance of taking a whole life approach to carbon assessment to inform sustainable decisions.



## BOX 6: Suitable metrics to compare options

The choice of boundaries for measurement is very significant. The inclusion of CO<sub>2</sub>e ‘embodied’ in the construction programme has been seen to add about 50% (Keil et al., 2012) to annual operational emissions. It also drives water companies to start demanding CO<sub>2</sub>e emissions data on products and services from their supply chains, which in turn helps change mindsets and drive innovation in each of their specialist sectors.

The inclusion of customers’ water-in-use emissions in the total, from the energy used to heat water for cooking and washing, makes a much larger increase. These alone comprise more than 85% of the total emissions arising from the water cycle. They are at least eight times those coming from operating the water-company’s assets (Environment Agency, 2008). These wider measurements may be applied in choosing strategies and preferred solutions, such as managing water demand down, compared with adding more supply. However, the UK water sector currently only reports on annual operational CO<sub>2</sub>e, both as a total tonnes of CO<sub>2</sub>e per year and as average kilograms of CO<sub>2</sub>e per megalitre of water supplied.

Comparing alternative water supply–demand balance solutions, including customers’ use of water, highlights the need to use the right measurement units. Using the conventional ‘average kg CO<sub>2</sub>e/ML of water supplied’ measures efficiency per unit of product. It favours conventional ‘supply more water’ technology-efficiency based approaches, because it does not register the direct CO<sub>2</sub>e-emissions reduction that a more sustainable demand-reduction option, reducing water use per customer, would give.

The better alternative for comparing these radically different options is to use ‘kg CO<sub>2</sub>e/customer’. This is an ‘efficiency per customer’ service-related measure. It will include any direct reduction in CO<sub>2</sub>e achieved by a water-demand-reduction option, as well as registering fairly the reductions achieved by technology-efficiency options.

So units must be chosen carefully: ‘average kg CO<sub>2</sub>e/ML of water supplied’ units can be used when comparing technology choices at the detail design stage, or performance improvements during operation. But for outline design, ‘efficiency per customer’ units should be used to give a level playing field for evaluating non-assets-based solutions as well as assets-based ones (Ainger and Fenner, 2016).

## 4.3 Management innovations and strategies for carbon reduction in the water industry

### 4.3.1 Leadership and management approaches at Anglian Water

Since 2006 Anglian Water has illustrated a focussed commitment to climate change mitigation and adaptation activities. The company’s strategic direction statement covering 2010–2035 identified seven main challenges of which two were highlighted as of particular importance to the Anglian region: climate change and population growth.

Anglian Water is one of the largest energy users in the East of England. This is a large financial burden, as well as having an adverse effect on the environment through the resulting greenhouse gas emissions. In consultation with a range of stakeholders and as part of the 2015 – 2020 business plan, Anglian has developed ten outcomes to deliver for our customers and the environment. One of these outcomes is a smaller footprint, leading by example on reducing emissions and conserving the world’s natural resources. Anglian has also updated its “Love Every Drop” carbon goals:

- to exceed a 7% reduction in real terms in gross operational carbon by 2020 from a 2015 baseline; and
- to deliver a 60% reduction in capital (embodied) carbon by 2020 from a 2010 baseline

Minimising both the ‘operational’ carbon created in everyday

operations, and the ‘capital’ carbon used in building assets such as water mains, sewers and pumping stations, is vital to reducing our overall impact. With leadership in place through a clear vision and targets from the Anglian Water Board, management of carbon includes four distinct areas (see Figure 11):

- Quantification and tools: Over 1300 capital carbon models have been developed. These form part of the company’s baselining activity and option selection in identifying the optimum solutions for reducing carbon and reducing cost. The models are available to the Anglian Water supply chain as part of our carbon and water foot- printing modelling tool.
- Governance: Operational and Capital Carbon are measured on three separate occasions through design and build at a project level, and are tested against a baseline. Design engineers have to explain actions taken to reduce carbon against the baseline as they progress through project delivery.
- Reduction Hierarchy: Design engineers are provided with a four-stage process to challenge the root cause of, and need, for any new asset; and to deliver a lower carbon solution.
- Our Supply Chain and People: Regular training and masterclasses are provided for engineers across the supply chain and performance is recognised through company awards.

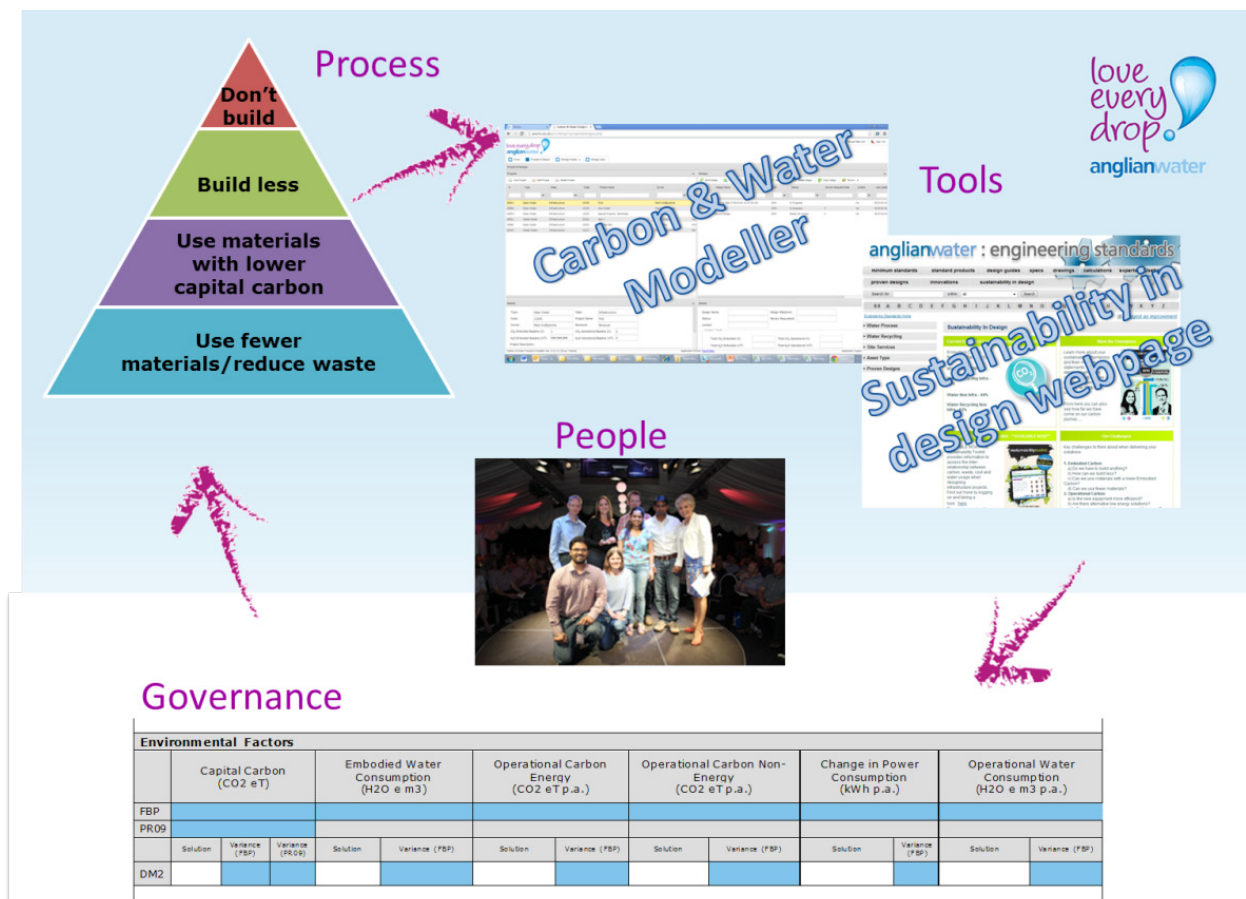


Figure 11: Illustration of the supply chain and governance at Anglian water

Capital carbon now accounts for around 15% of Anglian Water's overall carbon footprint, and is where the biggest reductions are made. In 2015 the company reduced the capital carbon in new built assets by 54% from a 2010 baseline, and exceeded its operational carbon goal.

#### 4.3.2 Energy and water resource efficiency at Thames Water

The first principles at the highest level of the water sector have two main functions: to provide wholesome and safe drinking water on demand; and to provide an effective wastewater service. There are choices to be made on how to deliver these functions, in a way that balances the competing needs and aspirations of customers, wider society, the environment and shareholders. Furthermore, these services and functions do not start with a blank sheet of paper, since there are many existing assets and infrastructure (Table 2) at a scale which is not always appreciated outside the water sector.

Water and sewage are heavy and therefore moving them around is inherently energy intensive with energy costs in the order of £100 million a year for Thames Water. Therefore anything that can be done to reduce this is good for customers, good for the environment, and can reduce pressure on the energy grid. Currently, the energy demand at Thames Water is estimated at 1293 GWh/year, of which 159GWhr is self-generated from various sources of renewable energy. In addition to these, the overall energy efficiency has improved by 149GWh between 2010 and 2015.

Looking forward, there are ambitious plans to reduce grid energy consumption by ~200GWh/year by 2020. This can only be achieved by becoming more energy efficient in the operation of existing assets; replacing grid electricity through the self-generation of renewable energy; and/or developing new infrastructure solutions that require much less energy to operate.

A range of low-carbon and sustainable approaches have been employed at Thames Water to improve water resource availability, whilst at the same time improving energy efficiency and managing carbon intensity. Foremost among these are:

- managing short-term supply and demand balance in Swindon through the promotion of behavioural change;
- developing the North London Aquifer Recharge Scheme (NLARS), a strategic drought supply scheme located underneath London, made up of 48 boreholes in the confined Chalk aquifer which can provide 230MI/d of water a day during times of drought to supply Londoners;
- developing the London ring main, a 90km tunnel that acts as a 'ring of water' around London, allowing water to flow in either direction under gravity, resulting in large energy savings as expensive overland pumping is reduced (Figure 12); and
- developing Horton Kirby Aquifer Storage and Recovery



Figure 12: The only visible part of the London Ring Main

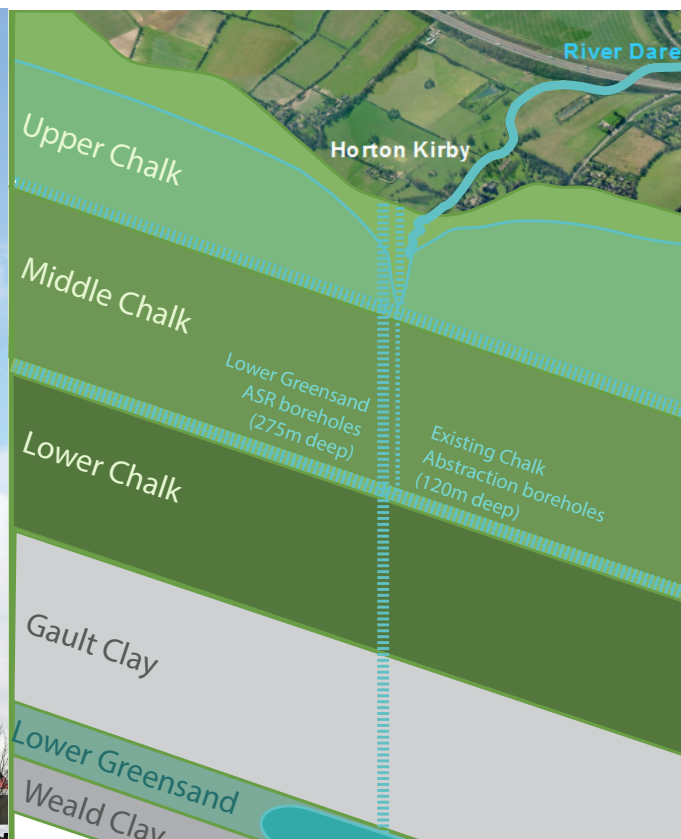


Figure 13: Horton Kirby ASR Scheme

Asset Type	Description
Number of customers	15 million waste, 9 million water
Water and Sewage treated per day	8.0 billion litres
Water Treatment Works	102
Length of water main	31,100 km
Water pumping stations	235
Desalination Plant	1
London Ring Main	90 km
Sewage Treatment Works	350
Length of sewer	109,400 km
Pumping stations	2,350
London intercepting sewers	132 km
Lee Tunnel	6.5 km
Sludge Powered Generators	2
Renewable energy generation types	AD+CHP, THP+AD, Sludge Incineration, PV, Wind, Hydro

Table 2 Key Facts on assets and infrastructure for Thames Water

Scheme, which uses an innovative approach of water storage using underground rock reservoirs (figure 13).

With the Horton Kirby example above, there are multiple benefits associated with its delivery including; improved supply and demand management including water resource resilience during droughts, a significant reduction in disruption to the community during its delivery, a lower cost than alternative water resource schemes with a shorter lead time. Additionally, there are significant resource sustainability and GHG emission reduction benefits, such as increased resilience to the impacts of climate change, reduced environmental and ecological impacts in delivery and operation, a lower embodied carbon footprint, and the avoidance of potential water chemistry issues arising from mixing waters from different sources.

## 4.4 Technologies and energy generating potential of the water industry

### 4.4.1 Converting waste-sourced carbon dioxide into energy

GHG emissions from the water sector have been estimated at 3-10% of total global emissions (McGuckin et al., 2013) with the electricity demand of the water sector accounting for ca. 3% of the UK's national consumption (Rothausen and Conway, 2011). Implementation of anaerobic digestion (AD) for sludge treatment is one of the most promising solutions

for increasing renewable energy production and reducing the sector's carbon footprint. Currently, the  $\text{CO}_2$  contained within the biogas produced by ADs is generally emitted to the atmosphere. Although biogenic carbon emissions are not accounted within carbon accounting inventories, their emission avoidance would be considered as negative emissions.  $\text{CO}_2$  sourced from biogas has been regarded as the most easily available stream for carbon valorisation within the wastewater treatment process and has been quantified at 270,000 tonnes  $\text{CO}_2$  per annum for the UK water industry (Byrns et al., 2013). Bioconversion of  $\text{CO}_2$  to  $\text{CH}_4$  in the AD process itself has proved a feasible treatment option for  $\text{CO}_2$

sourced from biogas (See Box 7). Initial studies were reported in the 1990's by Sato and Ochi (1994), who observed an increase in  $\text{CH}_4$  yield of up to 30% when maintaining a 60%  $\text{CO}_2$  concentration in the headspace of ADs treating sewage sludge. The possibility of  $\text{CO}_2$  being bioconverted to  $\text{CH}_4$ , without addition of external  $\text{H}_2$ , was also proved in upflow anaerobic sludge blanket (UASB) reactors by Alimahmoodi and Mulligan (2008) and for ADs treating different feedstocks by Bajón Fernández et al. (2014). In spite of these and other initial investigations on the topic, the literature on bioconversion of  $\text{CO}_2$  into  $\text{CH}_4$  in anaerobic processes without addition of external  $\text{H}_2$  is scarce.

### Box 7: Distribution of $\text{CH}_4$ production enhanced with $\text{CO}_2$

Severn Trent Water, WRAP and Cranfield University have worked collaboratively to investigate the feasibility of bioconverting on-site exogenous  $\text{CO}_2$  to methane ( $\text{CH}_4$ ). The potential for bioconversion of  $\text{CO}_2$  in anaerobic digestion (AD) was proved in laboratory scale ADs and observed to be different depending on the substrate treated. The observed increase in  $\text{CH}_4$  production during the 24 hours following saturation with  $\text{CO}_2$  was higher for ADs treating sewage sludge (up to 2.4 fold) (Figure 14) than food waste (up to 1.16 fold).

A mass balance of  $\text{CO}_2$  in the laboratory scale ADs, led to an estimation of a potential  $\text{CO}_2$  reduction of 8 to 34% for sewage sludge ADs saturated with molar fractions ( $y_{\text{CO}_2}$ ) of 0.3 and 0.9, respectively. Benefits of 3, 10 and 11% were estimated for food waste ADs enriched with  $y_{\text{CO}_2}$  of 0.3, 0.6 and 0.9, respectively.

The mechanisms of  $\text{CO}_2$  bioconversion to  $\text{CH}_4$  were investigated by utilising fluorescence in situ hybridisation (FISH) for monitoring alterations in methanogenic communities. A significant change in the methanogenic communities of ADs periodically enriched with  $\text{CO}_2$  was observed, with an up to 80% increased activity of *Methanosaetaceae* (obligate acetoclastic methanogens and main contributors to  $\text{CH}_4$  formation in sewage sludge ADs) obtained in ADs periodically enriched with  $\text{CO}_2$  at  $y_{\text{CO}_2}$  of 0.9. Utilisation of exogenous  $\text{CO}_2$  in ADs was then confirmed to proceed biologically, and postulated to be reduced by homoacetogenesis (Wood-Ljungdahl mechanism) with the acetate generated by this route being converted to  $\text{CH}_4$  by acetoclastic methanogenesis.

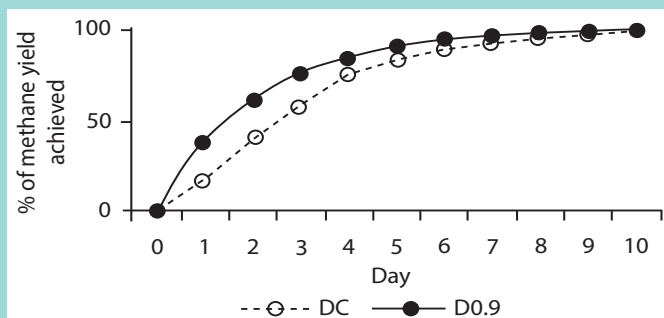
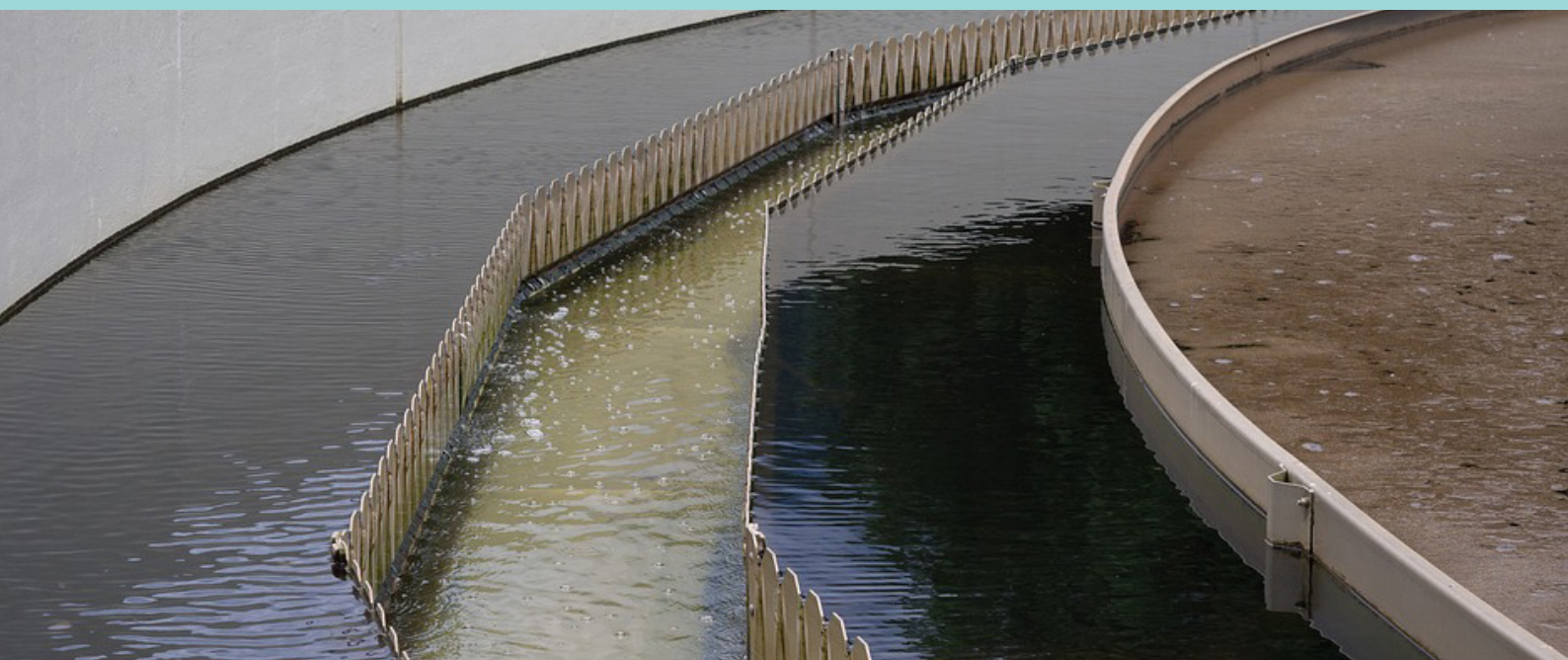


Figure 14: Distribution of  $\text{CH}_4$  production over time in ADs treating sewage sludge. DC: control digester; D0.9: digesters enriched with  $y_{\text{CO}_2}$  of 0.9. Adapted from Bajón Fernández, et. al. (2014).



#### 4.4.2 Capturing energy from water distribution systems

Gravity-fed municipal water distribution systems present an opportunity for harvesting energy simultaneously with the core operation of water supply. The underlying principle is to utilise the velocity and volume of moving water in pipelines to drive installed turbines to generate electricity. An example of a commercial success story of capturing energy in water distribution systems is the LucidPipe™ Power System by Lucid Energy Inc. in Portland, Oregon, USA. This water-to-wire energy recovery solution enables water-intensive industrial, municipal and agricultural facilities to produce clean, reliable, low-cost electricity from gravity-fed water pipelines and effluent streams. LucidPipe™ uses an in-pipe turbine that captures energy from fast-moving water inside large diameter pipelines, with no restriction on flow or operation. Depending on head pressure, flow and pipe diameter, each LucidPipe turbine is capable of producing up to 100 kilowatts of renewable, zero-emissions electricity by extracting excess head pressure.

To maximize power generation, multiple turbine units can be rapidly and easily installed into a single pipeline. A schematic illustration of this technology is shown in Figure 15. The system utilises a unique, lift-based, vertical axis spherical turbine technology that is inside large diameter (24"-96") water pipes. Water flows through the hydrodynamic turbine, generating power as the turbine spins. This enables power generation across a very wide range of flow conditions, volumes and velocities. Additionally, the turbines have been designed to maximize efficiency and power generation without interrupting the flow of water.

A successful installation in Portland, Oregon generates 200kW for Portland General Electric under a 20 year Power Purchase Agreement, the first of its kind from a municipal owned water pipeline. The system is expected to generate an average of 1,100 megawatt hours of energy per year, enough electricity to power up to 150 homes.

#### 4.4.3 Opportunities for thermal heat recovery from wastewater

There are three places where energy may be extracted from wastewater: in the home, within the sewer system and at the wastewater treatment plant. At any of these stages some key questions need to be answered including; how much energy is recoverable; and how and where can it be used? About 15% of thermal energy supplied to buildings (e.g. in Switzerland) is lost through the sewer system (Frijns et al., 2013) with the heat value in domestic wastewater being estimated at an average of 21.3 MJ / home /day.

Recovering heat from sewage effluents and wastewater has been practised around the world since at least the 1980s with early examples in Tokyo where heat recovered from Ochiai WWTP has been used in administrative offices; in China where recovered heat from buildings has been used in Beijing train station; and the first heat recovery system in North America was deployed in Whistler during the 2010 Vancouver Winter Olympic Games to heat the residential village. In Europe, well developed heat recovery systems can be found at wastewater treatment plants in Oslo, Zurich and Helsinki. For a detailed review of wastewater heat exchangers in wastewater source heat pump applications, see Culha et al. (2015).

In individual houses, simple heat exchangers can be installed to recover heat from domestic hot water used in showers and baths, costing about £1000 to install; some estimates suggesting a saving on domestic gas bills of £20-30 a year (The GreenAge). Another possibility is the recovery of thermal energy at housing estate level, such as in Hamburg where heat exchangers in the sewer provide heat to 215 houses. This scheme is claimed to reduce GHG emission by 700 tonnes CO<sub>2</sub>-eq/year (van der Hoek, 2011). Similarly in Wintherthur, Switzerland a heat exchanger installed in the basement of a high rise building withdraws about 440 kW from the municipal wastewater through cooling by approx. 2.1°K. A heat pump uses this energy source to generate about 590 kW heat with an electrical power input of approx. 150 kW (achieving a coefficient of performance of approx. 4.0).

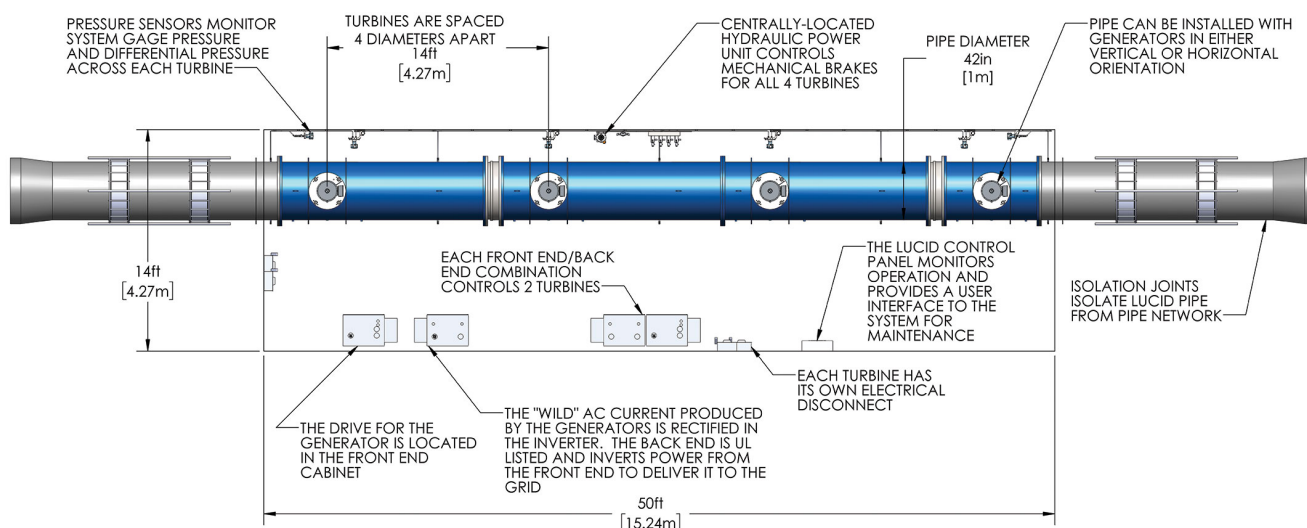


Figure 15: Illustration of LucidPipe in-line pipe turbines (© LucidEnergy™)

Work has been carried out in Italy to assess the variability of flow rate and temperature in Bologna's sewers (Cipolla and Maglionico 2014), and similar studies are being conducted in the Czech Republic to identify locations that are suitable for installing direct heat exchanges in sewers. These installations can be hampered by biofilm formation, corrosion and solids deposition reducing their efficiency. A further constraint is that the resulting lower wastewater temperatures could adversely affect the efficiency of wastewater treatment processes, in particular for nitrification processes. Nevertheless a recent study has shown that even by restricting the temperature reduction to just 0.5°C, 16.3 TJ per season could be recovered (Stransky et al 2014).

A pilot study in the UK at 4 wastewater treatment plants in Southern England (Fenner and Hawley, 2012) showed at the largest works that c300,000 MWh/year was recoverable downstream of the treatment processes at the final effluent outfall, using a heat pump. This avoids interfering with the heat benefits within the biological treatment stages (ensuring temperature stay above 10°C) but requires limits to be set on acceptable reductions in temperature in the receiving waters (e.g. 1.5°C for a salmonid river and 3°C for a cyprinid river). Recovery at this point has the benefit of low BOD and solids in the effluent.

The recovered heat was considered for use in space heating, or within the plant itself for sludge drying or to boost the anaerobic digestion of sludge to a 55°C thermophilic optimum which theoretically can produce more methane and hence increase electricity generation by around 50%. Thermal energy recovery for district heating applications was found to produce the greatest energy savings, with the greatest carbon reduction potential, at lowest risk.

Using heat for thermophilic digestion had significant renewable energy generation potential, with high rate of return on investment (but also highest uncertainty and risk). By including the cost of carbon the financial feasibility of the re-use options was greatly improved.

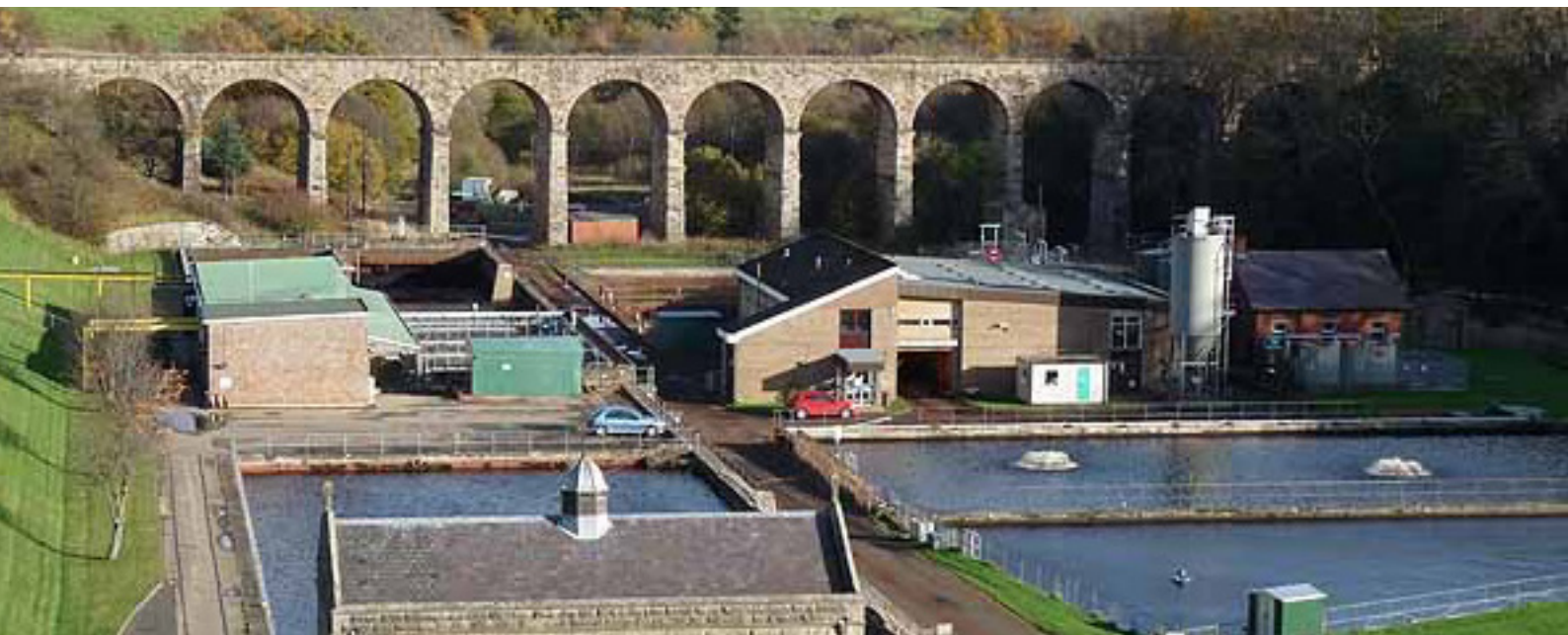
## 4.5 Key Issues and Priorities for Modelling and Research

There are strong incentives for the water industry to reduce its direct and indirect GHG emissions, since the energy costs (of water distribution and treatment) are very substantial (£100 million a year for Thames Water, for example). As a result, there has been significant investment in carbon accounting practices and in decision-support systems to enable the selection of project options that minimise operational and capital carbon. Section 4.1 identifies several outstanding issues associated with these methods. There is also an increasing role of the industry in engaging with consumers, in order to manage demand and reduce waste. Whether there is room for more engagement with the construction sector to explore how domestic water systems can be less dependent on a supply of potable water in new build housing stock may be an area for development.

What this section shows is that there is also room for technical innovation applicable locally; two different ways of recovering energy from water are discussed, one using efficient turbines in mains water delivery pipes, and the other using heat exchangers to recover heat from waste water. To scale up these ideas, and others that may still emerge, it may often again be necessary to involve end-user consumers in discussion about preferences and perceived problems, as in some cases there is a need to roll back from autonomous domestic systems to locally managed shared systems, and this is likely to require significant participatory decision-making.

Some key messages for research and modelling are:

- Nexus analysis of the water-energy system needs to include evaluation of changing carbon emissions as a performance indicator of alternative approaches to water supply delivery, and carbon accounting needs to be embedded and refined in the water industry;
- Support for innovation in coupled management of the water and energy sectors could lead to new forms of distributed energy recovery and production, both within supply networks and within homes and businesses.



## 5 The challenge of scale

### 5.1 Interdependencies of energy and water infrastructure

In addressing these nexus interdependencies, a National Infrastructure Systems (NIS) perspective is valuable not only for looking cross-sectorally, but also for thinking across scales, and for challenging decision-making where there is a lack of ownership in government circles of critical system interdependencies. The national infrastructure is the delivery system for the services of water supply, sanitation, energy, mobility and digital information. It involves large-scale (top-down), long-term investment, whose physical consequences are difficult to adapt, and are typified by lock-in (for example, where ageing buried pipelines can lead to polluting spills into urban watercourses). It is conventionally considered to involve public goods, most of which are ubiquitous and non-excludable; and are provided by monopolies subject to regulation.

However, these assumptions and definitions of what the national infrastructure represents are in practice fuzzy, and subject to change. For example, is the housing stock part of the national infrastructure? Perhaps it is becoming so, as questions of managing demand for services complement traditional top-down emphasis on supply, and as water management, distributed energy production, smart metering, and electrification of the car fleet devolve decisions about service delivery and use to household level. In addition, a multi-dimensional approach to services sees them as delivered by interconnected networks, which have the particular economic characteristics of initially high cost, but increasing marginal returns as the network structures and inter-connections are progressively augmented.

Thus, an NIS perspective is useful, although generally, water, waste, energy, transport and IT systems are considered separately, and are neither analysed nor planned as a system of systems. There have been increasing calls to rectify this, with the report *A National Infrastructure for the 21st Century* (Council for Science and Technology, 2009) emphasising systems perspectives on the modernisation of UK infrastructure. Infrastructure UK was then created as a Treasury unit in 2010, although mainly to professionalise major project management, rather than to think strategically in system of systems terms. The National Infrastructure Commission, created in 2015, was eventually established as an independent executive agency charged with producing a National Infrastructure Assessment that would seek to identify how best to meet Britain's long-term infrastructure needs.

A consortium of seven Universities, the Infrastructure Transitions Research Consortium (ITRC) (see <http://www.itrc.org.uk/>), has helped the Commission to think about the National Infrastructure in system of systems terms (Hall et al., 2016).

It has analysed and modelled the geography of demand for infrastructure services across the UK, dependent on a wide range of demographic and economic scenarios; and their delivery through a set of interconnected networks with given capacities, to derive multi-attribute metrics of system performance. This analysis considers feedbacks in which demand is shaped by opportunities, preferences, technologies, and prices; and understanding these processes and effects is acknowledged to be poorly understood and in need of further research.

The interdependencies of water, energy, waste, transport, and IT have been assessed in nexus analyses that often treat pairs of systems in top-down analyses (for example of energy use in the water sector), but it is also necessary to understand the correlations of these multiple demands at the end user level. The ITRC modelling results are for multiple scenarios based on future population, climate, economic performance and energy prices, with a range of options for modifying infrastructure. These show the persistent strength of demand imbalance across the country (maximised in the south-east), with energy demand provided by different infrastructure depending on the export orientation of the economy, and with different costs and carbon emissions for each scenario.

As far as water is concerned, modelling results show a general trend of reducing abstractions, because nuclear energy is increasingly located at the coast (using tidal and seawater sources for cooling), and because coal-fired plants are closed. This conclusion is modified, however, if there is widespread CCS deployment, which will increase freshwater abstractions. Although in aggregate these are not large, geographically they may be high enough to be problematic by 2050, especially in the NW, and along the Trent and Thames (Konadu and Fenner, 2017). Evaluating CCS abstraction needs against Environment Agency Abstraction Sensitivity bands, using CEH future flow data depending on a range of climate scenarios, and with licensable abstraction amounts at low flow set at 15% of the Q90 flow, there will be frequent days on the River Trent when abstractions have to be restricted.

CCS deployment as a basis for meeting GHG emissions targets therefore conflict with sustainable water use (Byers et al., 2016). Interestingly, although in the delivery of some services there are opportunities to devolve decision-making to household level and to manage demand, in water treatment, the opposite is true; the economies of scale favour large centralised infrastructure. However, this is again a geographically sensitive conclusion, as areas with more dispersed population will require technical innovation for cost-effective treatment in smaller-scale infrastructure.

Other questions that system of systems thinking can helpfully address include that of optimising the benefit from the infrastructure network to compare with costs, with benefit-

cost ratios often appearing higher from smart investment in demand management. However, there continue to be significant areas of uncertainty, especially if demand uncouples from economic growth. There are, for example, already suggestions that mobility demand may decouple in this way if car ownership declines. Nevertheless, these questions need to be examined if infrastructure planning is to anticipate future needs, and are best answered through a system of systems form of analysis.

## 5.2 Small scale water systems that drives sustainability

Whilst many of the challenges associated with the water-energy nexus play out at a national or regional scale, many of the solutions are likely to be small-scale systems associated with single households and individual behaviours. In the UK, some 90% of water service energy use and carbon emissions are caused by usage in the home, principally due to heating of water (Fidar, 2016). This underlines where mitigation priorities might best lie, although unintended consequences should be guarded against. Well-meaning attempts to reduce water consumption in the home, for example, have been shown to have the potential to increase energy use and carbon emissions, solely depending on the choice of domestic appliance (Fidar et al., 2010). Early water-saving systems such as rainwater harvesting often used more energy to supply non-potable water than the centralised potable water supply (EA, 2010; Memon et al., 2014). However, modern systems for commercial buildings can now supply water at comparable energy levels (Ward et al., 2012) and newer single household systems are moving towards low or zero operational energy use.

## 5.3 Key Issues and Priorities for Modelling and Research

The key issue implied by the examples considered here are that water and energy futures will need to be addressed across a very wide scale range - from the individual consumer and household through to a “system of systems” that includes all of the infrastructure required in the management of the resource nexus of water, land and energy, and also (as seen in section 4) the greenhouse gas emissions to the atmosphere that drive climate change.

Further modelling and research thus must address these multiple scales and sectors, and could include:

- Increased research emphasis on demand management strategies that can complement a conventional focus on increasing supply, so that users/consumers are sensitised to the financial and opportunity costs of resource (over-) use;
- Institutional reform at all levels - in research, disciplinary structures, organizations, administration and regulation - to enable multi-disciplinary approaches to research and management questions (“nexus” or “system of system” approaches), and to institutionalise a process of testing single-discipline decision-making across the boundaries of multiple other disciplines.
- And, consistent with this, an increased attention to the tendency to relieve resource stress within the UK by exporting that stress to other regions and countries.



## 6 Recommendations

On the basis of the analysis and discussion presented above, some key recommendations are suggested in the light of increasing water and energy demand, and the potential implications of a changing climate. First and foremost, there is a need to recognise the importance of the user/customer in the water/energy nexus. It is their behaviour that drives demand and therefore is an obvious starting point for reducing demand in both resource sectors. Behaviour of course can be influenced by technology e.g. roll out of smart meters for energy (happening) and water (much localised) linked to smart tariffs. It is important to recognise that the most significant intersections of the water-energy nexus at the local scale is through heating of water in the house, especially for shower use. Further research is needed to optimise this nexus and to develop technology to facilitate reduced demand, but caution is needed in recognising the potential unintended consequences of chasing single targets (such as water reduction alone). There is also a need for enhanced business models to not only drive cost reductions but also deliver environmental benefits. More work is needed on linking water and energy at different scales, for example by separating out retail uses from residential use, and the implications, e.g. for Multi-Utility Service Companies (MUSCOs)

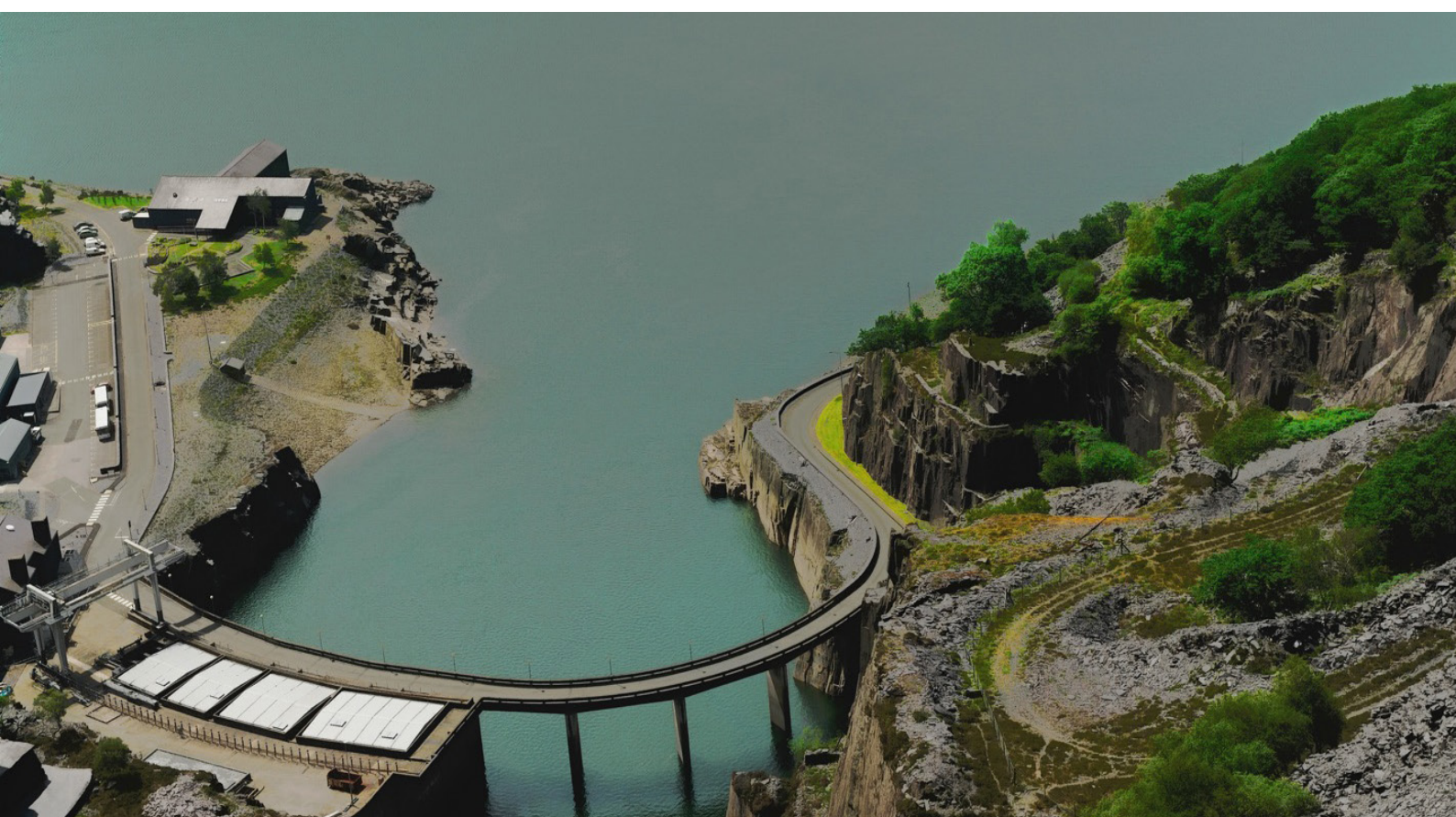
Secondly, the combined effects of climate change and a growing population - together with the requirements, under the EU Water Framework Directive to improve water bodies which are currently not at good status, suggest that, in some GB regions, less freshwater might be available in the future for consumptive use.

Consequently, present water uses might not be sustainable

without an increase in efficiency and/or a re-allocation of water to different users and uses, possibly by 'optimizing' the contribution that water use makes to society and economy.

Furthermore, modelling and assessment of water requirements by power sector water use under climate change must reflect the key system variabilities and uncertainties. As a result of the variability of the gross use of water and consumption rates associated with the different available cooling technologies, and uncertainty in timing of closure of existing plants and the opening and placement of new plant, the future development of water requirements by the Power Sector can only be assessed with a very substantial uncertainty. The level of uncertainty tends to increase with time and spatial resolution (e.g. single 'River Basin District' vs. 'National scale'; or 'freshwater' vs. 'total water' gross use or consumption). This indicates the necessity of approaching the analysis in a probabilistic way (as opposed to a deterministic one) and highlights the requirement of conducting comprehensive uncertainty and sensitivity analysis before any 'robust' conclusions might be drawn.

Water-energy nexus dynamics are fundamentally spatio-temporal. There is therefore the need to improve the spatial and temporal resolution of emerging integrated assessment models which aims to elicit insights on the evolution water-energy nexus under climate change to reflect these dynamics. Moreover, it is imperative to balance the decision-making at different spatial scales to reflect appropriate regional variations in terms of resource availability, demand and potential stress across the UK. This is particularly important as future climate change projections suggest both increased frequency of flooding events in some parts of the UK, whilst increase severity of drought are projected for other regions.



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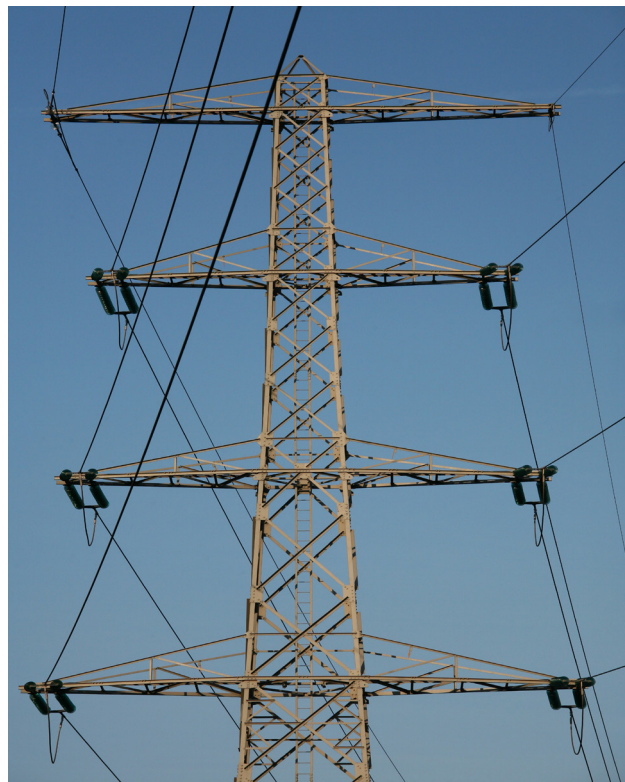
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## Notes

1. Green water: the precipitation on land that does not run off or recharge the groundwater but is stored in the soil or temporarily stays on top of the soil or vegetation. Eventually, this part of precipitation evaporates or transpires through plants.
2. Blue water: fresh surface and groundwater, in other words, the water in freshwater lakes, rivers and aquifers.
3. Less than 1,700 cubic metres per person per year (UNEP)
4. UKCP09: UK Climate Change Projections 2009
5. <http://www.itrc.org.uk>

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## About wholeSEM



The Whole System Energy Modelling Consortium (wholeSEM) is a ground breaking, multi-institution initiative to develop, integrate and apply state-of-the-art energy models. Our aim is to employ extensive integration mechanisms to link and apply interdisciplinary models to key energy problems.

The aim of wholeSEM is to build and link energy models, providing a foundation for the UK's national strategic energy modelling activity. The initiative will ensure continuity of funding during the period from 2013 - 2017, enabling participating organisations to develop new models and link modelling frameworks in innovative ways to answer new research questions.

wholeSEM is led by University College London and consists of Imperial College London, the University of Cambridge and the University of Surrey. There is further significant engagement with stakeholders in academia, government and industry.

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