Report

AMP8 Long Term Delivery Strategy for Anglian Water – Final Integrated Technology Scenario Development Report

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Executive Summary

The UK water industry is facing a period of unprecedented challenge. 2022 brought significant stresses within the sector, including prolonged periods of dry weather, record-breaking temperatures and an acute risk of drought. Alongside this threat to security of supply, river water quality has risen high up the public, regulatory and Government agenda. Looking ahead, the changes driven by climate change, regulation, sustainability, social goals, and shifting customer expectations mean pressures on the industry are likely to continue increasing at pace.

Against this backdrop, the need for transformation on an unprecedented scale is evident. This is where emerging technologies within the sector can deliver a true step-change in performance over the coming AMP periods.

The cycle of managing long-lived assets with relatively low replacement rates, repairing on-time or on-failure and reacting to incidents that affect either customers or the environment needs to be broken. The industry must move to a preventative and proactive maintenance regime, driven by data and insights from connected assets. This must be achieved whilst working to improve the natural environment and utilising low carbon energy sources, as well as driving down customer bills. This will only be possible through positive relationships with both technology and change. To aid with this, utility providers must forecast which technologies are likely to impact their businesses and plan for their implementation, or risk further incidents, unhappy customers, and negative news reporting.

As part of the 2024 Price Review (PR24), the industry regulator Ofwat requires all water companies to set out their 5-year business plan within the context of a 25-year long term delivery strategy (LTDS) (2025 - 2050). A requirement of the LTDS is to test company plans against a series of plausible future scenarios. One of these scenarios is the impact of future technologies. Anglian Water welcomes this opportunity for the industry to systematically consider technology in our future plans for the first time, and to recognise that such planning helps us to better understand and plan for how we will address our challenges of today and the future, at an affordable cost to customers.

Anglian Water (AW) have engaged Cambridge Consultants and Capgemini Invent to help identify the range of technologies that AW should consider, beyond the minimum specified in Ofwat's common reference scenario. These advisors, working alongside of dozens of stakeholders within AW, have identified the most critical technologies expected to deliver significant impact for the water industry and for AW's business over the long-term planning period up to 2050.

This report provides an **in-depth analysis** of the nine technologies (summarised in Table 1) considered to be the most impactful to the water industry and to Anglian Water's business over the coming 25 years, across 14 main topic areas defined by Anglian Water. Eleven additional technologies that were judged to be lower priority but still worthy of further investigation have been covered through a shorter, **high-level analysis** for each in Section 4 of this report.

Table 1 Technologies covered in this report

Technologies for In-Depth Analysis	Technologies for High-Level Analysis
3.1 Internet of Things (IoT) Enabled Assets and Infrastructure	4.1 Technology Influenced Demand
Error! Reference source not found.	4.2 Cognitive Engagement
3.3 Artificial Intelligence & Machine Learning	4.3 Quantum Computing
3.4 Advanced Sensing and Sensor Platforms	4.4 Self-healing systems
3.5 Household and Consumer Technology	4.5 Carbon Capture Technologies
3.6 Renewable Energy Systems3.7 Scaling Nature-Based Solutions	4.6 Desalination Technologies
3.7 Scaling Nature-Based Solutions	4.7 Low Carbon Construction
3.8 Bioscience Solutions for Wastewater Treatment	4.8 Decentralised Infrastructure
Error! Reference source not found.	4.9 Open Data
	4.10 Trust & Assurance in Technologies
	4.11 Web3 Technology

Summary of key takeaways from the report:

For both the water industry and AW to build a successful future and deliver on the long-term goals laid out in PR24, a deeper understanding of and engagement with the key technologies discussed in this report will be critical. Preparing effectively for the long-term direction of the industry, and how technology will enable this, will help AW to set the right direction for the coming 5-year period, as well as to prepare for the coming 25 years.

To maximise the opportunities these new technologies offer, AW should focus on the following:

- **Capturing data from assets will be a critical early step, and managing data effectively will also be key**: Using new technologies such as advanced sensing and IoT to improve data capture from assets and turn this data in to actionable insights by the business will be at the heart of driving future value and efficiency. It will enable the business to move from a reactive to a proactive approach to challenges and shocks, and towards an ongoing cycle of asset improvement. A pro-active and thoughtful approach to data management will also be needed, in the face of ever-growing data volumes, to maximise data value and ensure its integrity. Technologies such as trust assurance architectures can be an important tool for this.
- **AI and Digital Twin technologies offer the prospect of true operational transformation** for AW and for the water industry as a whole. While still early stage, in time AI will be able to support a wide variety of applications requiring faster, more accurate, 'human-like' analysis of large and disparate datasets, from developing deeper customer behavioural insight to optimising water networks for maximum efficiency. Effective AI adoption will drive efficiency and quality, informing decision-making and eventually providing autonomous functionality throughout the water network. It will also support safety and sustainability and will help the network to become more adaptive and resilient. This will

require changes to process and approach as well as to IT and OT – AW must be ready to work in a more agile way to make best use of the insights and eventual autonomy that AI can deliver.

- **Cybersecurity will become an increasingly important consideration for AW and for the industry:** While the focus now is more on customer data protection – which will continue to be critical – digitalisation and autonomous machine-led control of operations opens water companies to significant new risks from malicious cyber activity. Any future technology strategy must plan for this from the beginning. As the industry becomes more reliant on connected assets, a structured data and cybersecurity foundation is critical and will require investment and enterprise level transformation to deliver secure and sustainable benefits.

- **Net zero and sustainability targets urgently require adoption of renewables, changes to energy usage, and improved use of bioscience solutions:** If AW are to meet net-zero targets for 2030, then renewables and alternative methods of energy usage must be adopted. Sustainability ideas such as carbon capture and credits, which were once novel, are now mainstream and being accelerated by a series of alarming weather and climate events. Anaerobic digestion for onsite combined heat and power, distributed energy and microgrids and the growing hydrogen industry will be major factors shaping the future of the AW business and the way assets are utilised.

- **Changes to consumer behaviour will be a key part of the puzzle:** Domestic households will need new technologies within the home, to understand and control the amount of water used per day, and enable conservation and water recycling. Achieving this change will require broad adoption of new home and consumer technologies such as smart water meters, greywater reuse systems and other water conservation technologies, as well as behavioural and service model changes by consumers and home appliance providers. The latter may shift to new business models (e.g., appliance-as-a-service, smart home platforms) which could enable faster take-up of more environmentally friendly home appliances, but may also add complexity for customers and partners. Water companies will need to play a more active role in promoting adoption and behaviour change.

- **Alternative revenue streams for AW are most likely to come from two main areas: Bioresources and Data.** Bioresources is perhaps a more natural shift, as AW capitalises on generating revenue from sludge as fertiliser or feedstock, on producing and selling natural gas products, and on selling final effluent to the hydrogen industry. All of these will be possible over the coming 25-year period. For data revenue, as AW collected and analyses increasing amounts of data, it could sell the resulting insights to the industry. Examples of valuable insight could include key failure indicators from vibration sensors, key process treatment parameters and so on. Some data may be shared via open data platforms instead of being monetised, which can help to develop, drive and inform relevant technology applications that will bring value to the industry overall, to customers and to society.

The technology-led opportunities for the water sector over the coming 5-25 years are exciting, transformational, and offer a view of a better, more resilient, and sustainable future for the industry. Figure 1 below shows how technology impact will evolve over 0-5 years, 5-10 years, and 10-25 years, looking ahead to the future.

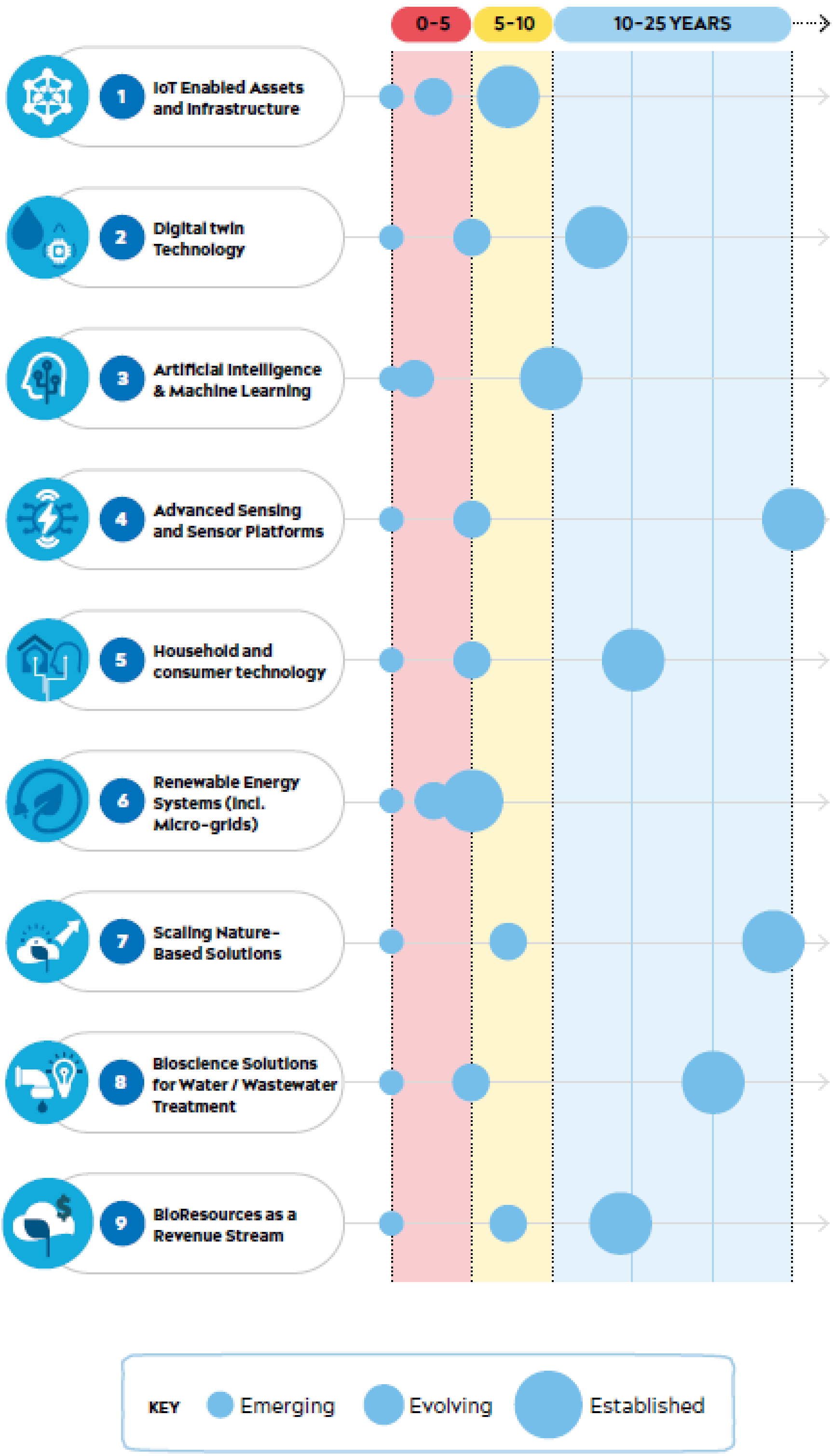

Figure 1 Technology evolution timeline

However, none of the above opportunities can be realised through a single technology deployment. They will require a step-by-step approach, enabled by different and interconnecting technology initiatives over a period of years. A systemic approach to technology planning, and a clear understanding of technology interdependencies, are as important as the selection of the correct technologies to invest in. Further, the right organisational support at all levels will be a prerequisite for success. It has been the case too often that a technology has failed to be successfully implemented and scaled due to a lack of the supporting structures required, whether these are technical, process or organisational in nature.

Capgemini Invent and Cambridge Consultants look forward to supporting Anglian Water and the broader water industry on the next steps in the journey of preparing for a brighter, more technology-enabled future, with benefits for all.

About the report authors:

An innovation, design, and transformation powerhouse

By combining strategy, technology, data science, creative design, and engineering expertise with an inventive mindset, Capgemini Invent partners with clients to innovate and transform their business, enabling them to navigate today, while plotting a course for the future. Capgemini Invent challenges and transforms the status quo, drives growth, and helps their clients get the future they want.

Innovation unconstrained by current thinking

Cambridge Consultants delivers innovative technology R&D and business strategy to world-leading clients across a range of industries and technology areas, including AI, wireless communications, satellite, quantum, bioinnovation, advanced sensing, robotics, advanced engineering, smart devices, digital services, sustainability, and innovation business models. We help our clients identify, create and launch breakthrough products and services that disrupt their markets. With over 60 years in delivering world-changing innovation, 5,000+ patents and over 800 multidisciplinary engineers, developers, designers, scientists and consultants, Cambridge Consultants goes beyond current thinking to enable our clients to confidently address their toughest and most urgent challenges.

1. Introduction

This report summarises the work undertaken by Capgemini Invent and Cambridge Consultants for Anglian Water to date. It outlines our approach, summarises the key findings, and provides recommendations for further steps to help inform AW's long-term technology strategy, as well as AW's response to Ofwat's PR24 reporting requirement. The analysis in this report draws on expertise from our collective breadth of technology knowledge and industry experience, supported by supplementary research.

Longer term technology predictions are notoriously difficult. Analyses of the evolution, likely adoption, and eventual impact of future technologies are by their very nature highly speculative. While this report focuses on those technologies we judged to have the greatest longer term impact on the water sector, there is a vast range of additional technologies that will provide smaller incremental benefits across the industry. For this work, we have been mindful to adhere to Ofwat's guidance to focus on a range of plausible futures, and to limit ourselves to those which we think have the potential for a transformative impact over 25 years.

Figure 2 outlines the main impact categories that we have used to categorise and prioritise potential technologies for inclusion in this report. This report focuses on **transformative technologies** for the Anglian Water business over a **25-year time horizon**. Technologies that might materialise over a longer period were generally considered too speculative for inclusion. Conversely, those technologies with a narrow impact, or which only require limited adaptation to implement, are considered simply as enablers of improved productivity rather than truly transformative, and thus also fell largely outside of the scope of this report.

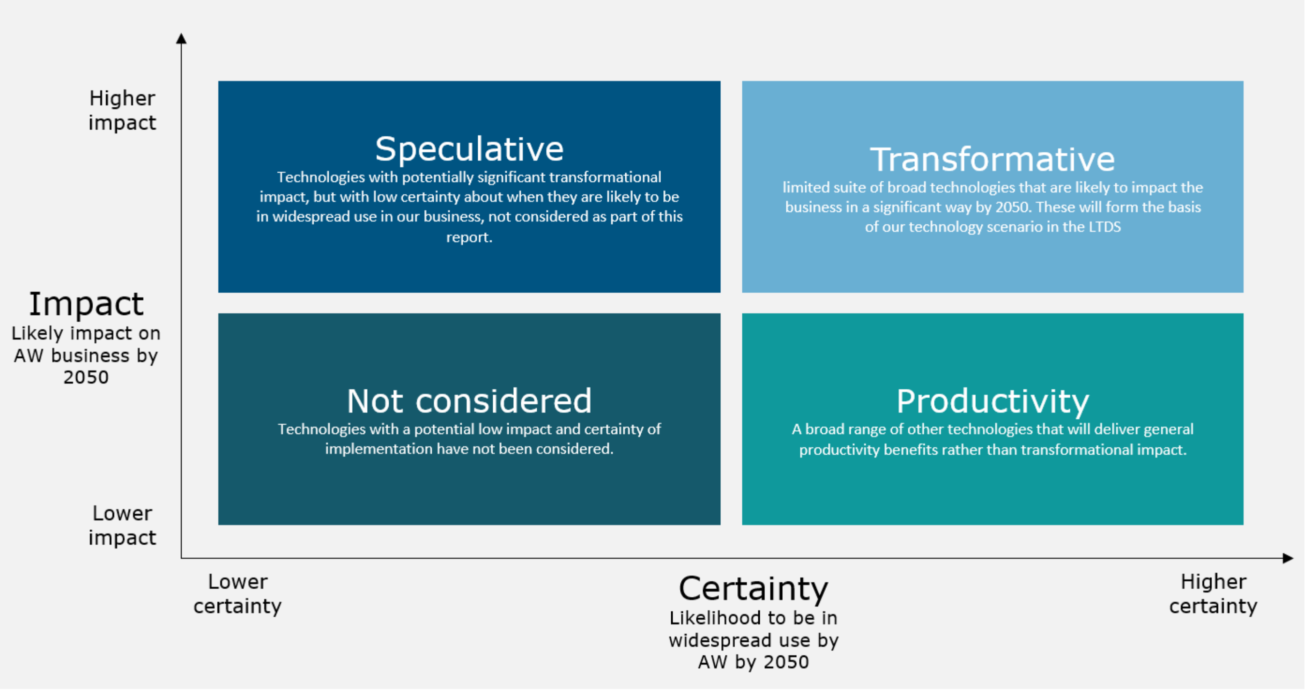

Figure 2: Definitions of Technology Categories Used to Prioritise Analysis Areas

This report describes the nine transformative technologies in detail, providing overviews, relevance to the water industry, and a technology and impact outlook for the future. These are:

- **IoT-Enabled Assets and Solutions**
- **Digital Twins**
- **AI and Machine Learning**
- **Advanced Sensing and Sensor Platforms**
- **Household and Consumer Tech**
- **Renewable Energy Systems**
- **Scaling Nature-Based Solutions**
- **Bioscience Solutions for Waste/Wastewater Treatment**
- **Bioresources for Additional Revenue Streams**.

A further list of eleven technologies which did not make the short-list for full analysis, but which are still highly relevant to the future of the water industry, have been included in an abbreviated higher-level analysis section (Section 4), focused on their expected future impact.

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2. Methodology and Technology Selection Process

2.1 Technology selection

A systematic approach is followed to identify technologies that have the greatest potential to deliver long-term impact to Anglian Water's (AW) business, as illustrated in Figure 3.

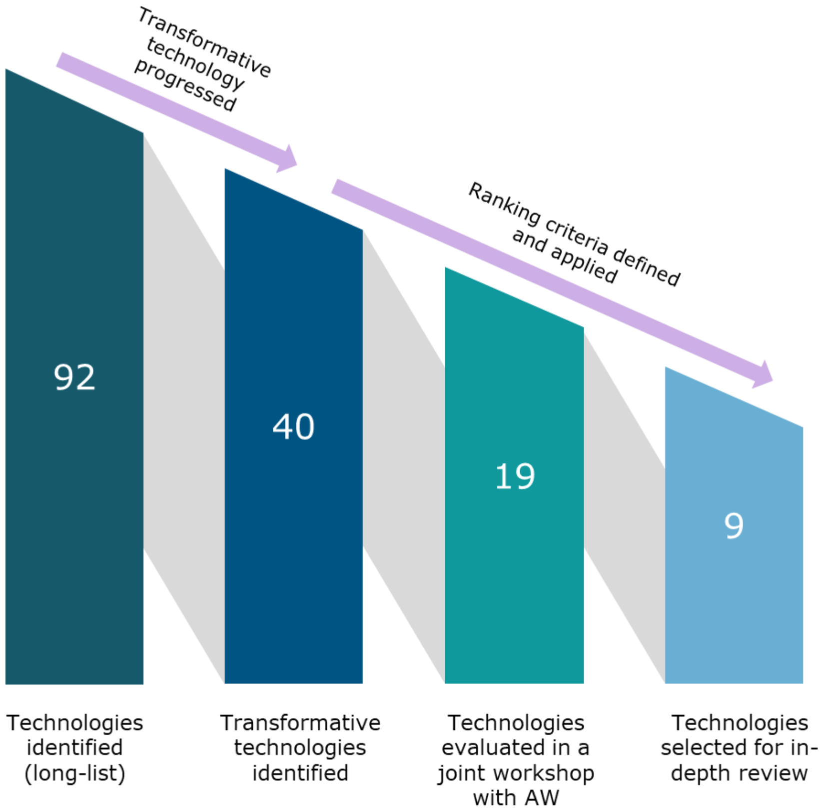


Figure 3: Project methodology

The first step was to create a technology long list based on

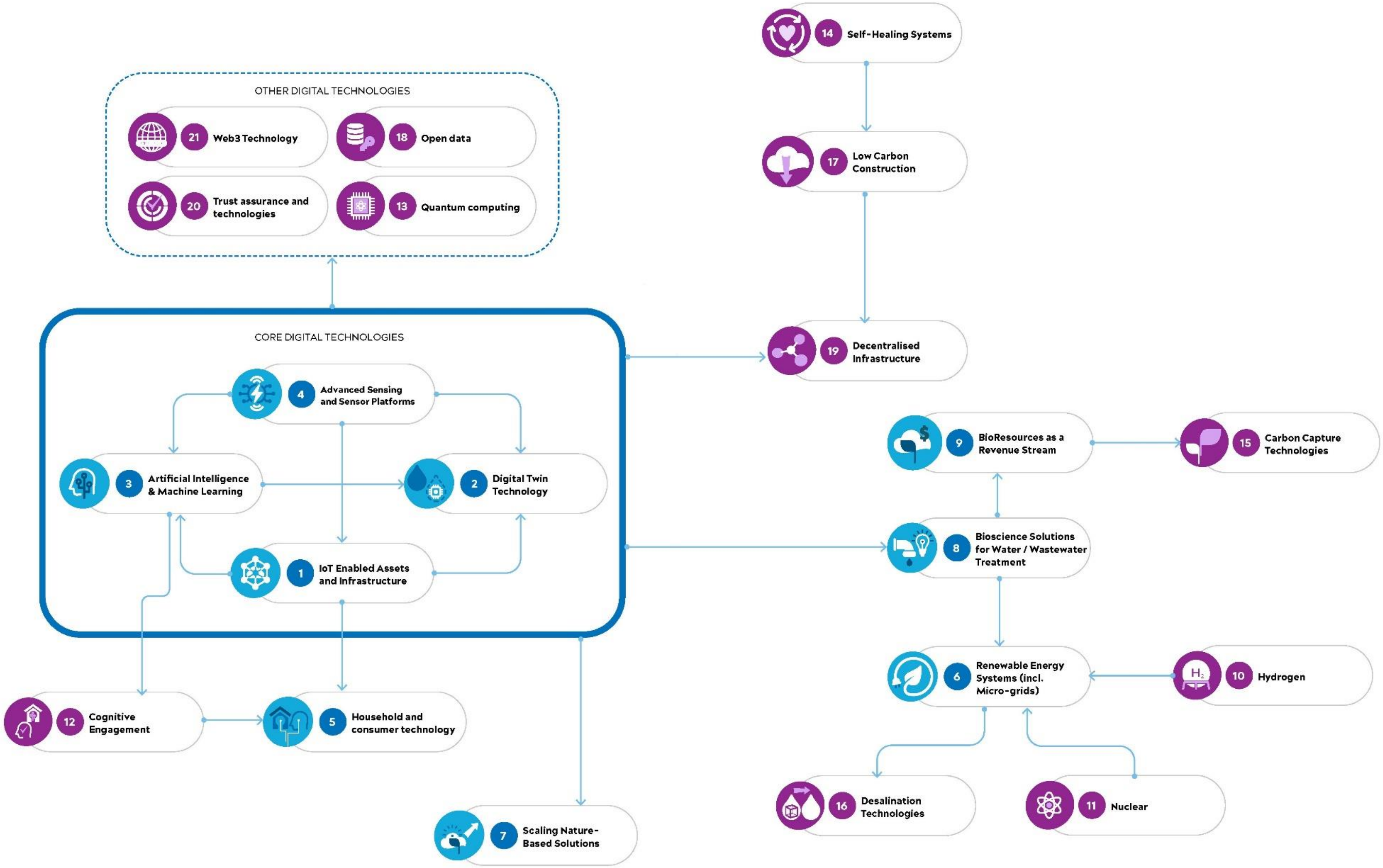
- Ofwat guidance
- AW's existing focus areas, particularly those being explored in their Smart Programme (See Appendix)
- technology expertise within Cambridge Consultants and Capgemini
- additional horizon scanning research

From the initial 92 technologies in the long list, 40 transformative technologies were identified (see definition in Figure 2) which were then screened using a clearly defined set of criteria (details are included in the Appendix). From this list, working alongside dozens of stakeholders within AW, we have together prioritised **nine critical technologies** that deliver significant impact for AW business over the long-term planning period up to 2050.

2.2 Interdependencies and Enabling Technologies

When reviewing the most impactful and relevant technologies for Anglian Water and aligning with the views of the wider industry, it was important to adopt a systems-thinking approach to the analysis, viewing the technologies not as mutually exclusive but as a network of interdependent systems. Figure 4 shows the interdependencies: technologies chosen for in depth analysis are shown in blue; technologies for high level analysis in purple; and the arrows show which technology is enabling another.

Figure 4:


14 Self-Healing Systems
OTHER DIGITAL TECHNOLOGIES
21 Web3 Technology
18 Open data
20 Trust assurance and technologies
13 Quantum computing
17 Low Carbon Construction
CORE DIGITAL TECHNOLOGIES
19 Decentralised Infrastructure
4 Advanced Sensing and Sensor Platforms
3 Artificial Intelligence & Machine Learning
2 Digital Twin Technology
1 IoT Enabled Assets and Infrastructure
9 BioResources as a Revenue Stream
15 Carbon Capture Technologies
8 Bioscience Solutions for Water / Wastewater Treatment
6 Renewable Energy Systems (incl. Micro-grids)
10 Hydrogen
12 Cognitive Engagement
5 Household and consumer technology
16 Desalination Technologies
11 Nuclear
7 Scaling Nature-Based Solutions

Technology Interdependencies

Based on our analysis and on collaborative input from the AW team, **3.6 Renewable Energy** Systems is the technology area we judged to be most likely to be beneficial, based on potential impact and due to support from a strong base of existing and emerging associated technologies that can deliver value. However, for a truly transformational effect on the AW business, this must be linked to developments in several other key technology areas as well as driven by adoption patterns. **4.1 Technology Influenced** Demand – demand created by the emergence of new technologies in sectors such as energy and agriculture that will rely heavily on water **-** is very relevant as a driver and creates pressure for transformation (note this is not shown on the interdependencies map above, since it is an external driver rather than a water sector technology). Changing consumer habits which will impact and be impacted by **3.5 Household and Consumer** Technology are also highly relevant drivers.

As highlighted by Figure 4, the scaling and adoption of 3.4 Advanced Sensing and Sensor Platforms will provide a vast array of both short term and long opportunities to support the development of smart meters, Error! Reference source not found., robotics, **3.3 Artificial Intelligence & Machine** Learning, and **3.1 Internet of Things (IoT) Enabled Assets and** Infrastructure across the industry. This is critical for the industry's smart future and will likely be driven by advancements from the supply chain. AW can play a key part in this advancement through developing forward-thinking specifications and supporting OT architectures to enable these technologies to drive lasting benefits.

Open data, quantum computing, cyber security and trust assurance are all key enablers for the digitalisation of the water industry, even if they were not considered to be priority technologies for in-depth analysis in their own right in this report. Open data requires water companies to standardise on approaches to data governance to ensure that good quality data is shared publicly, and the benefits of this sharing of data could be critical to ensuring quality stewardship of the environment and shared assets. Quantum computing will allow us to draw insights from vast amount of data that classic computing technology is incapable of and Trust and Assurance technologies such as blockchain could provide a way of eliminating third party verification by enacting contractual arrangements within computer code, a truly transformational aspect of technology redefining business operations. However, all digital technologies inherently come with the risk of being attacked by malicious actors; an effective cybersecurity strategy will be critical to safeguard operations and ensure resilience.

As the water industry moves to a more sustainable future, decarbonisation based on emerging biotechnology and material technology (**3.8 Bioscience Solutions for Wastewater** Treatment, **3.9 Bioresource as a Revenue** Stream and **3.7 Scaling Nature-Based** Solutions) will become increasingly important, allowing more efficient use of raw materials. Some of these technologies are readily available, and hence can deliver productivity benefits; others are still too nascent and expensive but should form part of AW's broader vision moving towards 2050. Again, evolution of this technology will largely be driven by supply chains, but Anglian Water should focus on this when setting out requirements for Capital Delivery programs.

Overall, the key message is that technologies are simply facets of a much wider system, with many important interdependencies. By mapping and understanding which enabling technologies are key, and what actions Anglian Water must take to support their implementation, truly transformational use cases can be realised.

2.3 Use of Technology Readiness Levels in this Report

This document makes use of technology readiness levels (TRLs) as a standard way of assessing technology maturity across various sectors. Whilst the TRL classification scale was originally developed by NASA [1] it has since been evolved to apply to industries outside of space flight. This report uses the TRL levels as defined by UK Research and Innovation (UKRI) [2] as follows:

- TRL 1: basic principles observed and reported
- TRL 2: technology concept or application formulated
- TRL 3: analytical and experimental critical function or characteristic proof-of-concept

- TRL 4: technology basic validation in a laboratory environment
- TRL 5: technology basic validation in a relevant environment
- TRL 6: technology model or prototype demonstration in a relevant environment
- TRL 7: technology prototype demonstration in an operational environment
- TRL 8: actual technology completed and qualified through test and demonstration
- TRL 9: actual technology qualified through successful mission operation

3. Top Nine Technologies for Anglian Water

The nine key technologies discussed in this section have been identified as having the greatest likely impact for the water industry and Anglian Water, over the next 25 years. Alignment was arrived at by filtering, scoring, and discussion with a diverse group from across Anglian Water, Alliance Partners, Capgemini Invent and Cambridge Consultants.

The list is not exhaustive, and technologies do not and cannot exist in isolation. A further analysis of the interdependencies between the technologies is presented in the Appendix section.

3.1 Internet of Things (IoT) Enabled Assets and Infrastructure

Key takeaway:

IoT Enabled Assets and Infrastructure is one of the most important technology areas for AW to consider when planning for the next 25 years. It will be critical for ensuring efficient use of water resources and predictive maintenance of assets, for effective planning for scenarios involving dramatic changes in climate conditions and resource availability, and for improved delivery of value to customers. IoT has broad applicability in the water sector, with potential to deliver significant value and impact across water infrastructure assets, sites, and network elements.

Overview

The effective use of IoT-Enabled Assets and Infrastructure enables a wealth of benefits across the water industry. IoT is – and will continue to be - at the heart of the shift to Industry 4.0, where data drives the decisions made within an organisation. The benefits will include improved asset efficiency, increased situational awareness, better capital investment decisions, improved regulatory compliance, greater resilience in the face of climate change, and higher customer satisfaction and value.

IoT is a broad term, and encompasses a range of technologies, as discussed below. It refers to a connected network of physical objects (or groups of such objects) with sensors, computer power, software, and other technologies that connect and exchange data with other devices and systems over the internet or other communications networks.

The key feature of IoT is the use of ‘smart’ connected devices which can share sensor-collected data via a common platform. This enables data analysis and rapid action to address or prevent operational issues or to improve operational efficiency. In addition, IoT data and devices can help drive greater customer insight (for example through identifying peak usage times or changes in usage patterns), help to offset some of the impacts of climate change (by quickly adjusting to changes in environmental or ground conditions), and even offer the possibility of additional revenue streams through new circular economy type business models. IoT communications data may be collected and shared within a single site (such as a water processing or distribution facility), or communicate data and actions to remote sensors, devices on infrastructure or equipment out in the field or in customer premises.

IoT is already being widely deployed in utilities and infrastructure-heavy industries. By 2050, it will be a ubiquitous feature of water infrastructure operations. It interacts with several other technologies discussed in this report, including Advanced Sensing Technology, 5G, Edge Computing and Cloud Computing, AI/Analytics, and Cybersecurity. Looking ahead, important changes will include much greater access to and use of real-time data, to provide actionable real time insights to operators, as well as enabling automation and optimisation of assets.

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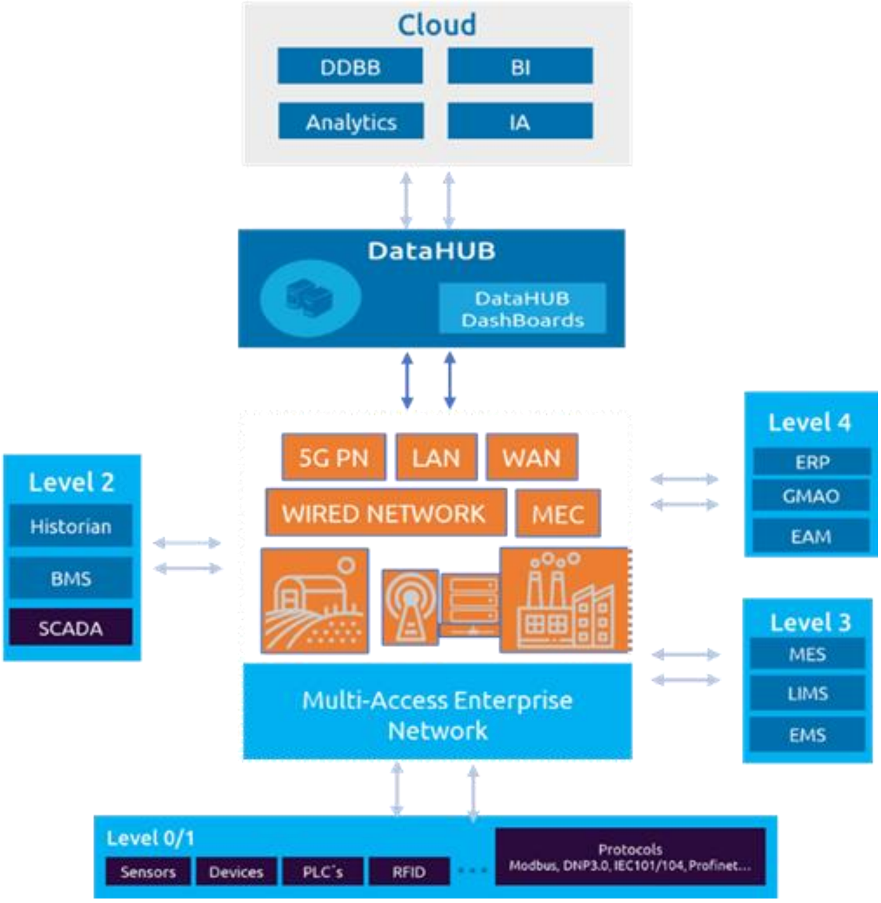

Figure 5 IOT Architecture

A typical IoT architecture is shown in Figure 5. With an IoT based system, not only can the health of individual assets be known but monitoring and trending data can be used to feed into machine learning algorithms or digital twin models to detect potential failures, enact preventative maintenance regimes, plan for future scenarios and better inform capital program investment.

While many IoT applications are low bandwidth in nature, greater bandwidth and processing power will be important for IoT to realise its full promise for the water industry. This will be enabled through wider utilisation of 5G and future communications technologies, Edge Computing to enable processing of data closer to where it is physically collected, and Cloud computing, alongside applications which extract this information to provide actionable data to business functions and inputs to AI and machine learning algorithms to manage the water network as intelligently as possible.

IoT is closely linked to **3.2 Digital Twin** Technology**;** IoT sensors, platforms, and data are key elements of any Digital twin application or deployment, as they enable real-time or near-real-time data monitoring, data collection and in some cases data analysis for infrastructure and operations of the system for which a Digital twin is being applied. Smart Metering deployments are another key application of IoT in the water sector. See discussions in **3.5 Household and Consumer** Technology and **3.4 Advanced Sensing and Sensor** Platforms**.**

Relevant Technologies

Table 2 outlines the relevant technologies and sub-categories that are considered important in the successful implementation of IoT enabled assets and infrastructure, along with a brief description where necessary.

Table 2: Relevant technologies for IoT enabled assets and infrastructure

Technology category	Specific technologies
Sensors	Temperature/thermal sensors, humidity sensors, pressure sensors, motion and proximity sensors, level sensors, atmospheric/gas sensors, water quality sensors, optical sensors, accelerometers and gyroscopes [3], [4] (also see **3.4 Advanced Sensing and Sensor** Platforms).
Actuators	Hydraulic, pneumatic, electrical, thermal, magnetic, relay [3]
Connectivity	LPWAN (incl. both cellular – e.g., NB-IoT – and non-cellular – e.g., LoRaWAN), 5G, 6G, short-range wireless technologies such as Wi-Fi and Bluetooth Low-Energy, wirelines/fixed. IoT communications can be via private or public (fixed broadband/cellular) networks.
Edge compute	Edge computing refers to processing of data at or near the location where data is collected or used. If IoT data is gathered and processed at the edge, rather than sending the data back to a datacentre or cloud, it can be a powerful way to rapidly analyse data in real-time, as well as potentially saving on data transmission and storage costs.
Cloud	IoT Cloud services provide storage and in some cases support processing or analytics for IoT data. The major enterprise cloud providers all offer specific IoT cloud services.
Platforms	Main types of IoT platforms are Connectivity Management platforms, Device management platforms, Cloud platforms, Application enablement platforms, Analytics platforms. Major providers include general enterprise software vendors as well as providers of the various types of hardware or software being managed.
Applications	Applications relevant for the water industry include condition monitoring, predictive maintenance, water quality monitoring, leakage detection, environmental monitoring, smart meters, Digital twins
Cybersecurity	Significant consideration in deploying IoT. Cybersecurity for IoT must be deployed at multiple layers in the network, including application, device, platform, and communications network. Suitable identity and access management, as well as device authentication and authorisation will be required for IoT devices IoT supplier security management will also be required. There should also be continuous monitoring, intelligence and the ability to patch the entire IoT ecosystem to ensure keep apace of the threat landscape. Cross-disciplinary risk assessments and appropriate controls will also be required for IoT devices that control or monitor cyber-physical systems (for example across performance, efficiency or safety).

Trends

Table 3 outlines the key trends that have the potential to impact or influence the successful implementation of IoT enabled assets and infrastructure.

Table 3: Key trends for IoT enabled assets and infrastructure

Category	Trend description
Technology Maturity	IoT technologies have been present in the market for over 10 years and many advances have been made during that time. These include the introduction of different and more advanced types of sensors, connectivity, and applications/analytics. Some areas of IoT technologies are mature, such as simple connected sensors with basic connectivity. In most cases this is via Wi-Fi or wireline connection, which sends information back to a central database or platform or performs actions at the network edge level such as closing a sluice gate automatically if water levels get too high. However, the real promise of IoT requires the collection and combination of data from multiple sources or sensors, tracking of trends over time to inform actions or decisions, and broader deployment of analytics to derive value from the sensor data being collected. This can then feed into applications that can improve agility, efficiency, and resilience of the water network; and into scenario-based planning.
Technology Applications	IoT applications cover a very wide range of use cases. Industrial IoT applications that are most relevant for the water industry include: • IoT technologies can be applied to monitor particular asset types, across a treatment works to optimise processes, to monitor underground assets and as the basis for large scale smart networks • Remote condition monitoring – to monitor the physical condition of equipment and infrastructure • Loss/leakage detection – across the water network and to support compliance and improved customer service • Predictive maintenance - for heavy infrastructure and the network, • Resource management – for water and energy; assurance and management, • Water quality testing for compliance • Digital twins • Smart water meters • Environmental monitoring – to measure weather impact, soil moisture, river/lake/sea levels, air quality, water quality or composition • Worker safety • Location tracking (for assets and people).

Category	Trend description
Drivers for adoption	IoT is primarily going to be adopted as a means of improving insight into asset, infrastructure and environmental conditions, as well as customer behaviours. The ability to obtain actionable data in real or near-real time has the potential to be highly valuable for water infrastructure operators. The effective use of IoT data can reduce costs and improve efficiency if more decisions and actions are automated, or if decisions can be better informed. For example, IoT could be used to detect leakage or malfunctions earlier than manual inspection on its own, potentially saving millions. Secondarily, the potential to monetise IoT data in various ways, or to use it to influence customer behaviour, is also a driver. This could be through deployment of new business models where dynamic pricing is applied based on usage or other factors; to motivate customers to make changes to usage by sharing information or providing rewards: or to provide data-as-a-service to interested partners or providers. There are also national level initiatives in the UK supporting the development and deployment of IoT, e.g., the National Digital Twin Programme [4](now under Digital Catapult) and EU legislation being developed to standardise approaches to IoT enabled networks [5], which could reduce the learning curve for new market entrants. Finally, as noted below, regulatory compliance is an important driver for IoT adoption given the requirement on water companies to meet a variety of compliance requirements relating to water quality, wastewater treatment, etc.
Barriers to adoption	There are several barriers to adoption of IoT 'on the ground'. • The requirement for physical asset upgrades - it may take a water company, such as AW, several asset management period (AMP) cycles to fully refresh the instrument and sensor arrays in the field. • The need to transform the operation technology (OT), information technology (IT) and workforce systems to fully support IoT enabled data capture, governance and analytics. • Requirements for changes to process and ways of working. IoT-supported automation, the effective use of IoT data to drive decision making and the higher level of transparency which such data can provide are complex to integrate into day-to-day operations and may create concern among employees about the potential for labour reduction or other potential negative impacts.

Category	Trend description
Cost	IoT can be deployed relatively inexpensively, or can be a major investment, depending on where and what is being deployed. IoT sensors are more expensive than traditional (unconnected) sensors. But over the period under consideration, we would expect IoT sensors and connectivity to become a much more standard feature or both infrastructure and devices in use by the water industry, and to decline in cost accordingly. According to data from Goldman Sachs and BI Intelligence estimates, the average price of an IoT sensor in 2020 was 70% lower than its price in 2004, a downward trend which we expect to continue, to a lesser extent over the coming years [6]. However, the sensor is only one part of the IoT solution. Increasing sophistication in both sensors and software will add cost, with an increasing reliance on software-as-a-service for IoT platform and cloud services, and for the analytics and AI required to effectively leverage IoT data. Likewise, the use of wireless communication technologies such as 5G (and future generations) will potentially add cost as further infrastructure will be required. Integration with supporting OT and IT systems are also required to capture and analyse the data coming from the sensor arrays. Cost savings and efficiency gains are one of the key selling points of introducing IoT solutions into the water network, so in the longer-term, the overall impact of introducing IoT solutions should be positive from a financial point of view.

Category	Trend description
Examples from other industries / geographies	Early stage IoT solutions have already been deployed widely across a range of industries, with the biggest impact being on asset-heavy industries where high value can be realised from more accurate and timely data on the condition of assets, particularly where this can be monitored remotely and delivered on a regular basis. Industries which have been early adopters include manufacturing, oil & gas, energy (e.g., through smart meters, smart grids, renewables), and infrastructure. While the value of IoT in industry is widely recognised, finding specific quantifiable impact data is still challenging given the relatively early stage of market adoption. McKinsey forecasts a potential economic impact of $930 billion from IoT in the Oil and Gas industry by 2025 [7]. One of the most significant impact areas is reduced downtime; for example, in upstream scenarios, a single pump failure could cost $100,000 per day in downtime [8]. Adoption of IoT in the Manufacturing sector provides a useful comparison point. In the United States, around 35% of manufacturers collect and use data generated from smart sensors to enhance manufacturing processes [9]. Given that manufacturing is one of the earliest adopters of IoT among industries, this gives an indication of the relatively early stage of market maturity, even though the technologies are widely available. There is still a long journey ahead when it comes to deriving value from analysing IoT data and applying this to newer use cases beyond asset monitoring, including prediction, planning, simulation, automation, and autonomy. The manufacturing sector offers many compelling examples of successful IoT deployment for operational efficiency. For example, Baker Hughes – a GE company - wanted to deploy an intelligent plant control tower for greater visibility into its manufacturing processes as well as the ability to manage production in real time. Baker Hughes partnered with Capgemini to implement an industrial IoT solution that gathers data from all its manufacturing devices and machines, to provide operators and engineers with a new level of insight and the ability to adjust production at a moment's notice. 1000 machines were connected across 11 plants within 18 months. Results: • Prevention of 26,000 hours of downtime over 12 months. • 12% increase in machine utilisation five months after the deployment of the solution. • Reduces waste and rework, improves efficiency, visibility and control, and improves speed to market. • Resulting in millions of Euros savings Source: Internal Capgemini

Key Impact Areas for the Water Industry

Table 4 outlines the key areas that are likely to impacted by the successful implementation of IoT enabled assets and infrastructure.

Table 4: Key impact areas for IoT enabled assets and infrastructure

Category	Impact area description
Performance impact	IoT can deliver significant positive impact on efficiency and performance. By applying an IoT enabled system to both assets and the wider network, the cycle of gradual asset deterioration and replacement could be shifted towards asset optimisation and improvement. Arming operators with the correct information at the right time can also reduce stress on the workforce and increase customer satisfaction through improved service provisions. The specific benefits include: • Real-time process optimisation can yield large improvement in asset efficiency • Reduced chemical demand on sites can mitigate the negative impact of treatment by-products on water and wastewater • Trends can be captured to automate process optimisation based on data input, reducing the need for operator intervention • Trends can also be fed into machine learning algorithms to enable predicative diagnosis and maintenance • Fault Detection time can be reduced to almost nil and field force can be automatically deployed with the right tools and information to resolve leakages and bursts. • Environmental events or breaches can be identified early and mitigated with intra-process monitoring • Data captured and analysed by water companies can be shared as open data or held as IP and shared with the wider industry as a revenue-generating service • Insights from increased asset knowledge can support strategic decision making for the wider business
BOTEX and Delivery Efficiency	IoT should deliver significant positive impact both to operational costs and capital maintenance linked to the benefits listed above. IoT will enable improved asset data capture, which in turn will enable improved future scenario planning through digital twins, based on trending data harvested from across the IoT network. Although an IoT enabled system cannot directly improve delivery efficiency, it can improve access to information during the project scoping phase, which can help to better define the required outcomes earlier, reducing time in the design phase. Data around the level of savings achieved is not available due to lack of case studies from industry.

Category	Impact area description
Use for Operational Risk Mitigation, Resilience and Compliance	Increased asset knowledge and control enabled by IoT reduces risk, and supports compliance in several key areas: • Compliance Risk/Regulatory Reporting – Improved access to asset data means that breaches can be reported more quickly, or even averted by early intervention. For example, we expect that IoT will be a key technology used in meeting the UK's new Security and Emergency Measures (Water and Sewerage Undertakes and Water Supply Licensees) Direction 2022 [10], which came into effect as of March 1st and details the measures, processes and procedures water companies are expected to have in place and follow, to ensure water supply continues, even in the event of unavoidable failure to piping. • Asset Failure reduction – Moving to a preventative maintenance regime extends asset life. Efforts can be spent improving and optimising assets rather than responding to asset failures. • Capture of Operator Knowledge – Capturing key trends, early indicators of failure and optimum operational conditions ensures that key knowledge is captured within databases or algorithms, to be utilised by future generations of operators, bridging the skills gap which persists in the water industry (see also the Error! Reference source not found. and **3.3 Artificial Intelligence & Machine** Learning)
Cybersecurity Risks from the Technology	IoT deployment has the potential to open up water companies to significant cybersecurity risks. The replacement of manual or mechanical processes with digital/data-enabled automation of functions or even decision making about actions to be undertaken by humans creates several risks: • Risk of malicious actors compromising the supply chain to ensure ongoing backdoors into the system via compromised IoT devices • Risk of malicious actors 'hacking' into the water network via connected devices to obtain customer or operational data • Risk of malicious actors taking control of elements of the water network via connected devices, creating OT failures or potentially harmful actions
Sustainability impact	IoT can have significant positive impact on water companies' sustainability efforts – if it is deployed in areas where sustainability-related impacts are being measured and if remedial or preventative action is then taken. In and of itself, it will not directly drive sustainability. Sustainability impact areas supported by IoT can include: • Extending life of infrastructure and assets through monitoring and predictive maintenance • Ensuring water quality and wastewater treatment approaches are having desired impact • Monitoring environmental conditions to support more effective management of water supply and river water quality.

Category	Impact area description
Impact on supply chain and partnerships	IoT has some potential to impact procurement and supply chain relationships and activities. Possible areas of impact include: • Potential impact on maintenance + management operations – which may now be supported more by data or automated activities rather than through manual data collection and inspection • Potential to enable as-a-service relationships with infrastructure or device suppliers, rather than outright purchase of equipment, e.g., using IoT data to deliver products-as-services with specified KPIs such as % up-time or achieved water quality.

There are several use cases for the impact of IoT in the Water Industry. IoT has been deployed in treatment works to improve process and performance, whilst reducing asset failures. IoT has also been used to support leakage reduction. Table 5 below describe some details of the use cases and benefits they deliver.

Table 5 Use cases of IoT technology in the water industry

Case study	Detail	Benefit / findings
Scottish Water IoT deployment for wastewater treatment	Scottish Water are investing in a £100M, 5-year programme to deploy IoT solutions to upgrade performance across their wastewater treatment works, the trial of this IoT solution known as the Wastewater Exemplars Programme, completed in 2022. IoT sensors are deployed on Scottish Water's infrastructure across 17 wastewater treatment sites. These allow Scottish Water to access new and existing operational data (including live data feeds and analysis) from across the infrastructure. Applications include wastewater quality measurement, environmental protection, and real-time monitoring of infrastructure. At the first site trialled, Laighpark WWTW in Paisley, Scottish Water now has real-time final effluent compliance data which, together with real-time control and intervention, is helping to reduce risk of compliance breaches as well as reduce energy consumption across the site. Condition sensors have also been installed on large assets such as pumps which, when they fail, can result in significant cost and pollution. By monitoring vibration and temperature, Scottish Water maintenance teams can proactively intervene if the signals go outside 'normal' operating levels, avoiding the cost of failure and pollution while extending asset life. Scottish Water has invested more than £5m in the wastewater 'exemplar' work and about £2m in the sensors in the network pilots so far.	IoT allows faster response times and reduces the reliance on site visits; for example, water quality measurements can be recorded and shared via IoT sensors, providing considerable savings as 600 samples are being gathered each day from across Scottish Water's 1,800 treatment works. Potential critical failures are being flagged up to 3.75 hours quicker than previously detected via callout. A mobile application and desktop portal provide access to critical data from the wastewater treatment sites in near-real time. [11]

Case study	Detail	Benefit / findings
Global Omnium (A Spanish Water Company)	Water company Global Omnium worked with IBM to implement an IoT solution to drive efficiency and cost savings for its Water Treatment process in 2018. IoT sensor data feeds into Global Omnium's Nexus Integra platform, and from there to SAP applications which deliver insight, helping Global Omnium to optimize drinking-water production to suit demand while streamlining operations. The company reports it is starting to see increased reliability of its water supplies and lower emergency maintenance costs, leading to enhanced competitive advantage.	10% reduction in energy cost of producing drinking water, saving USD 1 million per year. Boosts reliability of water-supply service by enabling predictive maintenance. [12]
SAUR (Société d'Aménagement Urbain et Rural – multi-national water company)	Capgemini and multi-national water company SAUR implemented a data management system & operation optimisation solution using industrial IoT systems. Every machine is connected via IoT sensors within a network that compiles, normalises and analyses data, to then generates a comprehensive report on an aspect of operations or raises an alert on a state of the distribution process. 50,000 sensors were implemented across 22 sites.	Enhanced visibility and insight. Real time management of distribution processes provides users with real-time status updates, analysis of historical data, and visual metrics dashboards. Reference: Capgemini Internal Source

Case study	Detail	Benefit / findings
Anglian Water – Leakage Detection	Monitoring and control solutions provider Ovarro has partnered with Anglian Water to develop a revolutionary remote leak detection device, called Enigma3hyQ, which links to a cloud-based data platform, PrimeWebA. The platform ingests data from different sources and of varying granularity levels, to form a master data set. Extensive advanced data analysis on this master dataset, as well as on leakage data, allows Anglian Water to obtain a better understanding of the leakage and factors affecting it. The master data set has been fed into a pipeline of various machine learning models that attempt to build the best model to predict leakage, while determining the most important factors. What's interesting? The use of machine learning and artificial intelligence (AI) type analysis and models, using different information like material, environmental factors such as weather, soil, pressure and its variation, density and population, etc., operational data, such as repairs and output from acoustic loggers (and hydrophones), to tune the pipe-level model that predicts the size of leak.	The sensor-based devices and associated platform are effective in detecting leaks remotely (over long distances), and inside plastic pipes. Between April 2018 and January 2021, the system found 6,783 leaks on its network, making it three times more efficient than traditional detection techniques. On average, Anglian Water sees a 1:1 ratio of leaks found to points of interest issued; demonstrating the system is highly efficient. [13]

Case study	Detail	Benefit / findings
SES Water and Vodaphone – Leakage Reduction	SES Water are embarking on a new IoT roll out across the entire network in partnership with Vodaphone. The self-learning network highlights issues in near real-time, so action can be taken more quickly to make sure customers continue to receive an uninterrupted supply of safe, high quality drinking water, and paves the way for the Company to more than halve its leakage by 2045. Depending on the size of the leak, the ground-breaking technology will enable SES Water to inform its customers of an issue before they are aware of it themselves. Data received from sensors in the network every minute directly informs SES Water's operational teams and speeds up their response time to reduce leaks and bursts and reduce the amount of supply interruptions for its customers. The combination of ground-breaking technologies is also better for the environment, with fewer risks of pollution incidents, less unnecessary site visits and lower carbon emissions by targeting where field teams look for leaks. Vodafone supports the system with its Narrow Band Internet of Things (NB-IoT) solution, which is optimised to provide efficient communication, long battery life and lower costs, using reliable cellular connectivity. Royal HaskoningDHV is providing its AI-powered Aquasuite® technology enabling SES Water to analyse the data being collected and make near real-time operational decisions.	SES plans to roll out intelligent technology across its entire water distribution network, and the plan is for this to help cut leakage by 15% during the next three years. [14]

Technology timeline

Table 6 below outlines the potential timeline for technology implementation for IoT enabled assets and infrastructure.

Table 6: Technology timeline for IoT enabled assets and infrastructure

Timescale	Technology evolution and Water Industry Impact
In 0-5 Years…	**Technology evolution:** IoT technology will be more widely adopted across multiple industries, with the focus being on using IoT to monitor condition of assets. IoT connectivity will still be primarily short-range wireless (e.g., WiFi, Bluetooth) with more limited use of LoRaWAN, cellular and wireline. Use of IoT data will be focused on specific applications and integration into more general operations and reporting will still be limited. Pilots of IoT assets are gradually scaled out to the wider asset network, with IoT Installations becoming more normalised for capital programs throughout AMP8. **Industry Impact:** The water industry will gradually transform its OT and integrate elements of its IT estate; this will move the organisation to a data-centric organisation, driven by actionable data insights.
In 5-10 years…	**Technology evolution:** IoT analytics will become more mature, with well-developed analytics platforms in use that support more effective use of IoT data to understand operations and trends, customer behaviour, accident prevention, asset life, etc. Majority of assets will be IoT enabled with data combined in a common platform. Predictive maintenance is becoming the norm, supported by reliable and actionable trend data. **Industry Impact:** Water industry companies will routinely use IoT to update an enterprise level data core, with a single version of the truth accessible through apps to those who need the information, when they need it. Supply chains are also mapped in to the IoT enabled network and consumable and field force management are automated.
In 10-25 years…	**Technology evolution:** The IoT enabled assets feed data into a real-time Digital twin for modelling of the Assets and Network health Automation. Machine learning is now applied to the data core within the OT estate, enabling more intelligent management of network and assets for maximum efficiency and sustainability. 6G and a variety of other IoT connectivity modes are in widespread use throughout the network. This enables real-time modelling and optimisation of assets and the network, as well as the external environment. **Industry Impact:** An enterprise level Digital twin provides automated data driven decisions for the day-to-day operations of the business, freeing up water company staff and management to focus on driving down costs for the customer and improving the water cycle for the benefit of the environment. Asset data is an asset within water companies, with Data as a Service opportunities realised to provide a secondary income stream.

3.2 Digital Twin Technology

Key takeaway: "Digital twins" are digital representations of systems and sub-systems which utilise real or near-time data from multiple sources to simulate expected, desired, or critical behaviour of the physical system. Digital twin technology has the potential to be a very powerful tool for water utilities, supporting more efficient planning, risk management, maintenance, and realise operational efficiencies. The concept of a network of digital twins is being pioneered by the National Digital Twin Programme, which will allow insights from interoperable twins to provide benefits for society, the economy and the environment, through data-driven insights not previously available from a single enterprise's data sources. This will be a key tool in resilience and scenario planning for utilities providers of all kinds.

Digital twins are still not widespread in the utilities sector, due to cost and complexity, but recent developments in sensors and IoT devices and the increasing availability of online data and compute capacity (e.g., via cloud computing), mean the use of digital twins is becoming a more realistic prospect. In the water industry there are two main trends driving this interest. Firstly, the availability of increasing amounts of data generated at water facilities and on customer premises with the introduction of various smart sensors and smart meters. Secondly, the business drivers around improved use of capital and operational efficiency.

Overview

Digitalisation can help address water industry challenges by providing real-time information which will enable the monitoring of systems performance and ensure greater confidence in decision making.

A "digital twin" is a virtual representation of a physical reality. The concept of "digital twins" started with creating digital models of physical objects, using data provided through connected sensors on the physical objects to enable construction of a digital twin to mirror the actual physical object or infrastructure in real-time or near-real-time. As such, it is closely linked to both **3.1 Internet of Things (IoT) Enabled Assets and Infrastructure** and **3.4 Advanced Sensing and Sensor** Platforms section. A digital twin can be created for one area of infrastructure, or to an entire system.

Extending the original concept further, a digital twin can be used to inform planning and design, or for scenario modelling and testing – for example, in the automotive industry it is common to use digital twins in new vehicle design, to understand the impact of different possible design choices on the overall vehicle. Looking ahead to the future, digital twin models can be extended to people, to processes linking real and virtual steps, to thought processes by automation and artificial intelligence, and even to modelling the activities and decision processes of enterprises and institutions. One example of this being taken further still is within the National Digital Twin programme's CReDO project where Anglian Water, along with UK Power Networks and Openreach have created an interoperable Digital twin to enable collaboration between organisations and increase the safety and resiliency of assets which share a geographic location, and therefore similar climate-based risks.

The term "digital twin" is often misunderstood and is viewed as a simple 3D model, but it is often not represented as a 3D model. This technology is a virtual replica of a system that can model, simulate, monitor, analyse, and constantly optimise assets and networks in a manner which is useful to the asset owner or operator.

There is no single accepted categorisation of different types of digital twins. Generally, they fall into one of several types:

- Asset or Product digital twin – Digital twin of a single physical asset or a single product. Used for product design, testing, ongoing monitoring of asset condition.
- Process digital twin – Used to monitor or test impact of changes to a specific process

- Performance / Operational digital twin – Digital twin of an entire system, including processes. Captures, analyses and acts on operational data
- System of twins – Driven by common Information Management Frameworks, digital twins connect through Open Data to drive greater insights and collaboration across asset types and owners.

Digital twins rely on an integrated platform where information technology, operational technology, and engineering technology are all connected and integrated in one place. This can allow water companies to leverage the potential of big data in a way that was not previously possible by connecting legacy data with operational and engineering data, providing a more holistic view of a system and enabling data-driven decision making.

Capgemini found that, on average, organizations working on digital twins have seen a 15% improvement in key sales and operational metrics and an improvement upwards of 25% in system performance. Increasingly aware of the potential gain, organizations plan to increase the deployment of digital twins by 36% on average over the next five years. Digital twins also provide a unique opportunity to reconcile profitable growth and sustainability. Organizations have realized an average improvement of 16% in sustainability owing to the use of digital twins.

Relevant Technologies

From the technology perspective, a digital twin has three main elements: a digital definition of its physical counterpart (created from a design or modelling tool such as CAD, PLM, etc.), real-operational/ experiential data of its counterpart (e.g., IoT sensor data, real-world telemetry, data, environmental and location data, etc.) – which can be historical or real-time/near real-time depending on the requirement, and an information dashboard or other interactive user tool that analyses and presents data to drive actionable decisions. **Error! Reference source not found.** outlines the relevant technologies and sub-categories that are c onsidered important in the successful implementation of digital twin technology.

Table 7: Relevant technologies for Digital Twin Technology

Technology category	Specific technologies
Sensors	Digital twins use IoT sensors and other measurement tools such as location (GIS data) to gather real-time or near-real-time information on the status, condition and activities of infrastructure or objects, as well as process and operational KPIs such as water level, pressure, flow, quality etc. They provide a link between the physical asset, process or system, and the virtual representation of it.
Modelling tools	Geometric: AutoCAD, UG, 3D Max, OpenSCAD etc Physical: Hypermesh, Abaqus, ANSYS, LMS-Samtech etc Rule modelling: pycharm, spider, keras, MindSphere, Matlabtoolbox etfc Behavioural: ANSYS, Twin Builder, 3DMax etc
Connectivity	Digital Twin technology relies on connectivity to deliver data from sensors to the digital twin platform – this can be wireless (short-range/WiFi, LPWAN or LoRaWAN, 3G/4G/5G cellular, proprietary tech) or wireline.
Edge compute	Edge computing can enhance capabilities of digital twins by filtering and processing data closer to where it is actually collected, thus reducing the data transmission and storage requirements.
Platforms / software	Digital twin platforms and tools are now widely offered by both broad industrial technology players and specialist start-ups. Given that the specific applications and data requirements of digital twins are fairly industry-specific, many tools are designed with particular industries in mind.

Technology category	Specific technologies
Applications	Digital twin applications within the water industry include (but are not limited to): • Water distribution system design • More effective asset management and interaction with different stakeholders, including third parties • Investment and risk mitigation planning via future scenario analysis, performed with models calibrated with historical and data. • Data-driven decision support for selection of different operational strategies. • Customer consumption modelling • Operator training (via simulations) • Optimisation of water network operations for energy or resource savings or compliance management (e.g., to minimise carbon footprint). • Sewage epidemiology [IWA].
Cybersecurity	Digital twins open up the potential of greater cybersecurity threats for organisations using them to mirror and make decisions about physical systems. The threat is linked to the extensive nature of the data capture required to create and update the digital twin. Because the digital twin has to do simulations with the 'in service' data, the process of capturing the data must be highly secure in order to protect it. Conversely, there is an opportunity to use digital twins to enhance cybersecurity, by using them to test and model the impact of security or data breaches, allowing an organisation to then put stronger controls in place to mitigate such risks.

Brownfield vs greenfield digital twins

Most of the use cases we see for digital twins are in brownfield application, as organisations upgrade their IoT technologies and move towards building digital twins for assets that they already have to improve performance and efficiency. The benefits and challenges of brownfield digital twins are outlined in Table 8.

Table 8 Benefits and challenges of brownfield digital twin

Benefits of Brownfield Digital Twin	Challenges to Brownfield Digital Twin
• Give organisations the opportunity to improve their data and processes, leading to efficiencies and cost savings, for example, accurately schedule predictive maintenance using due to the real time data being generated and analysed • Asset lifespan can be extended and even yields improved by process optimisation enabled by Digital Twins. • Engineers can disrupt the system to synthesize unexpected scenarios, examine the system's reaction, and identify corresponding mitigation strategies. This will improve risk assessment, accelerates new product development • Real time remote monitoring can be used to control the system from anywhere, also helping improve employee health and safety. • Process automation and 24/7 access to system information allows technicians to focus more on inter-team collaboration, which leads to improved productivity and operational efficiency	• To minimise disruption of the physical and digital asset environment and operations: • Ensuring optimal data collection vs cost of maintenance • Managing data quality and guarding against data rot (i.e., the quality processes you have in place and the people who need to own that). Data is often siloed, or paper based and generally of inferior quality (so called dark data). • Cybersecurity of both the enablers of digital twins (e.g., the sensors, devices etc.) as well as the digital twin model itself. • Resistance to change is another challenge for brownfield sites. New technologies and processes disrupt established ways of working, creating fear of failure, fear of being replaced, and lack of buy-in. Effective organisational change management is imperative for all digital twin implementations. [15]

Error! Reference source not found. gives some examples of brownfield digital twins used in infrastructure r elated applications.

Table 9 Asset performance improvement through digital twin case studies

Case Study	Detail	Benefits/Findings
City of Chattanooga in Tennessee, USA	Researchers at Oak Ridge and the National Renewable Energy Laboratory partnered with Chattanooga to build a digital twin that helps anticipate and alleviate traffic congestion. Information from 500 different sources, including traffic cameras, 911 emergency-call data, radar detectors, and weather stations, feeds into the city's digital twin.	Upon conducting experiments in traffic-congestion relief using the twin, the city has shown an improvement of up to 30% in traffic flow, resulting in greater energy efficiency as well as reduced passenger delays. [16]

Case Study	Detail	Benefits/Findings
Nanyang Technological University (NTU) and IES	IES delivered a 3D master planning and visualisation model, along with virtual testing and building performance optimisation, for Nanyang Technological University (NTU)'s 250-hectare flagship Eco-campus. Delivered in two phases, the project provided high-level visualisation and analysis of testbed energy reduction technologies on site, before delving into detailed simulation and calibrated modelling of 21 campus buildings.	Created 31% savings in energy use and a reduction of 9.6 kilotons in carbon emissions [17].

The opportunity to develop greenfield digital twins exists along the BIM development framework. Current capital programs are moving towards a federated model approach to design; indeed, some are already mature within federated models and model-based systems engineering (MBSE). The development into digital twin comes when we then roll the design models, through the as-built state and translate them into the asset owner's asset management and OT data systems.

This relies on a whole asset life-cycle approach, where the required systems are integrated into the capital planning and design and build phases of the project. With this approach, new sites can be scoped, designed, optimised, built and operated within a common data environment.

This common data environment can then be applied to the enterprise level Data Core to provide insights to those who need it, when they need it. The common data environment, along with operational, analytic and dashboarding tools is now a digital twin, being fed new greenfield twins as new sites are onboarded to the system. Such a system needs to be designed to be scalable and requires the asset owner to have an enterprise capable of governing and utilising the data being received by the various sites.

Greenfield digital twins are only starting to emerge, for new assets, digital twins will reduce the time to operate and optimise the total cost of ownership. Examples of greenfield digital twins are shown in Table 10. To build a greenfield digital twin in general is an optimisation process between the parallel processes of:

- Design of digital twin setup – engineering of the digital twin and the real-world system its representing – data acquisition and analytics and – mechanisms for feedback into design
- Developing and deploying adequate systems for data acquisition and analytics
- Developing mechanisms for feedback into the design

Table 10 Examples of greenfield digital twins

Case Study	Detail	Benefits/Findings
Amaravati, a smart city being built in India	Amaravati, the new capital of the Indian state of Andhra Pradesh, uses digital twin technology to ensure the city is built as effectively as possible; everything that happens in Amaravati will be scenarioized in advance, optimizing outcomes. The digital twin is a portfolio of smart networks, software, services, meters and sensors to help its customers better manage electricity, gas and water resources for the people they serve [18].	Bringing the virtual and physical worlds together in this way can help to better inform decision-making, reduces risk and also acts as a citizen engagement tool. The benefits of building a digital twin city are using the data gathered to be able to change things on the fly, optimise between different disciplines. City planners, architects, constructors, operators can all have their say, and allow citizen engagement without having to physically bring them to a location.
Singapore Hospital Digital Twin	In building the digital twin of the future hospital a new framework of simulation and optimization for the hospital logistics and transport system is proposed. The main components include the RPA solution development, 3-D building information collection, activities and flows simulation and optimization, and scenario analyses [19].	The findings of the digital twins' simulations recommended the number of trolleys and robotic porters needed for the hospital to run most efficiently and at different capacity levels, allowing the hospital procurement to go to market to source for the right number. The scenarios determined the best output for the delivery time windows for each supply chain and found the delivery sequence in which there was no congestion or bottlenecks present.

Trends

Error! Reference source not found. outlines the key trends that have the potential to impact or influence the s uccessful implementation of Digital Twin Technology.

Table 11: Key trends for Digital Twin Technology

Category	Trend
Technology Maturity	Digital twin concepts have been in discussion and development for nearly two decades and started to gain traction as a design tool in the astronautics and aerospace area, being part of NASA's technology roadmaps [20]. The technology to enable digital twins to become a more broadly used and less specialist tool has advanced significantly in the past 5 years, as IoT sensors and connectivity have become more widespread and cheaper, and as cloud-based storage and compute platforms have enabled much greater data storage and processing capabilities. Digital twin usage is rapidly expanding across the following industries: engineering systems, automobile manufacturing, aircraft production, railcar design, building construction, manufacturing and logistics. However, adoption is far from being widespread. For a digital twin to be effective it must be highly accurate, the up-front investment required for sensorisation, data integration and platforms is significant. The ongoing cost of running and maintaining a constantly active digital twin model must also be taken into consideration, although efficiencies made through use of the twin should cover this. Digital twin technology is still in the relatively early stages of adoption and is therefore judged to be at TRL 8. While the technology is in use for product design, its use as a real-time operational tool is more limited, due to the challenge of integrating with real-time data streams, accurate data gathering, filtering and processing in real-time [21].
Technology Applications	Digital Twin applications that are most relevant for the water industry include: • Planning and design of water network infrastructure or end user devices (such as smart meters). • Remote real-time monitoring of equipment, infrastructure, and operations. • Modelling impact of process or equipment changes on worker safety. • Scenario testing for impact of operational or infrastructure changes, impact of external shocks, etc. • Compliance scenario testing to support decisions on most efficient/effective way to meet compliance requirements (environmental, service quality, etc). • Modelling of environmental impact of changes to operational processes or infrastructure, e.g., moisture, river/lake/sea levels, air quality, water quality and composition. • Digital twins of natural assets such rivers to understand the impacts on river water quality.

Category	Trend
Drivers for adoption	Fully integrated digital twins provide utility companies with reliable and accurate data, which can be used to conduct what-if analyses and make informed decisions throughout the lifecycle of a water system including long-term system vulnerability and capacity planning to instant performance monitoring and emergency response. Currently, utility companies have most of the necessary data required to develop a digital twin (SCADA, GIS, sensors, hydraulic models). The main requirement now is for a data centric platform to be developed, which will integrate, concentrate, and standardise the information coming from different sources. This platform will act as a database that will feed the digital twin with the real-time information and will enable utility companies to draw actionable data driven insights.
Barriers to adoption	Successful deployment and uptake of digital twins will require utility companies to overcome numerous challenges: • Insufficient data quality • Isolated systems that are not integrated • Complexity that comes with running a virtual simulation model that must be constantly kept up-to-date and operate in real time • Need for investments to go hand in hand with an innovative organisation and culture • Requirement for behaviour change and upskilling of resources
Cost	Sophisticated digital twin technology can have very high upfront and implementation cost, as it is not off-the-shelf software. Instead, every digital twin is assembled, built, customised and evolved using real-time dynamic datasets that change over time.

Key Impact Areas for the Water Industry

Error! Reference source not found. outlines the key areas that are likely to impacted by the successful i mplementation of Digital Twin Technology.

Table 12: Key impact areas for Digital Twin Technology

Category	Impact area description
Performance impact	Digital twins can provide water companies with the tools to analyse and understand past and present performance of their systems, as well as predict and optimise future performance and have a real-time view of their entire system. The specific benefits include: • Optimising real-time process can yield large improvement in asset efficiency. • Detecting unexpected or weakening performance at a very early stage enabling water companies to optimise operations and maintenance of systems. • Enabling operational staff to gain a more in-depth understanding of their assets, thereby empowering them in their daily work. • Understanding customer usage behaviour trends will automatically adjust water system management to cater to customer needs, which will improve customer satisfaction. • Data captured and analysed by water companies can be shared as open data or held as IP and shared with the wider industry as a revenue-generating service. Insights from increased asset knowledge can support strategic decision making for the wider business.
BOTEX and Delivery Efficiency	The ability of a digital twin to go beyond conventional PID (i.e. proportional–integral–derivative) control, using model-based control and data-driven optimisation can lower capital expenditure. Digital twins can leverage data from existing work management and asset management systems, as well as other enterprise systems to support risk-based strategic lifecycle asset management. These benefits help water companies optimise lifecycle costs, extend the useful life of assets, and prioritize capital improvement projects. It is possible to scale the use digital twin technology to see improvements and efficiency across the whole organisation. Capgemini and Airbus worked together in 2021 to build a digital twin of the entire single aisle production chain to boost performance and create a blueprint for future aircraft production. The Airbus VIMS aims to reduce downtime and improve production efficiency in the drilling process of several aircraft parts. Using data from vibration and acoustic sensors, an ML algorithm determines the beginning and end of the drilling process and if it has been performed correctly. Early benefit estimation shows break-even after 4 years and net benefits of >35M€ cost savings over the next 10 years. The use of a digital twin has also led to a collaborative delivery model integrating business, technology and shop floor and fully value-driven optimized transformation management [22]

Category	Impact area description
Use for Operational Risk Mitigation, Resilience and Compliance	Digital twins enable organisations to adapt quickly and safely to any circumstance, irrespective if it has happened before or not (such as emergencies or climate change-related events). It is possible to simulate events such as pipe failure, power outages, fires, and contamination by incorporating a hydraulic/water quality model of the system that reflects current conditions with the help of a digital twin. As a result, the model helps utilities analyse the resilience of their systems and assess their risk. Digital twins anticipate risks and identify required measures to prevent emergencies and minimise their consequences. Digital twins allow water companies to test new ideas and changes in a virtual model first before making a decision in real life, which reduces risks, time and costs. These models can be interlinked with third parties and other utilities to enable a more holistic view of underground and above ground assets, as any climatic or weather event in a common geographic area (such as. flooding) will have an impact on all assets in the area. A great example of this is the CReDO (Climate Resilience Demonstrator), which is a pioneering climate change adaptation digital twin project that provides a practical example of how connected data can improve climate adaptation and resilience across a system of systems, this is a joint project between Anglian water and UK Power Networks, underpinned by the Digital Twin hub, part of the National Digital Twin Program. An example of where this technology has been used successfully elsewhere in the Utilities Sector to is Apex by BP, they have used digital twin to improve their existing assets to increase yield. Apex by BP is a production optimisation tool that globally virtualised all the company's productions systems. It helps with significantly accelerating some of the processes, a systems optimisation procedure that used to take 24 hours can now be done in ~20 minutes. In 2017, BP had stated that APEX can be credited to produce more than 30,000 additional barrels of production globally for the year. [23]

Category	Impact area description
Cybersecurity Risks from the Technology	Regarding digital twins there are risks on two fronts: • The first is any malicious input or modification of the digital twin itself. This could happen because of problems introduced in the simulation software, the platform on which it is modelled or stored or in the software supply chain. The problem could also happen at the source (such as with sensors or communications to and from the digital twin), or also within the IT infrastructure that the digital twin activity sits on (breaking into someone's account). This is likely to result in incidents in real life if outcomes of experimentation in the digital twin drives decision making. • The second dimension of digital twins is that they are representations of critical national infrastructure. As such, any information disclosure with regards to the twins could be picked up by bad actors who may then use it to gain knowledge of the infrastructure or drive reverse engineering activity in order to blueprint or target attacks. They may also be used by bad actors to analyse for weaknesses or vulnerabilities that can be exploited.
Sustainability impact	Digital twins decrease organisations' carbon footprints by: • Reducing carbon dioxide emissions from raw material extraction, design, production, operation, and service maintenance • Minimising the amount of physical material and energy required to design, develop, produce and service products and processes • Making it simpler for teams and organisation to gather data from existing products and processes to be used for improvement of future designs
Impact on supply chain and partnerships	Digital twins allow companies to run a parallel virtual version of the supply network with the same supply entities, parameters and financial targets to predict any risks and challenges and have an ability to come up with mitigation actions ahead of time. This will help management make rapid and accurate decisions with a high degree of confidence in outcomes.

Technology timeline

Table 13 outlines the potential timeline for technology implementation for Digital Twin Technology.

Table 13: Technology timeline for Digital Twin Technology

Timescale	Technology evolution and Water Industry Impact
In 0-5 Years…	**Technology evolution:** It is essential for water companies to start their digital twin journey by identifying what real-time data they have access to now to decide on where the application of the digital twin will bring the most value and enable more informed operational and planning decisions. Once that analysis is complete, the next step would be to capture targeted existing physical assets via a variety of surveys and reality capture techniques (point cloud scanning, drones, photogrammetry, drawings/sketches, etc) and converting them into object-based 2D map/systems or 3D models. Next step would be connecting captured information to design information, material specifications, and asset management information and will be further enhanced with Building Information Modelling (BIM), all of this should be underpinned by a common approach to Information and Data Management, allowing data to be shared without translation by numerous parties. **Industry Impact:** Digital twins at this maturity level will provide utilities with a single reference point from which all data can be viewed and analysed resulting in reduction of errors, uncertainties, and costs. It will also allow water companies to run integrated multi-physics, multi-scale, probabilistic simulations against the asset either via the Twin or through connected simulation applications with other utilities and asset owner.
In 5-10 years…	**Technology evolution:** Transformative digital twin with augmented operations, remote collaboration, immersive training. This level of maturity will be enabled by sensors, connected devise and IoT, which will allow companies to obtain and display dynamic or operational data in real-time through one-directional data flow from the physical to the digital asset. The next step would be to introduce two-way integration and interaction between the physical and virtual assets, which would require additional sensor and mechanical augmentation of the physical asset. Open twins become more widely adopted by critical infrastructure. **Industry Impact:** Digital twin technology at this maturity level will provide utility companies with data-driven decision-making capabilities, remote and immersive operations of their assets and having a full control of their physical asset network via the twin.

Timescale	Technology evolution and Water Industry Impact
In 10-25 years…	**Technology evolution:** Cognitive digital twin with autonomous operations, drone assisted maintenance, virtual to physical convergence. The aspiration is for the digital twin to learn and evolve as a living repository for institutional knowledge, gathering enough experience about the behaviour and state of the infrastructure. This will result in the digital twin becoming completely autonomous in its operations, having the capability to react to any issues and take the necessary corrective action with limited or no human intervention, climate impacts can be mitigated via full interlinked twins between asset owners. Open data allows user to build applications within digital twin systems for the benefit of the wider population. **Industry Impact:** An enterprise level digital twin will provide automated data driven decisions for the day-to-day operations of the business, freeing up water company staff and management to focus on driving down costs for the customer and improving the water cycle for the benefit of the environment. Asset data is an asset in its own right within water companies, with Data as a Service opportunities realised to provide a secondary income stream.

3.3 Artificial Intelligence & Machine Learning

Key takeaway: AI and Machine Learning are certain to play a leading role in the water industry's digital transformation. While most AI is still early stage, in time AI will be able to support a wide variety of potential water applications where faster, more accurate, 'human-like' analysis of large and disparate datasets can be useful, from developing deeper customer behavioural insight to optimising water networks for maximum efficiency. There will also be significant potential for the use of AI in achieving sustainability goals.

AI will work hand-in-hand with IoT, Advanced Sensing, and Digital Twin technologies, to drive efficiency, quality and customer insight in the water industry, informing decision-making and assisting human operators and end users. More accurate analysis based on AI algorithmic techniques will be able to support recommendations for human actions and eventually inform and trigger autonomous activities at multiple points throughout the water network, e.g., robotically controlled valves, smart water meters that automatically reduce household water flow in anticipation of droughts, predictive maintenance which automatically orders new parts or even repairs or reroutes water network infrastructure, etc. As AI evolves, more sophisticated techniques such as Sentiment Analysis and Biometric Analysis can help to deliver more personalised training, improve operational safety, adaptively adjust water quality measures, and enhance customer experience.

Predictive maintenance is expected to be one of the earliest and most important applications of AI for the water sector. There are a variety of real-world examples already demonstrating results, with quantifiable benefits from predictive maintenance improvement and asset failure reduction across industries including water, oil and gas, brewing and other utilities. A key benefit of predictive maintenance is cost savings from reducing both unplanned repair costs and unnecessary monitoring visits for manual inspection. Unplanned repairs can be 10 times as costly as scheduled maintenance [24]. At the same time, unnecessary regular maintenance and inspection visits (i.e., for preventative maintenance) also add cost. Data from the US Department of Energy [25] shows that predictive maintenance can result in a 70-75% decrease in breakdowns, a 25-50% reduction in maintenance costs and a 35-45% decrease in downtime over traditional reactive maintenance.

Overview

AI is the blanket term used to refer to digital, algorithm-based systems capable of performing tasks normally requiring human intelligence. In many cases, trained AI systems are able to perform such tasks more quickly and/or accurately than humans, particularly where this involves processing of large amounts of disparate data. AI can help to deliver meaningful analysis and insight in dynamic, complex interconnected environments, where the volume or breadth of data is rapidly growing beyond the capabilities of human analysts. It offers effective ways to identify patterns spread over many data sources, that a human can't discern easily, but a machine might be better able to. Going forward, using approaches such as sentiment detection, emotion analysis and natural language processing, AI should eventually be able to support systems that interact more directly with humans to deliver highly personalised customer service, training, and other high-value interactions.

Machine Learning (ML), a subset of AI, refers to systems which are adaptive and learn in response to repeated inputs of different datasets and patterns – for example, an ML-driven image recognition system that gets better and better over time at identifying when a pipe is misplaced or about to burst.

Work on evolving AI technologies and solutions is ongoing, led by a broad mix of academic, tech and industrial/consumer players. Figure 6 shows the evolution of AI technologies. Most AI techniques or solutions are still in the early stages of maturity. Recent advances in computer power, sensor capabilities and cloud platforms for data storage and analysis have significantly accelerated the capabilities of AI. Most AI-based applications will use a combination of different techniques, depending on the required analysis and outputs. Some of those currently being developed and commercialised for various applications include Natural Language

Processing, Image Recognition, Segmentation and Sorting, Complex Signals analysis, Neural Networks, and Reinforcement Learning.

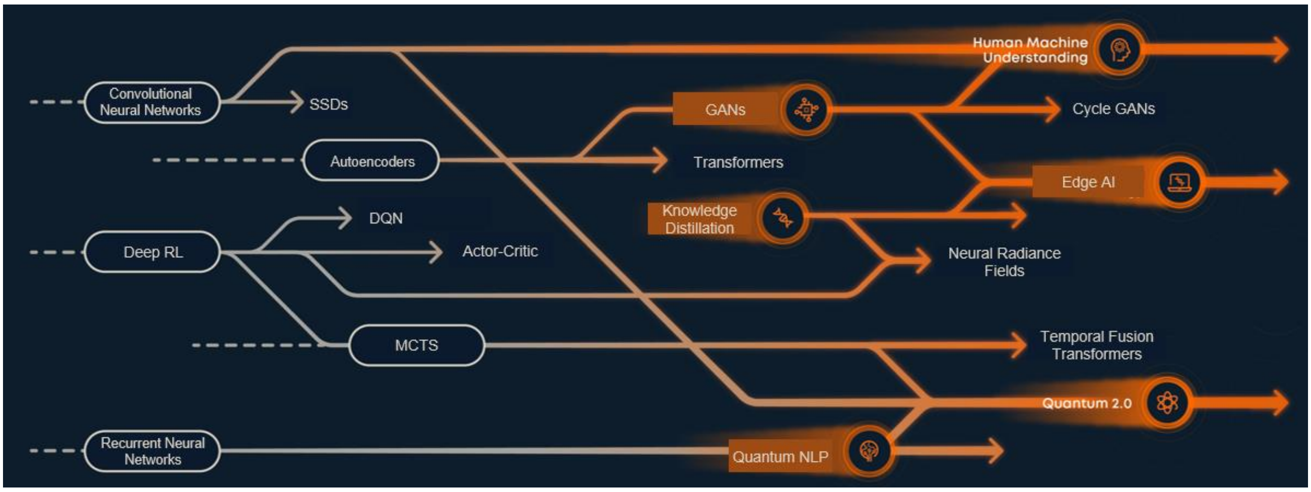

Figure 6: Evolution of AI technologies. Source: Cambridge Consultants

There is also a whole suite of Generation-After-Next (GAN) AI techniques that are still far from commercialisation, but which could have significant positive impact for the water industry as well as many others. Examples include Test relation extraction, Echo state networks, Argument-based ML, Bayesian ML, Inverse Reinforcement Learning, Automated Knowledge Graph Completion, Inherently interpretable models, Generation of counterfactuals, Affective Inference NLP. Some of these techniques – which are at least 5-7 years away from broader use - are designed to provide more accuracy or nuance to existing AI approaches; others bring different types of algorithms or approaches to the fore.

The benefits of deploying AI in the water industry can be significant. In the shorter term, these could include more accurate prediction of infrastructure failure, based on analysis of previous failures and ongoing monitoring for similar conditions or situations. AI should be able to deliver early alerts to significant changes in water quality, and recommended actions to mitigate the situation [26]. There is significant potential benefit from operational optimisation and for automating tasks and analysis that were previously done more slowly by humans. In addition, much more precise and targeted analysis of anything from water quality to customer preferences will be able to be executed more easily and quickly, as systems learn from previous data and situations and are able to apply those learnings to current or future requirements.

The most critical ingredient for successful use of AI is high volumes of relevant, high-quality data (numerical, text, or image-based). This is needed to provide inputs to AI algorithms and form the basis of machine learning, which will allow AI performance to increase over time, enable AI algorithms to learn and improve, and maximise benefit to the water industry, consumers, and the environment. Thus, AI is a later step rather than an initial step in a water company's digital transformation journey. Few water utilities today are in a strong position to collect and normalise large amounts of relevant data (AI can also help with the latter task) needed for AI. The first steps in AI will be to the use of data and AI in one area, rather than using it for multiple applications right from the start.

Relevant Technologies

Table 14 outlines the relevant technologies and sub-categories that are considered important in the successful implementation of AI and ML.

Table 14: Relevant Technologies for AI and ML

Technology category	Specific technologies
AI algorithms and software	A wide variety of AI algorithms and software are under development and/or commercially available. These range from highly case-specific AI systems to more generalised AI or Machine Learning engines. Some categories and examples of relevant AI technologies and applications include: • Knowledge Representation & Reasoning: *Expert Systems* • Learning: *Recommender Systems; Apprentices by Demonstration; Audio-Visual Content Generation* • Communication: *Machine Translation; Speech Recognition; Natural Language Generation and Processing; Sentiment Analysis* • Perception: *Facial Recognition; Text Recognition; Emotion detection* • Planning: *Transport & Scheduling Systems; Scenario modelling* • Physical Interaction (Robotics): *Assisted, Automated and Autonomous Driving and Operations; AI-controlled drones, Cleaning Robots; Logistic Robots; Inspection and Maintenance Robotics* • Social & Collaborative Intelligence: *Negotiation Agents* • Integrating Technology: *Virtual Assistants* [27]
Machine Learning systems	Machine Learning is a sub-set of AI – it refers specifically to intelligent digital systems that are designed to learn and adapt without following explicit instructions, using algorithms and statistical models to analyse and draw inferences from patterns in data. There are four main categories of machine learning, moving from lower to higher levels of autonomy: Supervised Learning, Unsupervised Learning, Reinforcement Learning and Semi-supervised Learning.
Open source data and algorithms	The early stage of AI R&D and the AI market generally, and the need for continual access to new and diverse data sets, mean that open data and open AI platforms are a key part of the ecosystem. This includes open source datasets such as street maps, government-led open source libraries such as the U.S.'s Data.gov, schemas for assessing and validating datasets (similar tools are also available commercially from players such as AWS), free platforms for Machine Learning (e.g., Google TensorFlow), and free libraries of algorithms (e.g., PyTorch). Specifically for the water sector, UNESCO's Naiades Water Observatory Project [28] is gathering open data on the sector and in time plans to develop a set of plug and play solutions for water companies to integrate into their AI initiatives.
Data fusion	Data fusion is the process of integrating information from multiple sources to produce specific, comprehensive, unified data about an entity. Data fusion is categorized as low level, feature level and decision level. Data fusion can be achieved through Machine Learning or other computational techniques, for example to achieve image recognition by combining data from multiple sources to help an algorithm recognise a pattern more easily and accurately.
Data quality enhancement	Data quality is critical for AI analyses to be accurate. Data quality can itself be enhanced using AI tools, e.g., through the implementation of machine learning-based anomalies. Along with correcting and maintaining data integrity, AI can also improve data quality by adding to it (see below).
Synthetic data generation	Where historical datasets have significant gaps that limit usefulness, or where data is needed to generate as-yet-unknown future scenarios, synthetic data generation is a useful technique to build out datasets that can feed AI models in order to perform their analysis as effectively as possible.

Technology category	Specific technologies
Cloud	The cloud can be used to host, process and store historical and synthetic data to feed into AI algorithms; algorithms themselves can be run in the cloud to enable access to greater compute power, which is needed for speed and breadth of analysis.
Edge computing	Edge computing is relevant for AI more for the future than currently. There will be a significant increase in the embedding of data storage, compute, and advanced AI capabilities in edge devices (devices which are used for data collection in the field, such as sensors, or for data aggregation close to where the data is actually collected). Edge compute can deal with data closer to the point of collection and is therefore important in supporting AI applications that may need to act on information in real-time.
IoT sensors and solutions	IoT sensors on water infrastructure, customer premises (e.g., through smart meters, moisture or flood sensors etc.) and in the environment will provide a critical source of data to feed AI and machine learning algorithms. Please refer to **3.1 Internet of Things (IoT) Enabled Assets and** Infrastructure for more detailed discussion.
Computer Vision systems	Systems that have an ability to identify items, places, objects, or people from visual images collected by a camera or sensor. Computer vision systems are one of the most common examples of machine learning in action, and can be trained to recognise particular situations or conditions (e.g., of equipment) through a steady training program showing them multiple positive/negative examples of the type of object or situation to be identified.

Trends

Error! Reference source not found. outlines the key trends that have the potential to impact or influence the s uccessful implementation of AI and ML.

Table 15: Key trends for AI and ML

Category	Trend
Technology Maturity	Today, only 12% of companies have advanced their AI maturity to the level of achieving "superior growth" and business transformation, based on a 2022 study from Accenture. The implication is that we are still quite early on the adoption curve. Nevertheless, in an interesting finding, companies who mentioned 'AI' in their earnings calls in 2021 were 40% more likely to have seen an increase in share price than those who did not. So, even the expectation of future implementation of AI as part of business operations is seen to add value [29]. There is maturity in terms of the technology itself, and maturity in terms of market adoption. AI is still an emerging technology category. We expect it to become far more mature and pervasive over the course of the next 25 years, but it is far from pervasive in the water sector (or in most other industries) at present. As mentioned above, different AI techniques and solutions are at very different levels of maturity, and given how diverse these are, it is not very meaningful to consider a Technology Readiness Level for the whole AI category. Generation After Next AI techniques are at TRL 0-2; while approaches such as machine learning for specific, constrained applications have a much higher level of maturity (eg TRL 7-9) but may not be fully generalisable.

Technology Applications	Potential AI and ML applications in the water industry include but are not limited to: **Infrastructure/network design:** • **Optimal design of monitoring and control networks** AI algorithms can help with many aspects of design optimisation, e.g., by optimising location of sensors in a particular network, to enable the maximum amount of information to be extracted about the whole system with the lowest CAPEX. **Infrastructure management and maintenance:** • **Active and predictive asset management programs** AI algorithms can help with defining optimal schedules for monitoring and replacing assets based on the statistical definition of their useful life, criticality, and other variables; and ultimately can be used to enable predictive maintenance by combining monitoring data with historical data to learn from previous instances [30] **.** • **Real-time and predictive leakage detection** Real-time detection and prediction of pipe bursts and leaks. AI algorithms can provide spatial information (real-time or predictive) on the amount and type of water losses, based on previous patterns of water loss data. **Operational Efficiency and Emergency planning:** • **Energy savings** AI algorithms can assist with energy savings in network operations by defining the most efficient operating procedures and identifying the most cost-efficient investment in each system (pump replacement, increased storage capacity, change of energy contract, etc) for energy savings. • **Definition of contingency plans and protocols** AI algorithms can optimise a response to an emergency based on either pre-defined or real time contingency protocols. **Customer behaviour and usage insight:** • **Classification of consumption patterns and demand forecastin**g AI algorithms can learn customer behaviour patterns under different conditions, and use this both to forecast water demand and to deliver 'nudge' recommendations to customers **Environmental Impact Modelling and Forecasting:** • **Weather and water level impact forecasting** Computer vision and weather and water level detection (or third party weather data) and analytics to monitor and forecast impact of rainfall/drought/flooding, including operational and water quality impact **AI-assisted water and wastewater quality management:** • **Improved Chlorination and Disinfection by-product (DBP) management** Using AI techniques to control chlorination, and ML to model and predict DBP formations / chlorine requirements. • **Predictive modelling of Adsorption Processes** for removal of contaminants and pollutants in water & wastewater treatment. AI can be used to model adsorption-process and better enable operator decisions, e.g., by calculating

Category	Trend
	and predicting adsorption efficiency, capacity, non-dimensional effluent concentrations, relative importance of input water-quality parameters. • **Water Quality Management** Using ML to predict the water-quality index, DO concentration, pH, BOD, ammonium nitrate concentration, water temperature.
Drivers for adoption	• Potential for AI to drive much greater and higher-value insight and decision support from operational, external and customer data • Potential for AI to deliver significant CAPEX savings in design and maintenance of infrastructure, and OPEX savings in water and wastewater operations, including optimisation of energy use • AI-enabled prediction capabilities for emergency events and ability to draw insights from historical emergency events at an accelerated rate. • More advanced decision-making intelligence to support operational staff. • Acceleration of transition to as-needed and predictive asset maintenance, enabled by AI modelling and tools that analyse both previous data and trends, and the current state of the asset • Potential for AI to capture expertise of key experienced operational (and other) staff through their feedback and input in AI model training

<table>
<tr><th>Category</th><th>Trend</th></tr>
<tr><td>Barriers to adoption</td><td>Data Relevance, Quality and Volume

Successful use of AI & ML methods and models is heavily dependent on the availability of data of sufficient quality and relevance, in sufficient volume for analysis to be meaningful. Ideally data series are available over time and representing a high volume of events or instances, so an AI or machine learning system to be trained on them.

Learning and Reproducibility Challenges

AI systems may struggle to scale for broader use in a real-life context (e.g., across multiple water facilities or multiple situations), because they may have been trained with too limited a dataset (meaning they can only deliver analysis with data that has relatively similar characteristics to the datasets they were originally trained on). Likewise, the application of a particular system may be very specialised and narrow.

Trust and explainability

An important barrier to AI adoption is the need for human users or recipients of AI-based analysis and recommendations to trust the outputs of algorithms. In mission-critical decision situations, it can be difficult for people to trust that AI is giving them reliable advice or answers, especially if the means of arriving at those answers is not transparent. Thus, clear traceability and explainability of AI algorithms is a key aspect of successful introduction into processes.

Concerns over potential loss of staff positions

The introduction of automation of what was previously a ‘human task’ can feel threatening to staff and may raise concern along the lines of ‘A robot is taking my job’. Such concerns need to be treated sensitively and AI should be positioned as a support to human effort rather than a complete replacement.

Difficulty of measuring return on investment (RoI)

Any AI system will require initial investment in both tools and time, and it is not always clear how quickly such an investment will pay back, if at all. Evidence of RoI is likely to take some time to be clear, which may not align well with water company investment plans and requirements</td></tr>
<tr><td>Cost</td><td>The cost of deploying AI depends on the nature of the application, and how much customisation and training time is required. Custom AI solutions can run into the hundreds of thousands (pounds) or even millions if systems require prototyping and significant integration. Consultancy and ongoing maintenance fees must also be included. More commercialised off the shelf AI solutions and applications can be much cheaper but are more limited. For example, adding an AI chatbot to your website can cost less than £1000 per month, if no customisation is required.

Despite uncertainty over costs, most organisations see AI as critical to their future development and competitiveness. Global corporate investment in AI has increased from 12.75 bn USD in 2015 to 93.5 bn USD in 2021[31].</td></tr>
</table>

Examples From Other Industries

AI is transforming virtually every industry, sparking innovations from education to transport to media and entertainment.

As a leading use case industry, AI is being used heavily in 'smart manufacturing', especially in advanced sectors such as automotive manufacturing where high levels of precision and customisation are needed. Use of advanced-data analytics has significantly improved risk management, data visualisation, supply chain management, and rapid decision-making processes. Examples of AI applications currently being deployed in advanced manufacturing:

- Predictive maintenance: leverages real-time data to identify core issues in the manufacturing process and repair or replace key elements of the production infrastructure before they break down
- Engineering design and testing: AI works together with digital twins in the car and component design process to improve the accuracy and safety of designs. In addition, AI is used to generate synthetic data to test out new designs and components under a very wide variety of conditions

The BMW Group uses automated image recognition for quality checks, inspections, and to eliminate pseudo-defects (deviations from target despite no actual faults). As a result, they've achieved high levels of precision in manufacturing[32].

Porsche uses autonomous guided vehicles (AGVs) in their manufacturing facilities, to automate significant portions of automotive manufacturing. The AGVs take vehicle body parts from one processing station to the next, eliminating the need for human intervention and making the facility resilient to disruptions like pandemics [33].

A survey on executives within the oil and gas industry asked for respondents to self-report the effects of AI. The survey found that AI investments generated a 32% return on investment in 2020 [34] with overall expenses reduced by 3% and revenue increased by 3%.

In a 2018 study by PWC and Mainnovation, 268 European companies across various industries were surveyed regarding their predictive maintenance initiatives and investments [35]. Whilst individual respondents achieved improvements of 25-30% in uptime because of predictive maintenance, the average self-reported improvement (including those who didn't report an improvement) for each predictive maintenance value driver is shown in Table 16.

Table 16 Average self-reported improvement from predictive maintenance [35]

Maintenance Value Driver	Average Improvement
Uptime Improvement	9%
Cost reduction	12%
Reduction of safety, health, environment & quality risks	14%
Lifetime extension of aging asset	20%

These value drivers have specific relevance for the water industry:

- Reduction in downtime and breakdowns which leads to lower disruptions to supply. Reduction in supply performance comes with financial rewards (£1M projected reward in the 2021 Anglian Water Annual Performance report [36]When supply is interrupted, water companies are liable to pay users under the guaranteed standards scheme [37].
- Fewer failures that lead to pollution events. Pollution events have led to £141M of fines for water and sewerage companies since 2015.
- The water industry is fixed asset heavy and so lifetime extension of assets is a particularly important value driver. For example, for an asset that costs £1M and is designed to last 15 years, the investment

in this asset each year is £67k. Therefore, for every year of life reduced, the cost is £67k. The 20% increase in lifetime that could be expected from predictive maintenance would be an extra 3 years, thus saving £200k.

Error! Reference source not found. below gives further real-world examples which demonstrate the q uantifiable benefits of predictive maintenance improvement and asset failure reduction using AI.

Table 17 Examples of AI based predictive maintenance in water and adjacent industries

Case study	Detail	Benefit / findings
Leading National Oil Company in the Middle East [38]	For this company, sand accumulations in desert regions often disrupted operations and critical infrastructure. These sand accumulations required manual patrols to identify and move and the interruptions resulted in significant lost revenue. Existing internal and external data sources such as satellite images, work orders and financial reports were used to predict sand accumulations and give a reduction in maintenance costs.	• A 27% decrease in maintenance-related costs. • Improved health and safety for works. • Reduced carbon footprint. • Higher plant uptimes possible.
Large US based electric utility [39]	A large US electric utility used Maximo (by IBM) to improve their asset management. Maximo is an application suite that uses AI, IoT and analytics to optimize performance, extend asset lifecycles and reduce operational downtime and costs.	• Reduced Capex by $450M per year, maintenance costs by over $500M/year and improved labour productivity by $60M • 43% less downtime.
ClearWater Analytica (solutions provider) – multiple customers [40]	ClearWater Analytica predicts algal blooms using machine learning. This enables early action to avoid harmful results of such blooms (e.g., development of excessive toxins in water).	• Algorithms predict harmful algal blooms with over 85% accuracy. • Predictions have helped city officials avoid follow-on emergency events which leads to reduced costs. The City of Salem (USA) authorities spent ~$80M improving its resilience to harmful algal blooms. This would have likely been less if this prediction software was available earlier. • The drivers of algal blooms can be identified which helps with environmental conservation.
Danone Group	Uses machine learning to improve its demand forecast accuracy [41]	• 20% decrease in forecasting errors • 30% decrease in lost sales • 50% reduction in demand planners' workload

Key Impact Areas for the Water Industry

Error! Reference source not found. outlines the key areas that are likely to impacted by the successful i mplementation of AI & ML.

Table 18: Key impact areas for AI & ML

Category	Impact area description
Performance impact	AI and Machine Learning can positively impact water company performance in different areas, although this is likely to be via a series of programmes implemented over the course of a number of years, rather than a 'big bang' approach. Anywhere that can be improved by faster, broader data analysis, especially where previous events or patterns can be determined and used as a guide to understand new situations. Key areas of potential performance impact include: • Using AI systems to improve water supply and distribution infrastructure management to minimise leakage, maximise up-time and adapt infrastructure investment plans • AI use to enable more accurate and cost-effective recovery, treatment and reuse of used water • Using AI to empower consumers by providing them with greater control, and intelligent, highly personalised recommendations on their water consumption and ways to reduce usage and costs. • In an example given by "Pumps&Systems", a leading resource for pump users worldwide, switching to a predictive maintenance strategy over a reactive maintenance strategy should save around $60,000 in yearly maintenance costs for every $1M of existing assets [42]
BOTEX and Delivery Efficiency	• AI can potentially save 20-30% on operational expenditures (OPEX), through such activities as reducing energy costs by identifying energy savings opportunities, optimizing chemical use for water treatment by learning from what has been most effective in previous similar situations, and enabling proactive and predictive asset maintenance to minimise water network downtime [43]. • AI can help with short-term operational decisions related to interruptions to supply and leakage and also help with the long-term investment plans (pipes maintenance and replacement) • AI can enable optimal design and flexible operational approaches for monitoring and control networks • Over time, ML systems should be able to learn and actuate certain activities autonomously, minimising the need for human intervention, and thus reducing labour costs while improving service levels.

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Category	Impact area description
Use for Operational Risk Mitigation, Resilience and Compliance	• AI can enhance ability to manage water pressure, identify and protect against water quality issues, and predict and respond to incidents. All of these are critical for compliance • AI can support more accurately and timely flood and leakage detection, and predict such events based on previous data • Predictive repair saves maintenance costs as unplanned repairs can be 10 times as costly as scheduled maintenance [24], yet unnecessary visits (e.g., for preventative maintenance) also add cost. Data from the US Department of Energy [25] shows that predictive maintenance can result in a 70-75% decrease in breakdowns, a 25-50% reduction in maintenance costs and a 35-45% decrease in downtime over traditional reactive maintenance. • As another indicator of potential impact on the water industry, the Samotics SAM4 solution is a suite of technologies including machine learning that “reduce costs, risk and energy in water distribution and treatment”. Their customers include Anglian Water, Yorkshire Water and Northumbrian Water. This solution has detected over 90% of developing faults across its installed base, up to five months before failure.

Category	Impact area description
Cybersecurity Risks from the Technology	AI opens up both risks and benefits from a cybersecurity point of view. On the benefits side, AI/ML can be leveraged to enhance cybersecurity including intrusion detection and activities such as asset discovery which would feed into security mechanisms and policies • There is potential to use deep learning algorithms for intrusion detection, or to be applied to behavioural analytics for detection of abnormal actions or data transmissions • Incorporating AI into cybersecurity platforms will become commonplace, given the importance of pattern recognition from high volumes of data which could be obfuscated On the risks side, there are many security implications with regards to AI/ML. Because AI/ML is non-deterministic and opaque (especially deep learning), there needs to be a security assurance case created for this. Risks can arise from: • Sabotage of datasets (gathering, labelling, curating, storing, transmitting etc.) • Sabotage or misuse of models and algorithms • Incidents in the DevOps process (for example if malicious libraries are used whether by accident or intentionally) • Breaches of the IT infrastructure which could lead to the above • Exploiting the deployment infrastructure (e.g. attack the sensors deployed) Potential harm from such activities will vary depending on the level of autonomy AI systems have, and/or the nature of the recommendations they are providing to human 'partners'. If the AI or ML system is being used for classification or prediction, for example, malicious hacking or data corruption impact could include inaccurate decision making, exposure of information, or even safety incidents. Suitable risk assessments and an AI assurance case will be required with cross-disciplinary considerations (e.g., prioritisations of areas with potential safety impact).
Sustainability impact	Areas of positive AI impact include but are not limited to: • Potential positive impact on water resource management, e.g., using AI algorithms to optimise operations in order to cut waste and predict demand/supply • Potential for AI-controlled precision water quality control • Potential for more efficient management of water company energy requirement via AI-controlled energy management systems

Category	Impact area description
Impact on supply chain and partnerships	• Successful deployment of AI will require close working partnerships with both hardware and software providers, as systems will need customisation in order to meet the specific needs of any given water supplier • Access to data from across the industry (or even from water industry players in other countries) could be an important input to successful AI development for the sector • Partnerships with academia and/or technology providers could be helpful in developing new innovative AI-based approaches to water management and operations

Technology timeline

Error! Reference source not found. outlines the potential timeline for technology implementation for AI & ML.

Table 19: Technology timeline for AI & ML

Timescale	Technology evolution and Water Industry Impact
In 0-5 Years…	**Technology evolution:** Active & Operational levels of AI Maturity. AI algorithms and systems are being developed for specific use cases, with key areas being pattern and image recognition, anomaly detection, prediction and scenario analysis, automation of operations **Industry Impact:** AI will start to be used for a limited number of specific, critical operational, compliance and safety use cases, e.g., real-time detection of pipe bursts in water distribution networks through the use of AI-enabled Event Detection Systems (EDS); predictive wastewater treatment plant control with the use of AI & ML enabled software that will connect to the plants' SCADA system[44]; AI-enabled scenario modelling of extreme weather impact on demand, water network performance, water quality.
In 5-10 years…	**Technology evolution:** Systemic level of AI Maturity. Wider adoption of smart meters and other monitoring tools provide data that enables AI systems to track and forecast water use on an industrial and household level. More sophisticated AI techniques combine data from multiple sensor types, weather data and customer data to deliver a clear picture of current and future states at a system level, with ability to detect anomalies and predict their impact across the whole system, and to model scenarios. **Industry Impact:** AI enables 24/7 real-time monitoring of water infrastructure, prediction of faults and identification of critical management activities or interventions for optimised water systems. AI-based water monitoring tools will allow suppliers to predict water demand, reducing both wastage and shortages of water. Water treatment and desalination processes will be precisely modelled using new AI tools, with outputs used to inform human or machine actions to ensure the highest levels of water quality and compliance and enabling new sustainability-critical capabilities such as maximising reuse of greywater through more precise and effective treatment approaches.

Timescale	Technology evolution and Water Industry Impact
In 10-25 years…	**Technology evolution:** Transformational level of AI Maturity. AI becomes part of companies' normal operations and is firmly embedded into the organisation and corporate strategy [45]**.** AI systems enabling more sophisticated analysis across multiple dimensions including areas such as affect detection are common, with adaptive AI/ML supporting automated actions becoming the norm in a number of critical control areas especially regarding prediction of and mitigation against safety incidents, environmental impact, and infrastructure failure. **Industry Impact:** AI is used across multiple levels of water businesses including in operations management, infrastructure management, water quality and wastewater monitoring and improvement, safety and compliance, and customer interactions. Water companies will have AI & ML enabled digital twins of their water system operations, which will be able to automatically run multi-variable models with non-linear relationships to optimise service quality, cost efficiency, operations, analyse risks etc. AI will support autonomous operation of various aspects of the water supply and distribution network. Customer interactions will be driven by AI with a more pro-active and personalised experience delivering higher customer satisfaction.

3.4 Advanced Sensing and Sensor Platforms

Key Takeaway: Greater understanding of the water value chain can be achieved through sensing technologies and the use of a variety of sensing platforms. The wide-ranging benefits of advanced and connected sensing to network management and customer service have been proven in trials around the world. Advanced sensing technology is already commercially available but high barriers to adoption have limited their use. New sensing technologies are being developed that will enable new parameters to be measured in more environments, but these will still face the same barriers to adoption. Unless the barriers to adoption are addressed, the transformative benefits of advanced sensing to the water industry will not be achieved.

Overview

Advanced sensors and sensor platforms are high impact technologies that can facilitate a wide range of improvements in the water industry. When these sensors are connected, they become truly transformative to the industry (as discussed in **3.1 Internet of Things (IoT) Enabled Assets** and Infrastructure). Many of these improvements are urgent and would deliver benefits to the water industry in a relatively short timeframe, example applications include intelligent sewer technology; automatic, enhanced sampling of environmental water quality; and smart water supply network. These are all specifically called out in the Ofwat PR24 guidance on technology scenarios for long-term delivery strategies. Advanced sensing and sensor platforms are also a key enabling technology for IoT, digital twin applications, digital workflows, visualisation and digitally-enabled asset delivery.

Efforts to improve processes in the water sector are far less effective without a detailed understanding how changes impact them that can only be achieved via sensing. Currently used sensing capabilities are limited by a range of factors including:

- inability to measure parameters online and/or continuously;
- high installation and operating costs;
- lack of appropriately trained technicians limiting correct installation and maintenance; and
- poor understanding of the network resulting in sub-optimal deployment of sensors.

Advanced sensors can help to over some of these challenges through more robust methods and better design. Many such sensors are commercially available but not widely deployed due to other barriers to adoption.

Developments in sensing platforms can enable existing sensing technology to be deployed in new environments and in different ways. This can allow for:

- previously hard to reach areas to become accessible, such as the use of drones and unmanned aerial vehicles in rural leak detection; and
- in-pipe robotics to diagnose and repair issues as they find them.

Continuous online water quality monitoring in the network and river catchment is one area where advanced sensing could provide new benefits in the water industry. Understanding how the water quality is changing through the network allows for the treatment process to be optimised in real-time. Wastewater monitoring of combined sewer overflows could reduce the number of incidents and associated environmental damage. Biosensors and photonics offer potential solutions for continuous online network monitoring within the next 10 years. There are limitations around regulatory testing, which require the use of specific methods, that could prevent the use of some new sensors for this purpose. As new sensors develop, regulation must adapt to ensure the advantages offered by advanced sensors to the regulator can also be achieved.

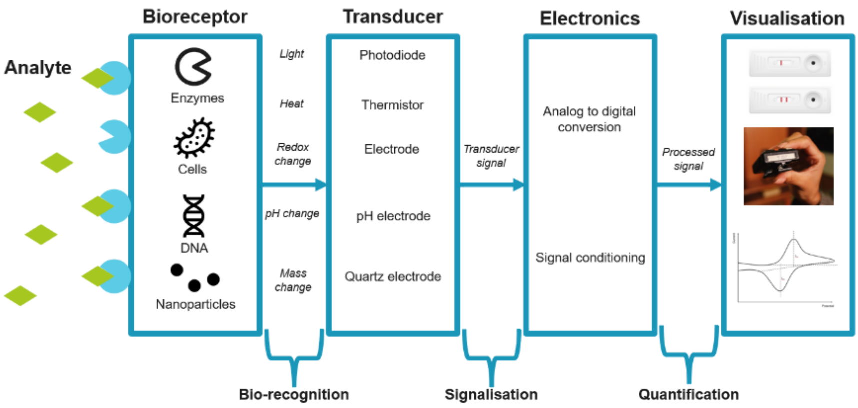
This section explores key advances in sensing technology and platforms that could transform the water industry through the improvements that they facilitate. Due to the broad nature of this topic, the following areas have been focused on as the most impactful:

- ***Advanced sensing:*** specifically, biosensors, advanced photonics, quantum sensing and advanced acoustic sensing.
- ***Sensing platforms:*** specifically, drones, unmanned aerial vehicles, submersibles, robots and magnetised crawlers.
- ***Sensor fusion:*** defined as the process by which sensor data is combined from separate sources to improve accuracy of machine perception, i.e., to provide insights or improved accuracy beyond what is possible using a single sensor or sensor type

Relevant Technologies

Error! Reference source not found. outlines the relevant technologies and sub-categories that are c onsidered important in the successful implementation of advanced sensing and sensor platforms.

Table 20: Relevant technologies for advanced sensing and sensor platforms

Technology category	Specific technologies
Biosensors	Biosensors are devices which detect a variety of substances (including proteins, DNA, small molecules) using biological entities such as enzymes, cells and DNA. Figure 7 reproduced from [46] and shows how bioscience works  **Figure 7 How biosensors work.** [46] Currently, the most common form of electrochemical biosensors is amperometric enzymatic biosensors. They are popular as they allow for continuous monitoring of substances that previously could only be measured by taking samples. Other types of biological sensors are based on the interaction of environmental substances with genetic circuits and can detect DNA, RNA and small molecules. This essentially allows real-time monitoring of virtually any substance.

Technology category	Specific technologies
Advanced Photonics	Photonics is the science and application of photon properties and transmission. It includes generation, detection and manipulation of photons. In the water industry, there are a variety of sensors already using photonics. For example, colorimetry measurements for chlorine levels, infra-red spectroscopy for organics or coupled plasma methods for heavy metals. Machine learning for deconvolution of signals in different types of spectrometry e.g. infrared spectrometry.
Advanced Acoustic Sensing	Advances in materials science could lead to better acoustic sensing. Advances in machine learning could allow further insights to be extracted from this acoustic data.
Quantum Sensing	Quantum sensing uses quantum phenomena such as entanglement, interference and tunnelling. Quantum sensors can measure many things to a ground-breaking level of sensitivity, although the practicality of their current implementations varies. Gravity / acceleration and electromagnetic fields are the best developed currently.
Unmanned Aerial Vehicles	Drones and UAVs are remotely controlled aircraft, and they can range in size from the 10cm Black Hornet Nano [47] to over 24 meters [48]. They are often used to transport payloads or carry sensors for surveillance.
Submersibles	Magnetised crawlers, eel-like robots, other submersibles
Robots	Pigging – the use of robotic devices within a pipeline for cleaning and inspection.

Trends

Error! Reference source not found. outlines the key trends that have the potential to impact or influence t he successful implementation of advanced sensing.

Table 21: Key trends for advanced sensing and sensor platforms

Category	Trend
Technology Applications	**Biosensors:** allow for continuous monitoring of substances that previously, could only be measured by taking samples, e.g. detection and/or monitoring of: • Small molecule contaminants in water • Pathogens in water (e.g. legionella) to give real-time alerts about risk to human health, • Biofilms to improve their performance, • Environmental DNA for biodiversity monitoring • Public health parameters in the wastewater. **Quantum Sensing:** Quantum gravity sensors could give much better information about buried assets [49], [50] which could enable development of accurate underground digital twins that could bring benefits such as minimising risk of damage to assets when digging. Existing imaging methods for underground assets are based on radio frequency technology such as Ground Penetrating Radar, however, soil attenuates the signal meaning that it cannot travel far enough below the surface [51]. Underground assets including cables and pipes are often deeper than this. Quantum gravity sensors can theoretically detect

Category	Trend
	much deeper objects as they are measuring a passive field rather than sending a travelling signal, although the achievable resolution decreases at large depths. **Other Sensor Types** Photonics (optical sensors) are currently used for colorimetry measurements for chlorine levels, infra-red spectroscopy for organics or coupled plasma methods for heavy metals. However, these are all lab tests that involve reagents, meaning that samples must be taken. Advancements are likely to allow photonics to be used for continuous in-line monitoring as opposed to having to take samples. Acoustic sensing is used in the water industry already to find defects and detect leaks. **Sensor Platforms** Drones could generally be used for mapping, monitoring and collecting samples. Using AI driven image detection could for example be used for detection of algal blooms, the foliage changes associated with a leaking water pipe or for mapping sites, to assist with the construction of digital twins. Submersibles are already used for inspection of water tanks, reservoirs, large pipelines and dams. Magnetised crawlers are used for inspecting the structural integrity of large metal infrastructure, across industry and infrastructure settings. They most frequently use acoustic sensing (in the form of ultrasonics) to measure the wall thickness and therefore detect faults. As they can move around the surface of a tank or large pipe there is no need for the erection of scaffolding or the use of lift equipment. Pigging is commonly used across infrastructure sectors (gas, oil, water). Downtime and cost of maintenance are reduced as the pig travels through the pipe (often propelled by the pipeline's existing pressure) without stopping the flow of the pipe. Sensors can also be piggy backed onto third-party, fleet-operated road vehicles, boats or aircraft. Examples include the detection of large puddles on roads which may indicate blocked drainage, image recognition of damaged manhole or drain covers, and image capturing of large bodies of water such as reservoirs from commercial aircraft while flying at low altitude such as on approach to landing or after take-off.

Category	Trend
Tech Maturity	**Biosensors** • The global market for biosensors is currently valued at $25.5bn, projected to reach $36.7bn by 2026 (CAGR 7.5% [52]). • Electrochemical biosensors for measuring substances such as arsenic in water are already commercially available. • Other amperometric biosensors such as those for measuring Covid RNA in the water are in development at approximately Technology Readiness Level (TRL) 6 [53]. • Generic circuit transcription factor-based biosensors are being deployed and commercialised [54]. **Sensor Platforms** • The growth of the inspection drone market is expected to rise from $1.9bn (globally) in 2021 to $8.6bn in 2031 [55]. • Submersibles are already used for inspection of water tanks, reservoirs, large pipelines and dams. As a result, there are several commercially available options. • Magnetised crawlers are already in use, with the future bringing improvements to their speed, cost and sensors.
Drivers for adoption	Advanced sensing is a key enabling technology for digital transformation. It is rapidly growing (CAGR 8.9%) [56]. Key drivers include the increase in demand for IoT based services (see IoT market drivers in **3.1 Internet of Things (IoT) Enabled Assets and** Infrastructure) and the process benefits that sensor-enabled automation and autonomy can bring, although true autonomy is unlikely to be realisable in the water industry in the near-to-medium term. Once a platform, sensor fusion technology and analysis technology have all been deployed within a water network or site, deploying more sensors is an incremental cost, but one which has a strong investment case as it provides excellent value for money. This does however assume that the sensors have a minimal operating cost, for instance they do not consume reagents or require regular maintenance.

Category	Trend
Barriers to adoption	Key barriers to advanced sensing include achieving scale of deployment, maintenance of in-field sensors and the analysis of vast amounts of the data to realize insights as data scientists are currently in short supply. The installation of large quantities of sensors may be especially challenging in hard-to-reach places. A common problem with any invasive sensor is the need to keep it clean and working. For example, sensors with windows film over and chemically sensitive sensors need to be topped up with reagents. Where sensors require any kind of maintenance or recalibration, there is a large barrier to adoption as this adds expense and complexity. A key barrier to scaling biosensors is the difficulty of manufacturing robust, highly specific, reliable, reproducible devices at scale. In the water industry specifically, being able to keep functioning within a pipe for years requires a level of robustness that may be difficult to achieve using biosensors. Nonetheless, it has been managed in the medical industry (e.g., in continuous glucose monitoring [57]). A lack of viable sensors for many drone applications will also delay adoption. The cost, weight or power usage of sensors need to be improved to further the commercial case for widespread inspection and monitoring drone roll out. The complete automation of drones will rely on unmanned air traffic management (UTM) including drone collision avoidance systems which can operate across drone type and manufacturer, these technologies are only at TRL 3 or 4. Finally, the interoperability of sensors, IoT platforms and other technologies could be a barrier; this is more likely to require solutions at the software and network level, rather than being a hardware issue, as digital interfaces for sensors themselves are increasingly standardised.
Cost	Individual cost of sensors is small, but can become significant when large volumes need to be deployed for continuous monitoring and/or data fusion purposes (i.e., for measuring multiple parameters or for increased granularity of measurement). Whilst sensors enable predictive maintenance and rapid response to faults, the exact financial benefit of this can sometimes be difficult to precisely predict and monitor, which can constrain investment in advanced sensing. Drones and other platforms offer a more straightforward cost-benefit analysis. Sending a drone to inspect a key piece of infrastructure or monitor a site requires less equipment than deployment of static sensors and can often be done with fewer people.

Category	Trend
Examples from other industries / geographies	**Biosensors:** Currently used widely in the healthcare sector, with examples of single use, e.g., Covid tests and pregnancy tests as well as durables, e.g., continuous glucose monitors for diabetics. They are also used in biomanufacturing environments. **Quantum Sensing:** Atomic clocks are used in GPS. Quantum sensors are still being developed primarily through academic research. **Other Sensors:** Continuous Raman spectroscopy is used as part of process control in bioprocessing industries to monitor cell culture process parameters [58]. **Sensor Platforms:** Pigging is used across oil and gas industries. Flylogix is an inspection and data gathering company for offshore oil and gas companies [59] that operates piloted drones beyond line of sight. S**ensor fusion** is used across a range of industries, e.g. autonomous vehicles and incident detection/traffic monitoring.

Table 22 outlines how advanced sensors and sensor platforms can be used to improve knowledge of underground assets and over what timescale.

Table 22 Potential of advanced sensing for underground assets

Application	Benefit of advanced sensors	Relevant sensing technology	Relevant sensing platforms	Timeframes
Leak detection	• Higher accuracy of leak location • Faster burst detection • Identification of leaks in hard-to-reach and rural areas • Improved prioritisation of repairs • Identification of leaks in the wastewater network	Acoustic Photonic Radar	Fixed invasive and non-invasive Drones Unmanned aerial vehicles Satellites Submersibles Robots	Advanced sensors for water leak detection are already currently available and have been trialled by Anglian Water. Future developments are likely to incrementally improve the accuracy and design of these sensors. The primary benefits of water leak detection from advanced sensing can already be achieved with current technology. Satellite radar leak detection is becoming available for wastewater. While currently not a regulatory requirement as environmental regulations evolve over the next 25 years this may change. Wider use of satellites for leak detection will enable wide-scale monitoring at a fraction of the cost of installing permanent sensors in the network over the next 5 years.

Application	Benefit of advanced sensors	Relevant sensing technology	Relevant sensing platforms	Timeframes
Condition monitoring	• Improved replacement planning based on actual condition rather than calculated risk • Enabling predictive maintenance • Improved location and nature of defects and faults (including blockages) • Informing use of in-pipe robotics for repairs	Acoustic Photonic Quantum	Fixed invasive and non-invasive Submersibles Robots Magnetic crawlers	Advanced sensors for condition monitoring are already available and have been trialled by Anglian Water. Future developments are likely to incrementally improve the accuracy and design of these sensors. The primary benefits of condition monitoring from advanced sensing can already be achieved with current technology. Quantum sensing could become available for condition monitoring in +15 years but is likely to be only used in specific situation as other technologies have failed. It will not likely become the primary method of condition monitoring.

Application	Benefit of advanced sensors	Relevant sensing technology	Relevant sensing platforms	Timeframes
Water and wastewater quality monitoring	• Optimisation of treatment process to ensure quality at the tap (reduce 'over treatment') • Location of contaminants/ pathogens entering the network	Biosensors Photonic	Fixed invasive and non-invasive	Biosensors for deployment in the network are likely to come after those to be used in the treatment works due to the additional requirements for working remotely. The first are likely to be seen in 5-10 years' time. Photonic sensors will follow a similar trend of being used in water treatment first then being developed for use in the network. However, photonic methods are further developed and could be expected closer to 5 years' time. The business case for enhanced monitoring of water quality in the network requires further development.
Event monitoring	• Better management of discharge from combined sewer overflows	Biosensors Photonic	Fixed invasive and non-invasive	Biosensors and photonic sensors for monitoring discharges could be commercial within 5-10 years. The development is likely to come in parallel with network water quality monitors but may be commercial sooner due to the clear business case around reducing sewer discharges.

Application	Benefit of advanced sensors	Relevant sensing technology	Relevant sensing platforms	Timeframes
Underground mapping	• More efficient on-site activities through reduced number of trial holes to locate asset • Improved on-site safety through knowing where gas pipes and electrical cables are • Improved accuracy of digital twins and network modelling	Quantum	Robots Portable instruments	Quantum gravity sensors are at a very early stage of development. However, great effort is being placed into ensuring they are developed in a way that allows them to be used in commercial products more quickly. Much of the development is specifically focused on detecting underground assets and so first-generation products would be suitable for use in the water industry. These products are likely to become available in 10-25 years' time

Key Impact Areas for the Water Industry

Table 23 outlines the key impacts of advanced sensors and sensors platforms on the water industry.

Table 23: Key impact areas for advanced sensing and sensor platforms

Category	Impact area description
Performance impact	Short Term (<5 years) there are large efficiency gains to be made through monitoring and control. Key benefits hinge around efficiency, compliance, and safety. • Sensors assist with compliance to regulation as data can be gathered in real time also saving labour in collecting samples. • An enabling technology for intelligent sewer technology, automatic and enhanced sampling of environmental water quality and smart water supply network (including automatic detection of potential leaks and asset condition information). These are all specifically called out in the Ofwat PR24 guidance on technology scenarios long-term delivery strategies [60]. • Drones can save time by being able to cover lots of ground quickly irrespective of terrain. Drones can provide rapid collection of up-to-date information helping to better inform decisions. Drones can access to dangerous and hard-to-reach places without putting people at risk, or significant cost Longer Term (>5 years) impacts will include widening of scope of automation; from automation of repetitive well-bounded tasks to machine autonomy whereby decisions and actions are automated. Biosensors will likely be used to monitor biofilms and biomass used in biological wastewater treatment (see 3.8 **Bioscience Solutions for Wastewater** Treatment) to improve their performance and robustness.

Category	Impact area description
Botex and Delivery Efficiency	• Accelerating the transition to predictive maintenance over reactive repair improves Botex efficiency. • The use of sensing platforms will increase Botex efficiency as it reduces the need for humans to go into environments which are difficult or dangerous to access. • Quantum sensing of underground assets reduces risks of damage to them during construction or repair. It may be possible in the future to use quantum sensing to understand asset condition to enable more informed decisions about when and if to dig. However, this depends on depth, volume and density of a particular anomaly. Determining whether it would be possible or not would require more information about a given scenario. • More information will lead to a more granular understanding of quality of water supply and quantity of water demand. Therefore, investment can be better targeted, making capital delivery schemes more efficient. • Improved visualisation during construction will be facilitated by sensor platforms such as drones.
Use for Operational Risk Mitigation, Resilience and Compliance	• Applications of biosensors in the short term include pathogen detection (e.g., Legionella) to map and automate responses to contamination [48][61]. This reduces risk of human harm. • Quantum sensing of underground assets reduces risks of damage to them during construction or repair. • Sensing platforms reduce the risk of human injury as it reduces the need for them to go into hazardous environments. • More comprehensive sensing decreases the risk of faults going undetected.
Cybersecurity Risks from the Technology	▪ Sensor platforms are at substantial risk of being attacked as they are exposed to the outside environment which means they could then be manipulated or damaged through the channels that they sense (e.g., shining a laser into a light sensor) ▪ Any subsequent processing (whether automated decision making based on thresholds or AI decision making) will also be affected with cascading impacts on the wider system. ▪ Sensors could also be compromised through the supply chain either through introduction of counterfeit parts which degrades performance, or with malicious hardware introduced.

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Category	Impact area description
Sustainability impact	• Where information from sensors is actioned to give an efficiency improvement, electricity usage can be reduced and waste minimised. • Sensors are normally low power. They are often battery powered as they may be physically far from a power source (e.g. a pipe underground cannot get mains or solar power). Sustainability of batteries is a key development area with new chemistries and even bio-alternatives to reduce use of unsustainable resources [62]. • Monitoring DNA in the environment can be a useful indicator of what species are present for use in biodiversity monitoring. Whilst biological methods for detecting environmental DNA (eDNA) are currently in large-scale use [63], and auto sampling approaches are being developed [64] samples are still processed manually. Advances in biosensors will enable continuous, real-time biodiversity monitoring which saves money, time and allows for more in-depth insights and patterns to be found in the data. This ultimately improves conservation efforts.
Impact on supply chain and partnerships	Advanced sensing enables easier and more granular communication with the supply chain and key partners such as the regulator and consumers. This helps to reinforce trust. Real-time monitoring of the network enables the supply chain to increase efficiency and reduce waste through predictive rather than reactive maintenance or diverting resources towards areas of high stress. The variety of real-time data enabled through sensors allows suppliers and other partners to get a better holistic picture of assets and operations, enabling them to better tailor solutions to the current situation, as well as predicting demand for future solutions.

Case studies highlighting the impact that advanced sensors and sensor platforms have had in the water sector and other industries are shown in Table 24.

Table 24 Case studies highlighting the impact of advanced sensors and sensors platforms

Case study	Detail	Benefit / findings
Leak detection: Satellite Radar, Asterra [65]	Asterra has been using radar images from satellites to identify underground leaks in the water network since 2017. Leaks in the wastewater network are hard to identify due to the nature of wastewater and how it flows in the network. Asterra have developed new algorithms that can be used on the same satellite image data to detect underground leaks in the wastewater network.	Over 10,000 water network leaks in the UK have been identified. Asterra is used by SES Water, Norther Ireland Water [66], South Staffs Water (2ML/day [67]) and others. Satellite data allows large areas of the network to be repeatedly inspected without any capital costs. Over the next 5 years this technology will become increasingly used for both water and wastewater leak detection.

Case study	Detail	Benefit / findings
Network water quality monitoring: Glucose and lactate sensors, IST [68]	IST have developed biosensors which are capable of continuous in-line or at-line monitoring of glucose and lactate in small-scale bioreactors. This type of sensor would be suitable for use in the water industry. Sensing parameters relevant to the water industry need to be developed and this is likely to happen in the 0–5-year time frame.	Data from the sensors allows the yield, quality and production rate of lab-grown meat and other bioprocess to be increased, through real-time process optimisation. Initial sensors are likely to be suitable for use in the treatment process, further development will be required for deployment in the network. Biosensors for network deployment could be ready in a 5–10-year time frame.
Underground mapping: Quantum gravity sensor, University of Birmingham [69]	Quantum gravity sensors are currently at proof-of-concept stage in all industries. Trials of quantum gravity sensors outside of the laboratory environment only began in 2022. The sensor developed by the University of Birmingham was the first in the world to be used in a real-word environment to detect an underground tunnel buried 1m deep. The sensor development partner RSK has been supporting with the aim of reducing the time to convert the prototype into a commercial product by influencing design from the start.	The sensor could become commercially available with 10-15 years. Initial use would likely be for critical and high-risk scenarios due to a high sensor cost and need to be operated by skilled engineers.

Technology timeline

Table 25 provides a timeline of the development of advanced sensors and sensor platforms over the next 25 years. Figure 8 (below the table) shows a visual representation of when sensor technologies are likely to be available for different parts of the water sector.

Table 25: Technology timeline for advanced sensing and sensor platforms

Timescale	Technology evolution and Water Industry Impact
In 0-5 Years…	**Technology evolution:** Advances in photonic and acoustic sensing are likely to happen via a series of incremental innovations, rather than the step change that we will likely see with quantum or biosensors. Beyond "line-of-sight" functionality for drones is likely to be available in the next 5 years. Electrochemical biosensors for detecting compounds in the water using enzymes that do not require any biological engineering will become commonplace. It is likely that electrochemical biosensors will be used for detecting pathogens such as E. coli and legionella in water [70], [71]. **Industry Impact:** The shift from more manual towards continuous, in-line monitoring using advanced sensing will enable a much better understanding of infrastructure functionality, wastewater content and the network in general. The insights it generates will start to be used to improve asset performance. Drones, pigging and submersibles will start to be used in constrained settings (e.g., not beyond visual line of sight) for detecting issues such as leaks and algal blooms. This will allow for more pro-active action.

Timescale	Technology evolution and Water Industry Impact
In 5-10 years…	**Technology evolution:** Biosensors that measure DNA and other molecules will likely be used to monitor public health through wastewater. This has already been tried for Covid-19 but will likely extend to other infectious diseases and indicators of public health such as concentration of drug compounds in the water. In the further future, we can imagine this health measurement operating at a household-to-household level to screen for serious health conditions such as cancer. Sensor platforms such as drones and robots will become autonomous, even beyond visual line of sight. Quantum gravity sensors may be integrated within practical instruments in the next 5-10 years, and start to be in pilot use in relevant environments [72]. **Industry Impact:** Public health data could be a new revenue stream for the water industry; however, care must be taken to respect data privacy in this use case. Autonomous sensor platforms will expand the use of sensors across the network, enabling a better coverage of the network as well as higher granularity in data. It will enable dynamic, real-time assessments of evolving situations such as floods. It will allow flexibility in the use of the most expensive and complex sensors, to automatically make decisions about where the monitoring would be most useful and act accordingly.
In 10-25 years…	**Technology evolution:** Quantum gravity sensors are likely to be commercialised and widely deployed in 10-15 years' time. **Industry Impact:** Quantum gravity sensors could give much better information about buried assets [49], [50] than ground penetrating radar. This assists with unlocking the potential of an underground digital twin alongside minimising risk of damage to assets when digging. In 10-25 years', time, advanced sensing will have transformed the water network in terms of efficiency and automation. Faults, leaks or contamination will be predicted or automatically detected as soon as they occur, and an action taken. Companies will monitor public health and may even take action on this through the personalised household health alerts or addition of nutrients to the water supply. Fleets of sensor platforms will be deployed during and after extreme weather events to dynamically monitor the supply of water and damage to infrastructure, enabling greater resilience to climate change.

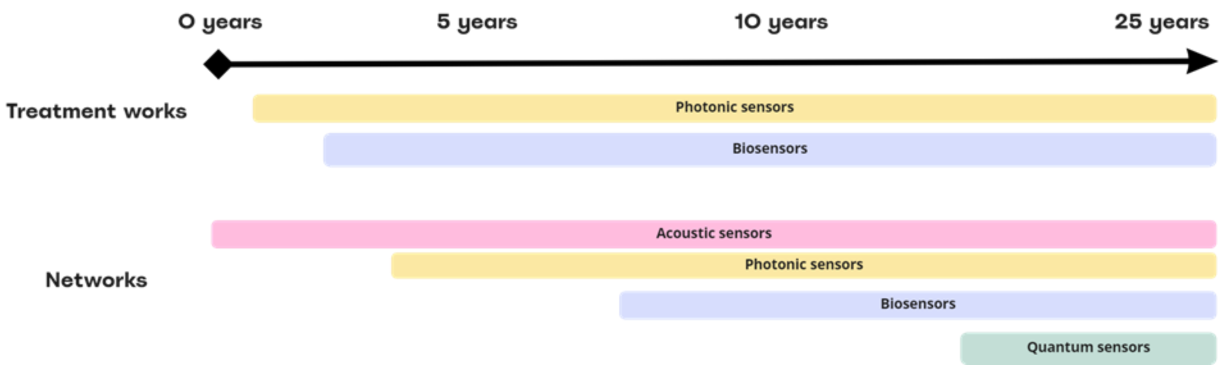

Figure 8 Timeline of commercial availability of advanced sensors for use in the water sector

Key: The colour denotes the specific sensor technology type (i.e. yellow = photonic sensor; blue =biosensor, pink=acoustic sensor, and green = quantum sensor)

3.5 Household and Consumer Technology

Key takeaway: It is predicted that without action to change behaviours as well as climate impact, UK customers and communities will be faced with longer and more frequent water restrictions between now and 2050 [73]. Reasons for shortages include climate change, increased population size, types of energy creation, land use and waste. Key targets are for water companies to reduce their leakage by 50%, and for individuals to reduce their consumption to 100 litres per day (down from the current level of ~140 litres per day) to balance out the risk of water scarcity by 2030 [73].

For domestic households to achieve significant water savings, they will need the support of new technologies within the home, to understand and control the amount of water used per day and enable conservation and recycling of water in the home where possible. Gamification can also be utilised to improve customer engagement and provide incentives for reducing water usage.

At the same time, water companies as well as consumers can achieve savings through early identification, notification and action to address leakage at domestic sites. Achieving this change will require broad adoption of new home and consumer technologies such as smart water meters, greywater reuse and other water conservation technologies, as well as corollary behavioural and service model changes by consumers and home appliance providers. The latter may shift to new business models (e.g., appliance-as-a-service, smart home platforms) which enable faster take-up of more environmentally friendly and/or connected home appliances (that could enable reduced water usage). Water companies can also play a more active role in promoting adoption of these technologies.

Overview

In the UK, the average household uses around 140 litres of water per head [74], every day. Most consumers do not realise how much water they use, with self-generated estimates generally falling between 50 and 100 litres per day, well below the actual figure.

A suite of water-saving products can help consumers save energy and water in the kitchen, bathroom, and garden. Household technologies that allow the customer to understand their water usage, and conserve water, are relevant for consideration here. These include smart water meters, technologies that enable rainwater and greywater harvesting, smart taps, water-efficient showerheads, greywater recycling, and dry toilets.

Anglian Water already provide consumers with water conservation enabling devices at home. As these evolve, we can expect to see significantly ‘smarter’ home and consumer tech enabling and automating domestic water conservation and reuse. But to gain maximum benefit from such technologies, and to drive uptake of them at scale, will require some time for wider commercialisation of connected home devices, and replacement of existing appliances. It will also be critical to drive behavioural change through education and engagement with consumers. As home devices become more connected, consumers will increasingly be able to monitor their own water usage and take action where needed. This connectivity can also deliver an improved user experience (e.g., through predictive maintenance alerts, leakage alerts, usage data trend analysis) which can feed into behavioural changes and more positive engagement with water companies.

Relevant Technologies

Purely mechanical water-saving appliances have not been included in this report (e.g., low-flow toilets, low-flow showerheads) as these technologies are not new. However, they are still likely to play an important role in promoting domestic water conservation in the UK in future years. It is expected that more of these devices will be Internet-connected and to form part of a connected home ecosystem (see Connected Smart Home Appliances discussion in Table 26).

Table 26: Relevant technologies for Household and Consumer Technology

Technology Category	Specific Technologies
Smart water meters	Smart water meters (SWMs) are connected digital meters that monitor how much water a household uses. These meters are provided and installed by the water company. SWMs read remotely, improving accuracy and timeliness of measurements, and minimising requirements for consumer self-reporting or water company meter reader visits. There are two main types of SWMs: Automated Meter Reading (AMR) meters and Advanced Metering Infrastructure (AMI) meters [75]. AMRs, which use older technology, enable meter reading remotely from a vehicle (or monitor) passing near the meter's location. AMR offers significant time and resource-saving benefits versus manual meter reading; for example, one vendor reported a utility customer in a small U.S. town was able to reduce its reading time from 30 hours a month to only three and a half hours [76]. AMIs transfer water consumption data to the water company's central data collection platform automatically and in general using wireless networks, e.g., public cellular or private radio networks. Flow data is collected in real-time and pulled on a periodic basis. AMI system components include the meter, a meter interface unit with wireless connectivity, other relevant sensors, and remotely controlled variables such as alert levels. The main benefits of smart meters regarding consumption reduction are: • Enabling detailed water usage data – identifying patterns and areas where conservation efforts can be focused. • Leak detection – abnormal usage patterns (such as a sudden water flow increase) can be quickly identified, allowing swift action to fix leaks and save significant amounts of water. • Implementing time-of-use pricing – encouraging users to shift their usage to off peak periods, or alerting if there is a current water shortage

<table>
<tr><th>Technology Category</th><th>Specific Technologies</th></tr>
<tr><td>Smart water meters – trials undertaken in industry</td><td>Several trials on the impact of smart water meters have been undertaken, 2 of which are showcased below.
In Sydney, Australia, a trial was undertaken with 1923 participants in 630 households. The trial examined the effects of the technology on the water consumption of an intervention group who were given a smart meter, compared with that of a matched control group with no smart meter. Smart metering was defined as the provision of near real time information enabling customers to understand and monitor their water use, and to assist Sydney Water in managing its network and providing better customer service [77].
Households with the smart meter reduced their consumption by 6.8% when compared to the control group.
A 3-year post trial period showed that consumption remained at 6.4% less than the control group – demonstrating potential long-term value of the technology.
As of 2021, Thames Water have installed 500,000 smart meters across London and Guildford in the UK [78].
This has enabled 28,000 leaks to be detected on customers' private supply pipes – saving 43 million litres of water a day
Smart meter customers use an average of 17% less water than those without a meter</td></tr>
<tr><td>Connected smart home appliances and measurement devices</td><td>Certain smart home devices that consumers can install themselves (or which are integrated with connected appliances) can provide water usage and other related monitoring information. These include connected washing machines, connected taps, connected showerheads, and connected toilets. This category also includes standalone consumer water/leakage monitors, as well as retrofitted water metering devices (e.g., Flume, etc), which can be used to add connected measurement functionality to non-connected water meters.

Smart home devices can be used to monitor and analyse water consumption and device functionality in real-time and can send usage or maintenance alerts. Leak alerts and detection are also a key domestic device use case, with functionality ranging from simple moisture level detection (e.g., for use in a potential damp or flooding area such as a basement) to more sophisticated monitors providing information on temperature, usage or even water pressure. Usually, the device can provide feedback to the consumer on water usage via a smartphone app which links to the connected household appliances; some can be connected to central smart home communications platforms such as Amazon's Alexa.

Such devices can also deliver predictive domestic usage data to water companies, although this requires integration with a common data platform, which is not straightforward given the current level of connected home technology market fragmentation. This has not been a focus of water companies to date, but as take-up grows, there is potential for this to become a valuable source of data for water companies in future.</td></tr>
</table>

Technology Category	Specific Technologies
Analytics AI/Machine learning	Can be applied to IoT data/smart water meter data to analyse and forecast water usage patterns for individual homes, neighbourhoods, different weather impact scenarios, etc.
Platforms + Cloud	Enable storage and processing of water consumption data and other relevant environmental data.

Rainwater Harvesting & Greywater Recycling	Greywater is wastewater generated from household activities, such as laundry and showering. By collecting and reusing this water for non-potable purposes (such as toilet flushing and non-crop irrigation), significant water savings can be achieved. In addition to conserving water, greywater recycling can also help to reduce the strain on municipal sewage systems and lower the cost of water treatment, as well as helping to improve water security in areas facing scarcity.
	
	Simple rainwater harvesting systems operate similarly. Reuse cases for such untreated water are very limited.
	
	More sophisticated systems apply filtering (e.g., sand filtering, microfiltration systems using membranes) and/or chemicals (e.g., chlorine) to treat water for broader reuse before pumping it to the reuse area (e.g., filling toilet cisterns, clothes washing), although it can never be recycled into potable water. Such systems can be expensive and complex to install, especially when retro fitted.
	
	New residential and commercial buildings can achieve significant water saving through greywater recycling. In the two examples identified below, this has resulted in 15 to 30% reduction of potable water consumption.
	
	• Kensington Residences (a new build housing development in London) utilised smart greywater recycling with SDS technology. This enabled water from baths and showers to be collected, pumped through a disk pre-filtration system, treated in a digitally controlled greywater system with chlorine, and then reused for toilet flushing [79].
	  ○ The results of this test showed that mains water demand was reduced by 15% to 90 litres per person per day.
	  ○ 3,000 litres of greywater were collected per day throughout the residential development
	• The Whitbread Hotel Group (UK wide) selected greywater recycling as a technique to reduce the Group’s water footprint and environmental impact across newly build hotels. It was estimated that the yield of greywater from showers and wash basins would equal the requirement for toilet flushing, helping to meet water reduction targets [80].
	  ○ 46 greywater recycling systems have been installed at new hotels between 2009 and 2017.
	  ○ Hotel potable water usage was reduced by 30%
	  ○ 113,635m^3 of water consumption savings were made through automatic meter readings and leak repairs
	  ○ 100% of toilet flushing requirements in new hotels comes from recycled greywater

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Trends

Error! Reference source not found. outlines the key trends that have the potential to impact or influence t he successful implementation of Household and Consumer Technology for water conservation and metering.

Table 27: Key trends for Household and Consumer Technology.

Category	Trend
Tech Maturity	Smart water meters are relatively mature and widely available, but have not reached full market penetration yet, lagging behind gas and electricity meters, largely due to fewer government mandates around water metering. However, the labour savings and improved accuracy and timeliness delivered by AMI water meters will be increasingly attractive to water companies, and providers such as Anglian Water are committing to significant roll-out targets. Consumers will see greater benefit once water meters can feed into automated alerts, and looking ahead, smart water meters should even be able to actuate control of domestic water systems if the consumer wishes. The addition of connected apps that measure and report on overall home water usage should also drive consumer interest. Interoperability with smart home platforms, and consistent wireless connectivity coverage, are also still not fully resolved; for example, getting a smart water meter to interact or share data with other smart home devices is likely to be complex or potentially not possible at present. Simple, mechanical household and consumer water usage measurement and water conservation devices (e.g., low-flow showerheads and cisterns) have been present in the market and available to consumers for many years, Digital and connected appliances in this space are newer, and at this point still have relatively low market penetration. In a study asking over a thousand participants whether they would accept a connected appliance in their residence if given a choice half of the respondents (47.3%) said they would accept (42.5% said maybe and 10.2% said no) [81]. Connected domestic appliances and home water and leakage monitors are going to see significantly greater take-up over the coming 10-15 years, although cost and long replacement cycles for major appliances are likely to be barriers in the short-to-medium term. There is also potential for data and connected devices to feed into gamification programmes that encourage consumers to reduce or better manage water usage. Such programmes have seen some success in drought-impacted regions such as the West Coast of the US and Australia. They are still relatively rare in other parts of the world, though interest is building in Europe due to growing mandates for sustainability. As climate change impact continues to grow, water companies and their application development partners are likely to continue developing more engaging and sophisticated approaches to gamification [82]. Through the use of smart meters, this can include: • Setting up challenges with friends / neighbours to see who can conserve the greatest volume of water in a time period. This may be achieved by using an app to connect to the smart meter, allowing users to track consumption and compare to others in their community on a leader board. • Providing rewards if users achieve a certain level of water reduction, such as a discount off of their water bill, similar to the recent national grid ESO trials.

Category	Trend
	• Sending notifications to users if they are approaching or exceeding their usage limits – which could be set up to be more engaging (such as remining them of their place on a leader board) to encourage action. Domestic water reuse systems (e.g., for greywater and rainwater harvesting), while commercially available, are currently expensive for home use, and thus are only likely to see significant take-up in areas with significant drought impact, for example agricultural areas. Looking ahead, for water companies, further value from householder and consumer technology will be realised via the collection and combination of data from multiple sources or sensors, enabling Open data initiatives (with appropriate anonymisation and consumer consent) should also enable water companies to share data with each other within the UK and potentially even across borders, enabling much more accurate modelling of demand and scenarios. The combination of data analytics and connected devices should also enable water companies to deliver an overall enhanced and more personalised customer experience to end users.
Technology Applications [83]	Household and consumer goods allow the user to conserve water and also cover a very wide range of use cases. Household and consumer goods applications that are most relevant for the water industry include: • Water usage monitoring (Conventional smart water meters and advanced smart meters) • Leakage detection • Water conservation and reuse • Improving water bill transparency and accuracy • Gamification around water management and usage for consumers • Enhanced and more personalised user experience • Enabling open data sharing for water information.

Category	Trend
Drivers for adoption	**Climate change and resultant water conditions:** As climate change progresses, drought conditions are likely to become more common in the UK, and both consumers and water companies are becoming increasingly aware of the importance of consumer actions and technically supported approaches to water conservation and reuse. Smart meters are particularly implicated in raising consumer awareness of water usage, although they are not yet required in the UK. Research from Arqiva and Waterwise [83] shows that smart water meters can drive increased consumer awareness and action when it comes to water conservation. **Water company consumer smart meter adoption initiatives**: Some UK water companies - e.g., Southern, Southeast, Thames and Affinity Water - have created compulsory meter programmes, which are helping to drive take-up of meters [84]. However, compulsory metering programmes are not the only way. Advanced deployers such as Anglian Water, who are working with Arqiva, have set ambitious deployment targets for roll-out without compulsory take-up programmes; AW intends to have 1.1M meters deployed by 2025, and aims to have them installed in 95% of customer homes by 2030. The main driver is meeting leakage reduction targets, but there is significant customer benefit that can be delivered as well.[34][34] **Insurance company initiatives:** Insurance companies lose a significant amount of money to water damage claims every year. Following the trend of incentivising consumers to adopt connected devices for monitoring health, driving behaviours and other areas of risk, some insurance companies (e.g., Chubb in the US) are starting to promote the use of water leakage and flood detection monitors in the home, and tying these to reduced insurance premiums. We expect to see this become part of the UK insurance landscape in future. Customers that use such devices could see insurance discounts of up to three percent for sensors and eight percent for active monitors capable of shutting off the pipeline [85]. **Building regulations**: UK building regulations (part G) [86] have been updated so that new homes must be built to a standard of 125 litres per person per day, with an optional standard of 110 litres per person per day in water stressed areas. This means architects and contractors need to make sure that any plumbing and appliance that enters a property is water efficient. **UK Water Sector Regulation and Framework:** The UK government published a 25-year environment plan in 2018, which sets out to reduce the amount of water people use and further reductions of leaks [87].

Category	Trend
Barriers to adoption	**Limited consumer awareness of the need for water conservation and role/availability of water conservation tech** Some of the main reasons people were not doing more to conserve water were [74]: • not perceiving a need to conserve, particularly for households on fixed water tariffs • having little or no feedback on their water use • lifestyle factors including cost, time and effort • questions over whose responsibility it is to identify and address leakages or to take action to conserve water **Resistance to deployment of smart water meters** • Uncertainty around impact on household water bills is a significant barrier to take-up of smart water meters. Given a significant proportion of UK houses are not water-metered at all but only pay fixed water charges (as recently as 2017 this was still the case for 50% of households [88]), there is often a perception that the installation of a meter of any kind is likely to lead to a higher water bill. Arqiva's recent survey found that the most common barrier to consumer uptake is the concern that household water bills could go up, with nearly 40% of consumers surveyed saying they would did not want a smart water meter for this reason [83]. Other barriers included not being offered a meter by their water company, and concerns about disruptive installation. **High up-front investment cost and disruption from installation** • This is a barrier for several potential water-saving technologies, including rainwater and grey water harvesting, and also, to a lesser extent, for more water-efficient smart appliances • Water reuse and recycling systems may be seen to have a poor rate of return on investment (and zero rate if not on a water meter) • There can be significant (and costly) disruption from installation in retrofitting water reuse systems in a domestic setting, including requirements to knock down walls and replumb pipes. **Concerns about ongoing reliability and maintenance of water reuse systems** • Consumers are likely to perceive risks related to how unproven the technology is • A further concern is potential for high ongoing maintenance costs due to the need to use specialist providers • Discomfort or perceived risk in using recycled water for home use in washing machines, showers, etc (reflecting concerns about how reliable the filter system would be).

Category	Trend
Cost	Cost to consumers is a significant factor impacting the take-up of some domestic water conservation technologies. The exception is smart water meters, where the cost is borne by the water company, and payback times can be calculated with a longer timescale and clearer benefit in mind in comparison to a consumer-purchased device. Even with water companies carrying meter costs, however, as noted above many consumers are concerned that the installation of such meters could lead to higher water bills. Measures such as water efficient shower heads are relatively low cost, but in many cases the consumer will not see a direct benefit (i.e., if they pay fixed charges). Connected water-efficient home appliances are available in the market but still very much high-end products. The focus of marketing around such products is heavily on energy efficiency rather than water efficiency – the majority of consumers are unlikely to be motivated to purchase purely on the basis on water savings. As sustainability becomes a greater imperative for consumer appliance manufacturers, more water-efficient appliances are likely to become the norm, but the timescale for technology commercialisation and new appliance adoption is longer-term rather than something that will impact short-to-medium term costs. On a larger scale, installing domestic rainwater harvesting and greywater Recycling will be very expensive, and there are few commercially active suppliers in the UK. Installation costs can also be an unknown variable. In the UK, the Aquaco Home greywater reuse system costs nearly £4,000 for a basic system, exclusive of installation costs [89].

Category	Trend
Examples from other industries / geographies	There are numerous examples of applications of demand-side water management technologies and tools in different parts of the world. Examples include: • Australia has implemented several broad and successful programmes to drive water conservation, which is critical given climate change challenges there. As well as widespread availability of ratings for water efficiency on domestic appliances, more than 25% of Australian households collect and store rainwater for domestic use. This is supported by a combination of domestic wastewater treatment systems, and integrated water management systems that relieves pressure on municipal supplies. Household reuse contributes around 177 billion litres to residential water supplies. Nearly half of Australia's domestic consumption is used outdoors, and cities restrict hosepipes and irrigation systems through voluntary measures. Cities with more restrictive measures such as Melbourne have used a combination of voluntary and non-voluntary measures including metering to reduce daily water consumption to just over 155 litres per person, vs the national average of 340 litres [90]. • In the US, a January 2022 study found that the use of AMI online portals to view meter information can play a valuable role in shifting consumer water usage behaviours, if consumers are approached 'at the right moment' and if the onboarding process is simple and seamless. Once adopted by a sufficiently large number of consumers, such portals can facilitate behavioural interventions to further promote conservation. US utilities have been able to make their AMI portals more engaging through the application of different behavioural science approaches [91]. • Analysis of 334 households in Valencia, Spain found that approximately 47% [92] of the households engaged in a water conservation programme promoted by smart meter-based consumption feedback and digital user engagement interventions changed their behaviours. The programme achieved a long-term 8% reduction of volumetric water consumption, compared with homes that were simply educated about water conservation.

Key Impact Areas for the Water Industry

Error! Reference source not found. outlines the key areas for the water industry that are likely to be impacted b y the successful implementation of Household and Consumer Technology.

Table 28: Key impact areas for Household and Consumer Technology

Category	Impact area description
Performance impact	Use of smart water meters and of water-efficient household and consumer goods can potentially deliver significant positive impact on water company efficiency and performance. By using advanced metering, water companies will gain a more accurate picture of usage and will be able to bill consumers more accurately as well as leveraging the data for planning. Domestic households will be able to understand the amount of water they use, and may change behaviours accordingly, although it is less clear how significant that impact will be. Impact could be enhanced with the use of gamification approaches and more significant impact could potentially come from wider adoption of domestic water reuse systems, or higher adoption of water-saving consumer appliances.
BOTEX and Delivery Efficiency	Use of household and consumer technology should deliver significant positive impact in this area. Smart meters connected household appliances and domestic water saving/leakage/flood monitoring devices will enable earlier alerts to problem areas, which can then be remedied more quickly, and they will also generally improve accurate data capture about consumer usage and behaviours. Ultimately this can inform future scenario modelling through digital twins, based on trending and modelling data harvested from across the IoT network. This will allow future capital allocation to fully reflect the optimised growth model. Benefits include deferred capital expenditures for system expansions for the utilities providing water, energy, and sewer services
Use for Operational Risk Mitigation, Resilience and Compliance	Installing household and consumer technology contributes to conserving water and energy and reducing wastewater flows. A critical compliance benefit is earlier and more accurate alerts to leakage issues; this will help water companies to meet Ofwat's leakage reduction targets more efficiently. Overall, if consumer tech can enable reduced water usage, this will also support the resilience of water company operations and their ability to deliver a good service to customers under changing conditions. Scenario modelling and digital twins, informed by the data collected, will allow testing of multiple risk situations and more effective mitigation planning; particularly critical as climate change impacts increase the need for water management scenario planning.
Cybersecurity Risks from the Technology	The installation of connected smart meters and more wireless connected consumer appliances could open households to higher risk of cyber-attacks if such devices are not appropriately protected (or if they are Wi-Fi-connected and the household Wi-Fi router is not secure). There is also the risk of such connected household devices being used as gateways to launch cyberattacks on the water providers operational and management systems. Depending on what is being monitored and how this data is transferred to and from household technology, consumer privacy could also be at risk, which could lead to potential issues with consumer safety (e.g., being able to monitor when someone is not at home).

Category	Impact area description
Sustainability impact	Installing water measurement, conservation and reuse household and consumer technology contributes to conserving water and energy and reducing wastewater flows. Sustainability benefits include a cleaner, higher-quality environment for all.
Impact on supply chain and partnerships	There is an opportunity to engage the smart metering and consumer appliance supply chains to jointly participate in cross sector collaboration to influence and shape policy and legislation, drive strategic and practical ambition in the water sector, run campaigns, and design and deliver consumer research. Network operators (Arqiva, UK cellular operators) will also be key partners going forward. In addition, there is a need to engage with the smart home platform ecosystem, to start work on integrating both smart meters and water-conserving home appliances with common smart home platforms and ecosystems. Further, there is an opportunity to engage with games developers and other specialist firms to develop compelling gamification propositions encouraging consumer behaviour change to conserve water.

Gamification has the potential to be a beneficial tool to reduce water usage. Smart meters can be valuable, as there are several ways that they can be utilised to provide a gamification experience. Table 29 shows some examples of the use of smart water meters including gamification and the impact on consumer water consumption.

Table 29 Case studies of Gamification using smart meters to reduce domestic water consumption

Case study	Detail	Benefit / findings
PUB – Singapore's National Water Agency [93]	PUB's aim was to gain a deeper understanding of household water usage patterns and what can motivate water saving behaviour. This included a Smart Shower Programme and an Advanced Metering Infrastructure (AMI) WaterGoWhere project. Smart meters were given to 525 residential households for a 6-month trial period. As part of this, a gamified mobile application (WaterGoWhere) was included to increase awareness on water consumption and improve engagement of the participants. The gamification allowed for competition between users and rewards such as points, status, and prizes, with the winner receiving a prize at the end of the trial. The app provided information on leaks, usage monitoring, and daily/weekly/monthly challenges to help them reduce their consumption. This information was also provided to PUB – allowing them to customise engagement strategies to aid conservation, as well as receive maintenance and operational information.	• 34% of participating households viewed their usage and participated in a challenge at least once per week • The app algorithm detected peak periods of consumption, then sending high consumption alarms or challenges at specific times throughout the day or week. • 6.9L of water per capita per day were saved, equating to 5% of usage. • Leak alerts enabled users to reduce the time taken to become aware of a leak and report this or fix it themselves/

Case study	Detail	Benefit / findings
SmartH2O gamification [94]	SmartH2O software implemented a feedback cycle between the water consumers and the utility provider. The consumer was provided with real time data on their usage. This also allowed the utility provider to implement strategies to reduce water consumption based on the usage patterns. The SmartH2O platform used a gamification style with the goal of motivating users to edit their water saving behaviour by using different incentives, such as a leader board to encourage competition and collect points, increased awareness of consumption and social norm.	Tessin, Switzerland, users reported a 10% reduction in water usage compared to their previous, unmetered readings. Valencia, Spain, users (~400,000 households) reported a 20% reduction in water usage.

Technology timeline

Error! Reference source not found. outlines the potential timeline for technology implementation for H ousehold and Consumer Technology.

Table 30: Technology timeline for Household and Consumer Technology

Timescale	Technology Evolution and Water Industry Impact
In 0-5 Years…	**Technology evolution:** Domestic water technology will be more widely adopted across households, with AMI smart water metering technology being deployed alongside conventional water saving devices (that may or may not communicate with the smart metering technology). **Industry Impact:** The water industry will play the leading role in smart meter adoption, through more widespread metering rollout programmes, and will need to widely promote and help consumers implement simple water conservation tech at home. Partnerships with organisations promoting water conservation such as Waterwise will play an important role. The industry will also need to engage the supply chain (including metering providers, smart home ecosystem providers, home appliance manufacturers) to come up with innovative technology developments. Policy and frameworks from government/Ofwat, promoting sustainability and leakage targets, will also drive this adoption. At least 60-75% of UK homes will have smart water meters by the end of the period.

Timescale	Technology Evolution and Water Industry Impact
In 5-10 years…	**Technology evolution:** Wider commercialisation of smart home water tech, as well as increased interest in sustainability and ongoing cost savings, will drive higher adoption of water-efficient home appliances by consumers. Many of these will be Internet-connected and able to share data with smart water meters (and other smart home devices) via a common platform, presenting app-based visualisation of usage, leak identification, flood risk, and costs to the consumer. 'Water Smart' homes will experience rapid innovation meaning consumers can now reduce their water consumption, get real-time data on water quality and better safeguard their properties from sudden leaks and unexpected burst pipes. **Industry Impact:** Consumer appliance companies as well as water companies will be the driving force behind this, with data pulled from smart meters and (with consent) consumer devices to inform research and development, customer interactions, scenario planning etc. In addition, ongoing climate change impact will be an important driver, as consumers themselves look to save water (as well as saving money). Some impact on sustainability and domestic water usage reduction will be seen.
In 10-25 years…	**Technology evolution**: Smart water meters evolve into control units, with two-way data flow and automated control of water flow to/from home appliances, acting as hubs to automatically action water savings, working together with connected appliances, leak monitors, etc. Water saving devices become the norm within UK homes, with potential for water reuse systems to become a standard feature of new-build homes, and much greater acceptance of reuse systems retrofitted in existing properties. Consumers will be able to see and understand the cross-impact between water and energy usage at home and adjusting timings of usage to ensure minimum cost will become standard practice. Water companies will be able to deliver more personalised customer service and interactions, supported by improved customer data and visibility. At the community level, we could see the development of 'Smart Water Communities' that approach water conservation as a holistic community practice, using Integrated Water Management (IWM) to combine infrastructure, technologies, policies, and behaviour change initiatives to improve lives through co-ordinated water management. **Industry Impact:** Water companies will need to be cognizant of changing consumer behaviours and service expectations and use customer data sensitively and appropriately to support improved customer service. Open data platforms that allow sharing of anonymised customer data more broadly could become powerful tools to understand and model usage, shortages and various scenarios. Water companies will need to play a central role in rethinking how their assets could support innovative new customer-led and community-led stewardship models, challenge regulatory and policy standards to support stakeholders by understanding stakeholder motivations.

3.6 Renewable Energy Systems

Key takeaway: Renewable energy technologies and alternative methods of energy usage will need to be adopted if AW are to meet their target to reach net-zero by 2030. The water industry is intertwined with renewables in two ways: both as a major consumer of energy, and as a significant energy producer. Anaerobic digestion for onsite combined heat and power, distributed energy and microgrids, and the growing hydrogen industry will be major factors shaping the future of the AW business and the way assets are utilised. With renewable energy becoming more accessible and affordable, the water industry needs to evaluate supply chains for ways to switch to renewables to start realising the benefits as soon as possible. Legislation, funding mechanisms and planning processes will also continue to be critical factors in the development and adoption of renewable energy in the water sector, so keeping a close eye on these and working in close partnership with stakeholders will be key.

Overview

The water industry consumes up to 3% of total energy used in the UK and, like other energy intensive industries, has an opportunity to exploit renewable energy for sustainability and commercial benefits [96]. The industry obtains 8.5% of its energy from self-generated renewable energy generation. Ofwat is taking steps to include renewable energy generation in its business requirements for the sector. Generation levels are required to be reported from the PR09 period forward. The following sections give an overview of the key renewable energy technologies and the impact, opportunities, and challenges they present for the water industry; sources include reports from Ofwat, EA, top-tier consulting firms and inputs from SMEs.

AW aims to deliver 44% of power from renewable sources by 2025 and then 80% by 2030. At the end of AMP 6, renewables provided 20% of their power.

The UK water industry will need to move toward greater and greater use of self-generated power. Energy generated through sludge combustion and digestion, and hydrogen energy generated through water electro-hydrolysis are the most directly relevant forms of renewable energy. In addition, microgrids powered by other forms of renewable energy such as wind and solar will have significant impact to the carbon footprint.

The main relevant approaches to renewable energy generation are anaerobic digestion of sewage; distributed energy technologies and microgrids; and hydrogen.

Anaerobic Digestion of Sewage

Anaerobic digestion is currently the most common way of utilising renewable energy within the water industry. Over 90% of current renewable energy generation in the water industry is through sludge combustion and digestion [97]. Biogas is generated during anaerobic digestion (AD) when microorganisms break down organic materials in the absence of air (or oxygen). AD of biomass and waste methane can be pressurised and filtered as a low-BTU natural gas to produce electric power and heat. Over 600 wastewater facilities utilise their waste gas for energy.

While AD is an established technology in wastewater treatment and already widely used in the UK, there are still avenues of further opportunity, including anaerobic digestion with co-digestion, and anaerobic gas export. In the latter case, the biogas produced from AD can be processed to create synthetic gas that can be exported to and distributed via local gas networks. Germany, Sweden, Switzerland, and the Netherlands have all practised the injection of processed biogas into local gas networks. In the UK, biogas has only been successfully injected into local gas networks at low pressures. Injection into the main grid would incur complications of higher pressures and hence increased risk, but may become feasible over time.

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Distributed Energy Technologies and Microgrids

Having the ability to operate independently of the centralised energy grid is crucial to achieving long-term energy resiliency for the water industry. Microgrids, which have distributed energy resources within clearly defined electrical boundaries, enable the facility to operate as an autonomous energy island.

Opportunities for wind and hydroelectric power are already likely exploited within the water industry and so further benefits may be relatively marginal [98]. Geographic and topographic features can affect wind and hydropower availability, as well as onerous planning permission requirements, due to local features such as sites of special scientific interest or high population density. For instance, Anglian Water has a relatively flat topography which makes it hard to exploit hydropower. However, there are opportunities to explore areas where Anglian Water can install more wind turbines as well as large solar arrays. Floating offshore wind also offers new opportunities and alternatives.

Hydrogen

Hydrogen energy is strategically important for both the UK and EU (and other major global economics) and has attracted substantial policy support, despite the net decarbonisation benefits still not being clear cut. A future hydrogen economy could also have an impact on the water industry. Water UK's Net Zero 2030 Roadmap concluded that "if hydrogen emerges as an alternative fuel, then water demand would increase 15-20%". This raises significant issues for the sector.

Wastewater streams could also become valuable as an alternative hydrogen production method. In 2021, using a recycled carbon-fibre material, University of Warwick researchers successfully produced hydrogen from wastewater for Severn Trent that could be used to power electric vehicles [99].

Significant challenges remain in the scaling of green hydrogen production (which is produced using renewable energy), and blue/grey hydrogen related carbon capture and storage (CCS) (grey hydrogen is derived from natural gas, and blue hydrogen is the combination of this with CCS). Nevertheless, with the huge policy support for electro-hydrolysis-based hydrogen generation, water companies need to consider the impact of hydrogen production for the industry.

Table 31 outlines the relevant technologies and sub-categories that are considered important in the successful implementation of renewable energy systems, along with a brief description.

Table 31: Relevant technologies for renewable energy systems

Technology category	Specific technologies
Microgrids (solar, wind, biogas etc)	• Specific technologies: solar panels, wind turbines, CHP, Supervisory Control and Data Acquisition (SCADA), sensors, controllers, Switchgears, inverters. • Microgrids increasingly employ a mixture of different distributed energy resources, including photovoltaic solar, wind turbines and biogas, which in addition to being renewable, significantly reduce carbon emissions. Microgrids can operate independently of the centralised grid, thus their use strengthens grid resilience and helps mitigate grid disturbances. Microgrids remain connected to the centralized grid. Battery banks store energy from the grid or from on-site renewable sources such as solar and wind that generate power only during certain times of the day. • Photovoltaic (PV) solar panels, a key component of solar power microgrids, these panels absorb sunlight to generate electricity. They can be installed in a variety of ways at water/wastewater utilities including ground mount, canopy, rooftop systems and floating solar where solar panels on a floating structure are installed on lagoons and reservoirs. An issue with solar panels is that current PV efficiency has reached its limit, and further panel deployment is often hampered by land use constraints. An emerging solution may be bifacial solar plants, which harvest light reflected from the ground via the Albedo effect to increase efficiency by 9% and generate up to 40% more power when combined with tracking systems [100]. In 2016, Lightsource Renewable Energy successfully completed construction of Europe's largest floating solar farm, installing 6.3MW on the Queen Elizabeth II Reservoir, near London. The solar farm is currently supplying green, renewable solar electricity to Thames Water via a Power Purchase Agreement (PPA), satisfying around 20% of its energy needs. • Wind power is also a key input to microgrids. The most interesting new technology area here is floating offshore wind – rather than wind turbines fixed in one position (whether on land or on the coast), floating offshore wind places wind turbines in larger and deeper offshore areas with higher wind potential, with the wind turbine installed on platforms anchored to the seabed by means of flexible anchors, chains or steel cables. Floating offshore wind is applicable in all areas with a coastline regardless of seashore profile, and thus could present interesting opportunities for Anglian Water and for the broader UK water industry.
Energy Storage and Fuel Cells	• Specific technologies: lithium-ion batteries, battery management system, power conversion system, hybrid inverter, energy management systems. • Battery banks store energy from the grid or from on-site renewable sources such as solar and wind that generate power only during certain times of the day. • Fuel cells convert energy from natural gas, biogas, or hydrogen into electricity through a chemical reaction.

Technology category	Specific technologies
Anaerobic Digestion	• Specific technologies: heat exchangers, digester tanks (steel or concrete) with insulation/cladding, double membrane biogas collection domes, biogas dome lightning protection, digester heating systems, digester mixing systems, biogas conditioning equipment, digestate removal pumps, fully automated control panels with remote access, site cabling/instrumentation. • Anaerobic digestion is a key means of producing biogas for use as a renewable energy source by water companies. Anaerobic digestion of biomass and waste methane can be pressurised and filtered as a low-BTU natural gas to produce electric power and heat. • This can be further augmented by introducing anaerobic digestion with co-digestion (anaerobic digestion of more than one waste stream). The process is identical to conventional anaerobic digestion and the biogas produced can be burned to generate heat and electricity. The sludge stream from wastewater treatment could be mixed with any biological waste from domestic or industrial sources. The co-fuel could include food waste, paper, or any other high liquid content waste mix.
Hydrogen	• Specific technologies: storage tankers, pumps, pipelines, electrolyser. • Water companies are sitting on a wealth of hydrogen in the form of ammonia in their wastewater streams, which could be used for hydrogen production through catalytic cracking. High level estimates suggest at least 18,000 tonnes of hydrogen could be produced via this method each year and the potential could be double this [101]. • Water and Sewerage Companies (WASCs) can deliver hydrogen production through the electrolysis of water using renewable electricity. Other potential pathways by which WASCs could create hydrogen include: ✓ Pathway 1: Final Effluent (FE) - using FE as a non-potable source of water for electrolysis. ✓ Pathway 2: Ammonia (NH3) - stripping NH_3 from sludge liquors and converting it into hydrogen, e.g., by electrolysis or thermal cracking technologies. ✓ Pathway 3: Advanced Thermal Treatment (ATT) - separation of pure hydrogen from the syngas generated by gasification or pyrolysis of raw sludge or treated biosolids. ✓ Pathway 4: Steam Biogas Reformation (SBR) - separation of pure hydrogen from the syngas generated by direct conversion of methane in raw biogas (from anaerobic digestion of sludge). ✓ Pathway 5: Steam Methane Reformation (SMR) - separation of pure hydrogen from the syngas generated by conversion of methane in biomethane upgraded from biogas (from anaerobic digestion of sludge • In 2021, using a recycled carbon-fibre material, University of Warwick researchers successfully produced hydrogen from wastewater for Severn Trent that could be used to power electric vehicles [99].

Trends

Table 32 outlines the key trends that have the potential to impact or influence the successful implementation of renewable energy systems.

Table 32: Key trends for renewable energy systems

Category	Trend
Tech Maturity	• AD, solar and wind are well-established renewable energy technologies (TRL 9) that already makes a significant contribution to worlds energy supply. • Bifacial solar, floating wind technologies (TRL 8) and more innovative ways to generate biogas from AD are promising new technologies. • Significant challenges remain in the scaling of green hydrogen production (which is produced using renewable energy and is currently at TRL 6-7), and blue/grey hydrogen related carbon capture and storage (CCS) (grey hydrogen is derived from natural gas, and blue hydrogen is the combination of this with CCS; TRL 8-9) [102]. Nevertheless, with the huge policy support for electro-hydrolysis-based hydrogen generation, water companies need to consider the impact of hydrogen production for the industry.
Technology Applications	Renewable energy technologies have several key applications in the water industry: • Production of renewable energy for use in own operations • Production of renewable energy for 'export' to the grid or gas network, or directly to other energy users • Cost-effective reuse of waste products. For example, Combined Heat and Power (CHP) is a technology that allows the simultaneous generation of electricity and heat from a source such as biogas, natural gas, or co-mingled gas. CHP is particularly attractive at wastewater treatment plants with anaerobic digesters, which produce biogas as a waste product. • Meeting compliance targets through processing of sludge/wastewater into renewable energy sources • Ability to leverage own land or other assets more effectively. For example, solar panels can be installed in a variety of ways at water/wastewater utilities including ground mount, canopy, rooftop systems and on water surfaces where solar panels on a floating structure are installed on lagoons and reservoirs. Wind turbines can be installed at utilities' sites. The trend is towards floating offshore wind which is based on floating structures rather than fixed structures.
Drivers for adoption	• Renewable energy technologies considered in this report can be localised at the water plants which improve overall resilience. A power failure in the water industry can lead to unintended ill consequences in other parts of the ecosystem. For instance, if water pumps fail, untreated sewage can be discharged into rivers and streams. This can also cause sewage backups in homes and businesses. Power losses also impact industrial customers that rely on wastewater treatment to keep their operations safe. • While renewable energy technologies have generally relatively high upfront costs, they incur less operational and maintenance costs than fossil fuel-based energy technologies. • Emissions at source is zero for renewable energy technologies.

Category	Trend
Barriers to adoption	• In general, costs are likely to be the main barrier to use of some renewable energy technologies, particularly those that would only be available beyond the next 5 years, given that up-front investment requirements for such areas could be significant and would be unlikely to see quick payback. Water companies are most likely to focus on nearer-term more commercialised technologies to reach net zero goals in the short term. • There are limitations on funding for process-related sources like solar, wind and river hydropower. • Regulation and actual feasibility are restricting factors for some future technologies. E.g., for microgrids, there are barriers relating to UK land use restrictions, as well as feasibility constraints from a geographic perspective (e.g., hills, coastline characteristics etc) • Regulation is a barrier to development and adoption of co-digestion in the UK. While there are many examples of AD with co-digestion globally, the major limiting factor in the UK is legislative restrictions on mixed waste systems. There is currently one trial in Scotland (Nigg WWTW) with distillery waste. There is significant opportunity to drive innovation in this area through new policy to simplify the process of planning, consenting, and operating a co-digestion site. Collaboration will then be required with the wider waste industry. • In addition, the UK has regulations on sludge disposal (needed for o-digestion) which would require addressing to allow this technology to be implemented. Co-digestion technology requires additional preparation of feedstocks through repackaging and maceration and may require sterilisation of the digestate produced. • For hydrogen, barriers include significant uncertainty around scale, resources used (e.g., renewables or fossil gas with carbon capture and storage), and timelines (to produce hydrogen, its distribution and end-use). • Planning and operational difficulties can be encountered through waste legislation that prevents digestion of non-sewage waste, as well as stringent requirements for biofuels and grid access issues for energy export. • Availability of land for sludge processing is an issue
Cost	• Distributed energy technologies have relatively high upfront cost, but they have proven to result in financial and operational resilience. • Payback is related to the cost of grid electricity and natural gas • Looking specifically at hydrogen, a price range of £2-5/kg would allow hydrogen to compete with alternatives [103]. Current projection is that green hydrogen product cost will drop to ~ £2 per kg by 2030 [104]
Examples from other industries / geographies	• CHP has been used in over 4,700 facilities (e.g., office buildings, hospitals, district heating systems and wastewater treating facilities) in the US [105]. • Biogas generated during wastewater sludge treatment has been widely used in the UK for electricity generation. In 2020, there were 194 sites engaged in this activity, compared to 164 in 2007 [106].

Key Impact Areas for the Water Industry

Table 33 outlines the key areas that are likely to be impacted by the successful implementation of renewable energy systems.

Table 33: Key impact areas for renewable energy streams

Category	Impact area description
Performance impact	• Renewable energy technologies reduce the industry's reliance on imported natural gas, which is prone to supply disruptions and cost shocks. • The role of renewable energy solutions in mitigating climate change is proven and thus contributes positively to long-term business continuity compared to fossil-fuel based alternatives. • Large weather incidents could however potentially impact operational resilience.
BOTEX and Delivery Efficiency	• Renewable energy facilities can typically be deployed relatively quickly. While solar and onshore wind farms normally take less than two years to build, gas-fired power plants can take as many as four years to become operational and can also require construction of gas pipelines [107]. • While renewable energy systems have relatively high up-front CAPEX costs, they follow 'learning curves', which means that with each doubling of the cumulative installed capacity, their price declines by approximately the same fraction. • Initial capex plus ongoing maintenance of a new renewable's asset is offset by the reduction in the (Opex) cost of buying energy from the grid. Ongoing operational costs for renewable energy systems also tend to be relatively low. Return on investment varies by asset size and complexity. It is also impacted by the availability of Feed-in Tariffs. • CHP engines have been proven to offer an organisation energy cost savings of up to 40%, with a potential payback period of 1 to 3 years. With blended hydrogen available, on-site generation is likely to be a future-proof choice [108].
Use for Operational Risk Mitigation, Resilience and Compliance	• Microgrids and the use of bio-resources to produce electricity and gas increases site energy resilience and reduces exposure to geopolitical risks and subsequent gas price fluctuations. • Distributed energy assets are also proven to bring increased financial and operational resilience. • Biogas injection into the grid needs to comply with strict quality control standards otherwise it will be rejected as waste.

Category	Impact area description
Cybersecurity Risks from the Technology	The rapid transition towards renewable energy could lead to additional avenues for cyber criminals to exploit: • Distributed energy technologies currently don't have any cybersecurity standards to follow as devices and mechanisms are usually heterogeneous, proprietary and may also contain legacy elements. • There may also be loose or improper segmentation of the OT networks that these distributed energy resources may be connected to, and networks that are connected to the Internet which opens additional avenues of attack. • Threat intelligence, monitoring and ensuring a strategy for periodic updates over the lifetime of distributed energy resources (such as security patches) will be a key element of risk management. • It will also be critical to create (and adhere to) cybersecurity standards and best practices for identifying assets, incident response and recovery in conjunction with other stakeholders.
Sustainability impact	• Renewables generate more energy than is used in their production, and produce fewer emissions than other power sources over their lifetime [107]. • Renewable energy sources typically emit about 50g or less of CO_2 emissions per kWh over their lifetime, compared to about 1000 g CO_2/kWh for coal and 475 g CO_2/kWh for natural gas.
Impact on supply chain and partnerships	**Possible areas of partnerships include:** • There are avenues for water companies to partner with energy companies, energy tech specialists and demand response aggregators to scale the adoption of microgrids, while decarbonising the grid and lowering the costs of grid capacity upgrades through balancing demand and supply (e.g., turning renewable energy assets up and down when grid capacity is lower/higher than demand). **Potential positive impacts on supply chain include:** • Avoid risks of fossil fuel price fluctuations and regulatory changes. • Attract partners interested in corporate responsibility. **Potential negative impacts on supply chain include:** • One potential supply chain impact will be on lithium-ion batteries for energy storage in microgrid systems, as the component elements will also be required for batteries used in EVs. There are emerging storage technologies that have the potential to address current storage constraint issues with lithium-ion batteries, which may help mitigate some of the supply chain risk (as fewer such batteries could be needed).

Technology timeline

Table 34 outlines the potential timeline for technology implementation for renewable energy systems.

Table 34: Technology timeline for renewable energy systems

Timescale	Technology evolution and Water Industry Impact
In 0-5 Years…	**Technology evolution**: Most anaerobic digestion systems are currently sludge combustion and digestion. Onsite solar to meet onsite energy demands (also called behind the meter) and wind technologies are well established, but more uptake is likely to be driven by 'sleeving' (process whereby an electricity supplier acts as an agent on behalf of the buyer to manage the offtake from a generator's asset, and provides for the electricity to be included in a wider supply contract) and cPPAs (long-term contracts under which a business agrees to purchase electricity directly from an energy generator). While hydropower has been exploited, micro hydropower, wave and tidal power generation should also be explored. These can be efficient energy sources that only require a small amount of flow to generate electricity. **Industry Impact**: With more innovative AD technologies, the water industry would be able to export biogas into the grid and support more widely decarbonisation of grid and downstream activities. Water industries will need to foster new partnerships and overcome regulatory barriers for co-digestion. Exploitation of tidal and wave power could help the water industry to capitalise on untapped renewable resources whilst simultaneously preventing coastal flooding.
In 5-10 years…	**Technology evolution:** The efficiency of solar and wind turbines will improve with new materials and flexible structures to capture more renewable resources. The cost of these technologies will also decrease considerably. PV modules have experienced learning rates of 18% to 22% and module prices have fallen by around 80% since 2010 [109]. Green hydrogen is also expected to take a more prominent role in the energy mix as production cost is projected to drop to ~2 USD per kg in the UK which will likely increase demand [110]. Green hydrogen can be used to power on-site heavy good vehicles (HGVs). On a 5-year horizon, AD will evolve to include more co-digestion processes, paired with fuel cells and gas export to the grid. **Industry Impact:** A greater uptake of renewable energy will be instrumental in reaching the water industry's Net Zero goals. Fossil-fuel based, and nuclear technologies consume relatively significant volumes of fresh water even if some power plants discharge some or all that water back into the local basin, lessening their impact on water availability. While hydrogen production will also affect water demand and water stressed regions should be avoided for hydrogen production, the industry can capitalise on novel hydrogen technologies that use waste streams as their input. By 2030, it will be imperative for water companies like AW to develop a strategy for how they can best play a part in a future UK hydrogen economy.

Timescale	Technology evolution and Water Industry Impact
In 10-25 years…	**Technology evolution:** Microgrids will be more sophisticated and used in combination with enabling technologies such as Artificial Intelligence (AI) and machine-learning features. These will allow modern energy management software to better learn how to anticipate load from the demand on the microgrid, and take into account generation from renewable assets; thus, optimising the system to operate in the most cost-effective way. The technology will also involve in 10-25 years to include more hydrogen injection into the grid. **Industry Impact:** Through better connectivity and more intelligent management, the use of renewables will be maximised whilst maintaining the reliability of equipment and the microgrid system. Matching of supply of electricity to demand will be automated by energy management software, within the parameters specified by the owner of the microgrid.

3.7 Scaling Nature-Based Solutions

Key Takeaway: Nature-Based Solutions (NbS) refers to a suite of actions or policies that harness the power of nature to address some of our most pressing societal challenges, including climate change, food and water insecurity, disaster impacts, and threats to human health and well-being, while reducing environmental degradation and biodiversity loss. There is a need for technology to help scale NbS, to maximise their impact and effectively combine such solutions with other strategies, such as engineered ('grey') measures for climate change adaptation, and decarbonisation for climate change mitigation. There is also a clear need for more and better-quality data on NbS, their impacts, and value-chains. Ways forward include harnessing advances in and data from sensors, drones, (IoT) devices and Geographic Information Systems (GIS), to better understand where NbS should be prioritised, positioned, and scaled to derive maximum benefit.

Overview

As defined by the IUCN [111], NbS is an umbrella term that refers to a suite of actions or policies that harness the power of nature to address some of our most pressing societal challenges, such as water insecurity, rising risk of disasters such as flooding, and mitigating against the effects of climate change. Nature-based solutions involve protecting, restoring, and sustainably managing ecosystems in ways that increase their resiliency and ability to address those societal challenges, while also safeguarding biodiversity and improving human wellbeing.

Ofwat expects water companies to adopt more Nature-based Solutions (NbS) approaches and to develop game-changing innovations to drive up performance. For the water industry, examples of NbS include:

- Improving aquatic terrestrial habitats through restoration
- Re-wetting peatlands and constructing wetlands to reduce flood risk
- Rethinking urban design to incorporate green infrastructure through Sustainable Urban Drainage (SuDS)
- Changing existing agricultural practices to integrate sustainable practices and conservation.

Anglian Water has made commitments to integrate NbS at the heart of their AMP8 strategy through the Green Recovery, in response to the Government's 25-Year Environment Plan [87] and the embedding of Six Capitals [112] into decision-making.

Current approaches to operating and monitoring assets have hampered efforts to realise the true potential of NbS. For example, carbon sequestration and storage are an ecosystem service that can be measured and tracked with reasonable precision and scale. But limitations in ability (or will) to measure other related important benefits have led to carbon often being used as a proxy for the many biodiversity, ecosystem and community co-benefits that come with, for example, a carbon-dense tropical forest, such as water quality and increased biodiversity.

There is a need to start structuring and broadening existing knowledge through sharing data between sectors and regulators. A regulatory push is also required to start building consensus on guidelines, standards, and frameworks; these can help to address the lack of knowledge and transparency which is a barrier to investment.

Identifying appropriate metrics to quantify the social-ecological benefits and effectiveness of NbS will be key for its successful adoption. Defining such metrics (e.g., reducing the impact of floods arising through increased precipitation) are often challenging due to complex and evolving factors that impact the effectiveness of NbS. There are concerns over NbS reliability and cost-effectiveness compared to engineered alternatives, and also concerns over which types of solutions provide greatest resilience to climate change. Emerging evidence suggests that NbS provide low-cost solutions to many climate change-related impacts, and offer key advantages over engineered solutions. Many of these observations are increasingly backed up by research where technology is being used to scale and monitor NbS.

Relevant Technologies

NbS refers to a collection of approaches, and there is no standalone method to monitor the performance of NbS in its broadest view. The technologies explored in Table 35 are most critical to the scaling up and monitoring of NbS.

Table 35 Relevant technologies for NbS

Technology category	Specific technologies
Advanced Sensing	Gauging stations, wireless sensor network, topographic LiDAR, multispectral and radar sensors. See **3.4 Advanced Sensing and Sensor** Platforms for further details
Digital Twin	Modelling and monitoring NbS performance. See Error! Reference s ource not found. for further details
Artificial Intelligence and Machine Learning	AI algorithms and software, Machine Learning systems, Open source data and algorithms, IoT sensors and solutions. See Error! Reference s ource not found..
Nature based carbon capture technology	Carbon capture at source at sludge treatment centre, carbon sequestration through regenerative agriculture and wetland/peatland management
Drone/robot	Remote monitoring using satellites and robotic maintenance.
Synthetic biology	Synthetic biology could be utilised within nature-based solutions to optimise their favourable characteristics. For example, reed beds could be engineered to be smaller, with the same performance to increase the scale of their household usage. Constructed wetlands could be engineered to remove a wider variety of pollutants so that fewer supporting treatment techniques are required, thus saving energy. For trends, barriers and costs of synthetic biology technologies, see **3.8 Bioscience Solutions for Wastewater** Treatment Specific Technologies: DNA sequencing (e.g. Sanger), DNA copying (e.g. polymerase chain reaction PCR), DNA editing (Crispr-Cas-9), bio-informatics, high-throughput sequencing, artificial intelligence, cell culture.

Trends

Table 36 outlines the key trends that have the potential to impact or influence the successful implementation of Scaling Nature-based Solutions.

Table 36: Key trends for Scaling Nature-based Solutions

Category	Trend
Technology Maturity	NbS is a concept that has been introduced in the past two decades to strengthen the role of nature-based approaches to solving environmental challenges, and to enable and facilitate this through policy-making – from the global to the site level. The use of nature is considered an option to complement, improve, or even replace traditional engineering approaches, for example, stormwater management (TRL8). The approaches and practices are mature in the sense that the scientific evidence and the design approaches are readily available. Anglian Water have rolled out successful schemes such as the wetland treatment site at Ingoldisthorpe in Norfolk. There are also upcoming capital projects such as the Future Fenland project which aims to provide flood defence with the provision of water for public supply, energy, and agriculture alongside the opportunity for social regeneration and sustainable new housing. Smart technologies may drive innovations in NbS design and management decision-making, especially regarding maintenance. Smart systems enable previously unavailable forms of data collection and modelling, which promote autonomous systems that require less human oversight (TRL 6).
Technology Applications	The maintenance of a constructed wetland can be determined by staff experience and knowledge and can be automated based on real-time monitoring as well as forecasting of soil moisture and weather events. Such an approach may promise more efficient water use and lower plant mortality, while potentially altering the noticeable characteristics of plants (e.g., leaf colour, species evenness). The use of open data can enable the development of regulators, Anglian Water, and consumers to further understand the importance, and pressures on the environment as well as any NbS schemes planned or executed. An example open data application could be making real-time water quality information being available on a smartphone app that allows anyone interested to understand the quality of their local inland waterbody (rivers and lakes). Another example could be the incorporation of smart technologies in stormwater management. Advances in sensing, computation, and wireless communication technologies enabled the development of smart stormwater ponds that are monitored in real-time and controlled across a watershed as a whole system [113], this allows for rapid response to extreme rainfall events and real-time response by opening weirs to allow for stormwater to drain through a catchment effectively.

Category	Trend
Drivers for adoption	The UK Government has committed to domestic and international targets that will require NbS to be deployed at scale [114]. To achieve the domestic net zero target by 2050, the Government's indicative pathway is that net emissions from the agriculture, forestry and the water industry must fall by between 70 and 80% by 2050. Internationally, the UK has committed to "reverse global biodiversity loss", and to ensure that 30% of land and 30% of marine areas are "protected for nature" by 2030.
Barriers to adoption	Constraints lie in the technology enablers for the successful implementation, monitoring and maintenance of NbS schemes. Smart technologies that enable real-time monitoring and control can transform NbS from passively relying on traditional environmental processes, to actively interacting and intervening with these processes to deliver more ecosystem services. This may help NbS to better respond and adapt to constantly changing and increasingly unpredictable environmental stressors. Other barriers include: • Evidence of the effectiveness of NbS is often presented in a way that is challenging for policy and decision-makers as well as the public to understand, and frequently not in a 'ready to apply' format nor tailored to the specific local challenge. • With multiple stakeholders, it can be unclear who is responsible for a given NbS. This can lead to issues with maintenance and impact monitoring. • The ownership and use of land will become a greater barrier,, as land is often owned by actors who put their financial interests above environmental goals [114].
Cost	The benefits of NbS have been found to outweigh the costs of implementation and maintenance in a range of contexts, including disaster (mainly flood) risk reduction along coasts and in river catchments [115]. There is also growing evidence that NbS can be more cost-effective than engineered alternatives, at least when it comes to hazard management and minimisation. For example, across 52 coastal defence projects in the USA, NbS was estimated to be two to five times more cost-effective at lower wave heights and at increased water depths compared to engineered structures. Natural flood management approaches in the UK (such as leaky dams and large woody debris placed in-channel) significantly reduce hazards associated with small floods in small catchments, but do not appear to have a major effect on the most extreme events (though data from such events are lacking). The financial return and efficacy can vary with intensity and frequency of threats, the resilience of the ecosystem to withstand climate change impacts and the vulnerabilities of the socioeconomic system). As a result, the response of ecosystems to NbS is much harder to predict and cost than engineered/grey infrastructure.

Category	Trend
Examples from other geographies	**Gorla Maggiore water park** in Italy utilised an urban constructed wetland development focusing on NbS to protect the city from flooding, improve water quality, remove pollution and increase biodiversity. A park was created with 3ha of space. This used reed beds, sand filter vertical beds and an extended retention basin [116]. • This program has allowed sewer overflow to be diverted into the park, which was able to reduce peak flow by 86% and downstream discharge by 8,900m^3. • Downstream dissolved organic carbon load has been reduced by 11.7t/yr
Examples from UK water industry	**United Utilities** (UU) [117] WFD requirements in the river Petteril to reduce phosphorus pollution from four wastewater treatment plants was disproportionately expensive to customers and failed to address wider issues in the catchment, like the agricultural contribution to nutrient pollution, exacerbated by flooding events. By working with the EA and others through a Catchment Steering Group, UU piloted the catchment nutrient balancing approach (CNB), offsetting some of its nutrient targets with catchment and farm interventions, using the LENS approach to cofound measures with Nestle, resulting in further savings for customers and delivery of wider natural capital benefits. **Upstream Thinking** (UST) by Southwest Water is a catchment management program (2010-current) with the goal of protecting surface and groundwater resources from detrimental landscape impacts by preventing pollutants from entering the water and on developing the natural capital stock of their catchments. The range of pollutants reduced includes farming-derived nutrients, pesticides, faecal coliforms, sediment, dissolved organic carbon (DOC) and new emerging issues such as veterinary medicines and antibiotics. Since starting UST, SWW have consistently met and exceeded their environmental responsibilities and the requirements of the WINEP. UST includes measures such as establishing new hedges and fencing off rivers from livestock. As UST prevented pollutants reaching the river in the first place, this helped to put less pressure on water treatment plants and potentially reduce the treatment costs. 2 x 5-year projects were completed over 18 catchments in Devon and Cornwall. [118], [119]. • New hedgerows lowered surface run-off and 'trapped' soil, resulting in reduced sediment and nutrient loss. • The measured water quality showed improvements across all catchments, with nitrate and dissolved organic carbon levels being at <0.01%, up to 1.8% for suspended sediments and 0.5% for total phosphorous content. • Farmers affected by this (1,700 farms visited) had their bottom line increased by up to £20,000 • £10.5M was invested between 2015-2020 from capital grants through Southwest Water funding, with £15.4M of matched funding **Wyre Natural Flood Management** (NFM) is a program to enhance catchment resilience and reduce carbon, improve biodiversity, improve water quality and

Category	Trend
	reduce flood risk. Modelling and existing benefits were used to pinpoint key areas for NFM – with an initial 5-year period to allow modifications according to performance data. The land managers (predominantly farmers) are responsible for hosting and maintaining the nature-based interventions that help to reduce flood risk. This is currently taking place over a 9-year period, with the potential to extend up to 50 years. The landowners or land managers receive an annual payment for hosting and maintaining the interventions, with the potential for additional payments if certain biodiversity targets are achieved. 30 sites have, so far, been impacted. [120] [120] • So far, NFM has increased water storage by 70ha • 32,000 trees have been planted, giving sequestration capability of 16,000 tCO_2/100 years • 39 hectares of woodland has been created • 15ha of peatland has been restored to reduce GHG emissions and sequester carbon • Revenue has also been generated for sellers to change land use • 5-15% flood impact reduction achieved • £1.5M of upfront capital was provided for the project, which reduced peak flow and improved catchment resilience by 10% • £850k was provided as a commercial loan by Triodos Bank, £627k as a grant from the Woodland Trust **Rainscape Llanelli** (SuDS Sustainable Urban Drainage) with Welsh Water managed surface water and reduced sewer flooding by separating out rainwater from the existing system – this slowed down the rate that it entered the network and also redirected it into local rivers. Shallow basins with plants, swales, porous paving and grass channels were implemented to catch and clean the rainwater, then soak it into the ground or allow slow run off into sewers. 36 projects have been completed since 2012 [121], [122] • 9761 trees planted and 14 basins were created as part of the project • 41 properties were removed from the flood risk register and 1.5 million m^3 of rainwater is now no longer pumped and treated annually • £115M was invested over 8 years

Key Impact Areas for the Water Industry

Table 37 outlines the key areas that are likely to impacted by the successful implementation of Scaling Nature-based Solutions.

Table 37: Key impact areas for Scaling Nature-based Solutions

Category	Impact area description
Performance impact	Scaling NbS can deliver significant positive impact on efficiency and performance. Instead of relying solely on traditional "grey infrastructure", companies can combine these efforts with natural solutions or "green infrastructure" (e.g., using wetlands to filter and store water, rather than industrial filtration systems and storage tanks). This allows natural systems to provide vital provisioning and regulatory functions, such as filtration functions of soils and natural vegetation to: The performance specific benefits include: • Improve river water quality. • Reduce erosion and sediment loading. • Lower pollution into surface waterbodies and groundwater. • Regulate seasonal water flows. Other wider ecosystem benefits can include: • Restoration of wetlands and other ecosystems can recharge groundwater levels and mitigate flood risk. • Healthy forests can filter water, reduce water treatment costs, and regulate how quickly water is released downstream. • Restoration degraded ecosystems can reduce the risk of wildfire by thinning overly dense forests, removing invasive species, and restoring the water-retaining qualities of meadows and riparian ecosystems.
BOTEX and Delivery Efficiency	NbS should deliver significant positive impact both to operational costs and capital maintenance linked to the benefits listed above when NbS is scaled with enabling and supporting technologies. Implementing NbS at scale allows for: • Improving water quality by reducing the levels of traditional pollutants such as total suspended solids (TSS), organic matter, nutrients, and heavy metals, reducing treatment costs. • Flood protection and risk management, reducing damage costs and improving asset resilience. For example, reducing stormwater volumes entering sewer system, serving as a stand-alone drainage system. • Blue-green infrastructure to work holistically; for example, large scale SuDS implementation that is more sustainable than flood walls. In combination, blue-green infrastructures provide health benefits for society and relieve the pressures on the environment and urban spaces.

Category	Impact area description
Use for Operational Risk Mitigation, Resilience and Compliance	• NbS, when operational, can enhance river water quality, reduce flood risk and improve habitat quality and diversity allowing for environmental compliance and improvement in regulatory performance. • NbS can widen the range of data available to the regulator, enabling a more comprehensive overview of water delivery and more insights into delivery, such as patterns of water usage or shortage. • NbS can play a key role in making the water environment more resilient to current and future threats, in a way that delivers multiple benefits to customers, society and the environment.
Cybersecurity Risks from the Technology	The foundational technologies enabling NbS - from the sensors to the parsing or processing of information, to modelling and simulation, storage of data, data analytics platforms and connectivity - will all depend on digital or cyber-elements. The distributed nature of NbS will make such solutions an easier target for cybersecurity attacks than centralised facilities. Although relatively smaller in terms of potential cyberthreat impact than the other topic areas discussed in this report, any breach will likely lead to reputation and financial losses. Risks include: • Risk of information leakage to bad actors who may themselves use the data as part of their planning • Loss or erasure of essential data for maintenance or updates • Intentional follow-on physical damage to NbS systems that have already been setup As such, cybersecurity of these components (and the cyber-ecosystem that they are deployed in) should be considered in a tailored and probabilistic manner to ensure as broad a coverage as possible of the risks.
Sustainability impact	Delivering and scaling NbS will address the availability and quality of water in rivers and aquifers, protect soil and biodiversity and likely reduce carbon emissions.
Impact on supply chain and partnerships	Scaling NbS provides a unique opportunity to not only enhance existing relationships with external stakeholders such as the Norfolk and Cambridge Rivers trusts but also engage them in a greater capacity than before. This approach brings together on-the-ground experiences from existing projects with top-down, strategic recommendations, joining up theory and practice to accelerate action. This enables the acceleration of a successful outcome. For the supply chain, closer relationships with all suppliers will offer a better understanding of the whole chain as an ecosystem, allowing for clearer definitions of responsibilities that minimise duplication of effort, more creative incentivisation and a fairer balance of risk.

Technology timeline

Table 38 outlines the potential timeline for technology implementation for Scaling Nature-based Solutions.

Table 38: Technology timeline for Scaling Nature-based Solutions

Timescale	Technology evolution and Water Industry Impact
In 0-5 Years…	**Technology evolution:** Pilots of scaled-up NbS schemes throughout AMP8. The pilots should aim to include the latest technology, such as digital twin and IOT, or be designed so that these technologies can be easily added in the near future. Partnerships will work on an open-data framework allowing for effective cross-sector collaboration and greater impact when investing, monitoring and maintaining NbS. **Industry Impact:** The water industry will invest and integrate elements of NbS to its core capital project delivery and investment planning; this will move the organisations to consider implementing NbS as a priority by expanding partnerships and engaging supply chain partners.
In 5-10 years…	**Technology evolution:** The majority of NbS will now be viewed in digital twin environments as well as the incorporation of advanced sensing techniques to enable proactive maintenance and trend data reliability. Long-term established partnerships continue delivering NbS with a greater focus on climate resilience, securing of public water supply as well as operational efficiencies. Greater role of citizen science involving members of the public having access to real-time river health, and river level information encouraging a greater connection with the environment. Changes in agricultural production are in line with legislation, allowing for greater involvement with local farmers and producers to play a key role in enhancing the environment. **Industry Impact:** Early NbS pilots become more established ecosystems, offering more benefits, for example larger plants are capable of absorbing and storing more water and contaminants. Sufficient data has been collected to enable annual trends and patterns to be identified and used in wider catchment management.
In 10-25 years…	**Technology evolution:** Large and scaled NbS schemes delivering a range of ecosystem services, fully integrated and operational at the catchment level. On-going maintenance and monitoring to ensure performance and compliance. A major aspect of carbon storage, particularly the construction and operation of the Fens for Future project and other major infrastructure schemes (planned reservoir). **Industry Impact:** The water industry will view implementing NbS as core to its business model.

3.8 Bioscience Solutions for Wastewater Treatment

Key takeaways: The water industry is the fourth largest energy intensive segment in the UK [123]. 10 billion litres of sewage are treated every day using 2,800 GWh of energy, 36% of the total energy used [124]. Biological wastewater treatment is currently used in the water industry (trickle filters, anaerobic digesters, membrane bioreactors etc.) as it offers low operational costs and often less harmful effects on the environment relative to other systems [125]. Bioscience solutions for wastewater treatment (including optimisation of biofilms and creation of enzymes and proteins with unique/improved functions) have the potential to dramatically decrease energy usage alongside costs by solving challenges related to efficiency and performance. Key challenges in wastewater treatment that could be tackled using bioscience include aeration, removing FOGs, removing microplastics, improving efficiency of biological waste treatment and improving sludge thickening efficiency.

Overview

Biological approaches to improving wastewater treatment efficiency mainly centre on biofilms and suspended biomass. Advancements (including cost reductions) of tools and approaches in synthetic biology enable us to generate and optimise biological systems with unique functions for wastewater treatment.

With these approaches biological systems will be more robust, more efficient and establish faster. This engineered control can be achieved through manipulation at one or more levels within the biological system as shown in Figure 9. Artificial intelligence is being used to speed up this engineering as it allows predictions to be made about what DNA to change to optimise a biological entity for a given condition, avoiding lengthy 'wet lab' experimentation.

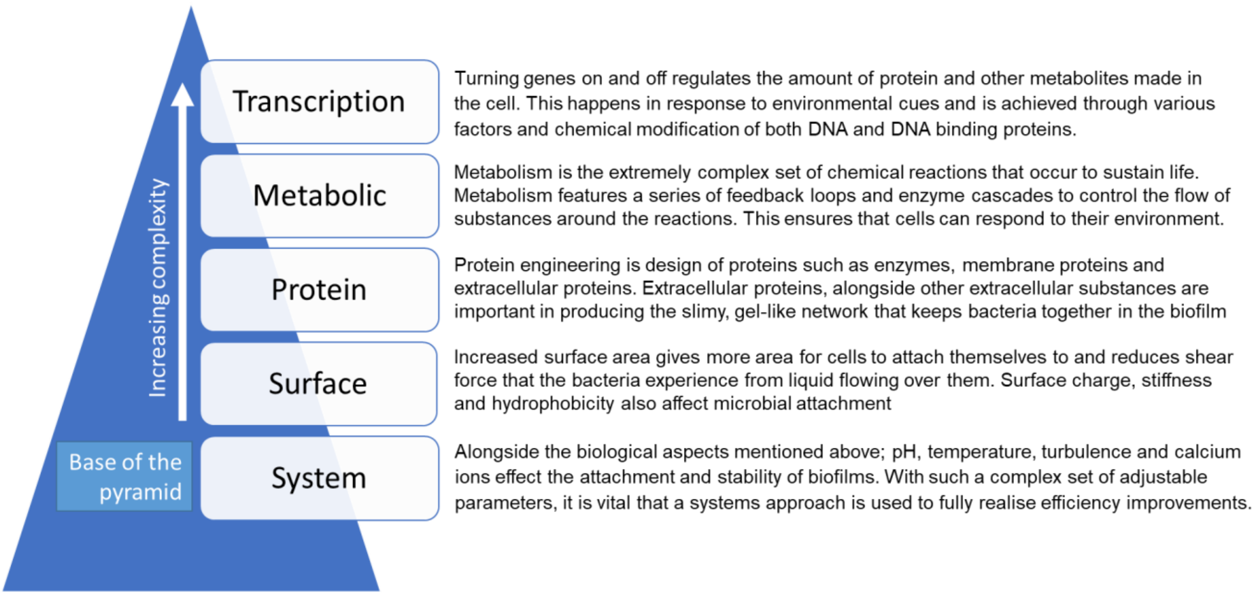

Figure 9 Building blocks of biological systems

Bioscience solutions can have further environmental benefits, such as the use of algae in biological treatment which along with reducing aeration costs by 31-33% can also reduce carbon emissions by 68% [126]. Commercially available polymers for sludge thickening made from biomass have half the carbon footprint of comparable fossil-based polymers [127].

While some bioscience solutions can lead to operational cost reductions, significant R&D work is required to ensure the solution works for the given situation. Local variations means that bespoke solutions can be required for each site, while in the future technologies such as artificial intelligence may make this process quicker it is currently time consuming. For plastic binding proteins in sludge, it is only cost-effective if the proteins can be recycled which add further complexity to the process. While enzymes can be effective at removing FOG from pipes and pumps it is currently difficult to dose so would result in minimal operational savings over current jetting practices.

Relevant Technologies

Table 39 shows the relevant technologies for bioscience solutions.

Table 39: Relevant technologies for Bioscience Solutions for Wastewater Treatment

Technology category	Specific technologies
Suspended biomass	In suspended biomass, micro-organisms absorb organic matter and other nutrients to grow and reproduce. At a certain size, they form micro-colonies and settle as sludge which can be removed. As biomass often has connotations related to algae and energy generation, from here on suspended biomass is included in the definition of biofilms.
Biofilms	Biofilms are a community of micro-organisms (bacteria) in which cells stick to each other ("sticking" of cells normally effects cell-cell signalling) and to a surface, forming clumps. They are used beneficially in the water sector as a natural filtering or treatment system within trickling filters, rotating biological contactors systems, constructed wetlands and membrane bioreactors. Challenges with creating and using beneficial biofilms include the time it takes to establish them, and the fact that substances within the water (e.g., high salt levels, disinfectants dumped in the water) can disrupt the biofilm, or even destroy it completely. Improvements to establishment speed, robustness and efficiency would be welcome. Technologies related to engineering of biofilms include synthetic biology, bio-informatic techniques and materials science.
Microplastic binding proteins	There are proteins that increase the binding between microplastics to enable them to flocculate and be removed [128] using larger filters (beneficial for energy use as lower pressure losses over larger pore size filters and beneficial for reducing clogging). Synthetic biology and artificial intelligence can potentially be used to improve these for greater effectiveness.
Sludge thickening proteins/biological molecules	Currently, polymers are used to thicken sludge, but inefficiencies in thickening sludge cost approximately £5 million per year for Anglian Water (Source: Internal Interview). Biological entities, such as proteins that can improve the efficiency of sludge thickening, could dramatically improve performance.

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Technology category	Specific technologies
Enzymes for removing FOGs	Lipase and other enzymes could play a role in the removal of fats, oil and grease (FOGs, colloquially known as fatbergs) [129] over the next 5 years. Whilst enzymes that remove FOGs have been trialled at Anglian Water (based on information shared by AW) and were effective, they were in solid form and so had to be dosed manually every week which was impractical. There were also issues with difficult storage conditions and short lifetime of the enzymes within the trials. Enzyme engineering that allows the enzymes to be suspended or dissolved in a liquid would be highly beneficial as it would allow standard dosing pumps to be used and consequently no requirement for manual dosing. Enzyme engineering that improved the lifetime and storage conditions required would also be beneficial. Lipase breaks down fats into fatty acids, glycerol and other alcohols. Some micro-organisms (e.g., *Yarrowia lipolytica*) can use fatty acids as food and thus would allow FOGs to be used as a feedstock [130] for bio-based products.
Synthetic biology	DNA sequencing (e.g., Sanger, NextGen,), DNA copying (e.g., polymerase chain reaction PCR), DNA editing (Crispr-Cas-9), bioinformatics, high-throughput screening, artificial intelligence, cell culture, metabolic flux analysis, analytical chemistry, high-throughput testing, lab automation.
Materials science	Surface fabrication techniques, scanning electron microscopy.

Trends

Table 40 highlights the key trend in bioscience solutions.

Table 40: Key trends for Bioscience Solutions for Wastewater Treatment

Category	Trend
Technology Maturity	• Surface engineering techniques are already available and are currently being researched in the context of biofilm formation [131][132] • Enzymes and proteins with unique functions have been trialled already at Anglian Water. • Microplastic binding proteins and sludge thickening proteins are at TRL4 [128] [133]. • Synthetic biology is already in use (TRL 8-9) but new techniques to speed up protein and metabolic engineering are developing rapidly and improvements will likely continue for the next 5 years. • Use of synthetic biology to improve biofilms is at TRL 1-2 [131], [134], [135].

Category	Trend
Technology Applications	• Biofilm engineering to improve efficiency and robustness of biological wastewater treatment methods. • Engineered proteins to flocculate microplastics. • Engineered proteins to improve sludge thickening efficiency • Cocktails of enzymes to remove or prevents FOGs.
Drivers for adoption	• The transition to Net Zero requires more efficient wastewater treatment as wastewater treatment uses 36% of the total energy used for water. • The water industry is facing a public backlash regarding stormwater discharge [136] and the government recently published a Storm Overflow Discharge Reduction Plan and increased the penalties for pollution [137]. • More efficient wastewater treatment would reduce the extra capacity needed for wastewater treatment, thus saving capital costs. • Inefficiencies in sludge thickening cost the water industry significant amounts of money - £5M per year for AW alone.
Barriers to adoption	• Upgrading biofilms using GMOs introduces new regulatory barriers and complexity. Where a biofilm is used within a closed system the contained use regulations will apply [138]. However, you cannot release GMOs into the environment in the UK currently at all (some crops can be used at field trial sites or within greenhouses, but the regulations are restrictive). This is a major barrier to using GMOs in open systems within wastewater treatment but may change over the next 25 years. • The establishment speed of new biofilms will be a consideration for replacing existing biofilms with the newly designed versions.
Cost	This depends on whether new infrastructure and equipment is required to contain GMOs. If new infrastructure and equipment is not required, the cost would be minimal once research and development had been done.
Examples from other industries / geographies	Enzyme engineering was used to achieve 53% higher productivity manufacturing of sitagliptin (a diabetes drug) [139]. Washing powders contain enzymes that have been genetically engineered to better remove proteins, carbohydrates and fats and be more thermotolerant [140], [141]. It is worth noting that as enzymes and other proteins are not organisms (they are not alive), they do not count as genetically modified organisms, and so are not subject to regulations surrounding these. Nonetheless, there are still restrictions on proteins; typically, you must demonstrate that any protein is free of the organism used to produce it.

Category	Trend
Microplastics in sludge	Microplastics in sludge remains a challenge. Whilst it has been shown that microplastics are effectively removed from water in drinking water and wastewater treatment, they are present at high levels in sludge [142]https://ukwir.org/view/6c29ff4e-e84e-4b1e-a0ab-143298491942. This is unfavourable for the use of sludge in agriculture and unfavourable for incineration. Currently there is no EU or UK legislation to limit microplastics within fertiliser, but this is likely to change over the next 10 years as research suggests microplastics are detrimental to agriculture [143] and the EU is conducting research to inform policies surrounding this threat [144]. Future regulation may therefore require microplastics to be separated from both the water outfall and the sludge. There is also a growing appreciation of microplastic transportation into the environment even after incineration [145]. Common methods of removing microplastics from water include reverse osmosis, distillation and ultrafiltration. All of these would likely be extremely expensive and difficult. Plastic binding proteins face a cost issue, however. They are engineered to be specific to certain plastics, meaning that they can flocculate microplastics separately to the rest of the sludge. This specificity means that the flocculation of microplastics can be done before primary settlement using a separate filter, tank or other apparatus. However a rough estimate of the cost of implementingsuch an approach could range from£9M to £77M per year (see footnote 1). The financial viability of this approach would be enhanced by reusing the proteins. If the proteins can be captured and processed for reuse every day for a year (assuming settlement takes roughly 24 hours), this cost comes down to somewhere between £25,000-£211,000 per year. Another option would be to use "plastic eating" micro-organisms (e.g., Ideonella sakaiensis bacteria) to convert the plastics into biomass (which can then be used for other, bio-based products). Whilst some organisms do this naturally, it is likely that genetic engineering would need to be used to improve the efficiency and so the reactor would need to be closed to the environment. This may prove to be more cost effective as biomass could have value for making other bio-based products. Plastic eating micro-organisms will have a high R&D cost (in the order of £10M), but low operating cost once established.

[1] A rough calculation of the cost of these proteins uses the following information:

- Anglian Water treats 927,000 m3 of water per day [230] generating 150,000 tonnes of dry solids per year [231].
- There are 2000-4000 particles of microplastics per m3 of water [232]
- Microplastics particles weigh 6.2mg each on average [233].
- These engineered proteins will cost roughly $15/kg. This is an assumption based on the target price of bio-based collagen [234]

Annual price = Price per kg x Number of kg needed. To work out the number of kg needed there are two approaches:

1. Assume that the ratio of flocculant needed to sludge is the same as with conventional flocculants ie. 5-15kg per tonne of dry-solids [151].
2. Assume that the weight of flocculants needs to equal the weight of microplastics in the water to bind all of them.

Under assumption 1, the cost of the proteins to remove microplastics is $75-225 per kg of dry sludge, or $11.25M-£34M per year. Under assumption 2, the price is $0.28/m3 of water treated or over $95M per year.
These numbers were converted to pounds at the exchange rate on 18/1/23 ($1=£0.81).

Key Impact Areas for the Water Industry

Key impact areas for bioscience solutions are shown in Table 41.

Table 41: Key impact areas for Bioscience Solutions for Wastewater Treatment

Category	Impact area description
Performance impact	**Short Term (< 5 years)** • Enzymes and proteins with unique functions could dramatically improve performance of sewer systems by removing blockages more easily or perhaps even preventing them in the first place. • Protein engineering on key enzymes within biofilms could improve wastewater treatment performance in the short term. • More efficient wastewater treatment could reduce the amount that goes to storm overflow • Increased efficiency in wastewater treatment is specifically called out in the Ofwat PR24 guidance on technology scenarios long-term delivery strategies [60]. • A switch to anaerobic methods reduces electricity costs associated with aeration, thus improving financial performance. • Biological entities for improving efficiency of sludge thickening could have a large improvement on performance. **Long Term (> 5 years)** A systems approach to biofilm engineering will dramatically increase performance of wastewater treatment.
Botex and Delivery Efficiency	• More robust biofilms increase operational and capital maintenance efficiency. • Proteins that flocculate microplastics and enzymes which prevent/remove fats, oils and greases would improve the efficiency of maintenance. • Biofilms which establish faster improve the delivery efficiency of capital schemes.
Use for Operational Risk Mitigation, Resilience and Compliance	• Improvement of biofilms to be more robust could increase wastewater treatment works' resilience to unusual events, such as high amounts of contaminants in the water. • Prevention and easier removal of fats, oils and greases reduces the risk of flooding, sewage backing up into people's homes and storm overflow events. • Enzymes that are used for sludge thickening or removal in lagoons should not create gas, as effervescence risks upsetting sludge blankets which risks discharging sludge (Source: AW Internal Interview).

Category	Impact area description
Cybersecurity Risks from the Technology	• Biological engineering often depends on specialist hardware and software. These are slowly becoming more powerful, more connected (and in some cases) imbued with intelligence such as machine learning. • This being the case, all the security risks involved with complexity (hard to audit), non-determinism (not able to guarantee outcome) and connectivity (opening up what used to be a closed system) apply. • The risk therefore is that vulnerabilities in software or hardware could be exploited to deliver faulty (or even intentionally malicious) bio-products. • There is also a risk of information disclosure to bad actors, who may co-opt sensitive bioengineering techniques or methods for malicious purposes.
Sustainability impact	• Biological wastewater treatment createsfewer harmful effects on the environment than alternative techniques [125]. • Techniques that reduce aeration requirements would save vast amounts of energy in the water industry. • More efficient biofilms would likely reduce the energy required in the treatment works. • More efficient sludge thickening using biological entities would be better for the environment as it would reduce transport requirements.
Impact on supply chain and partnerships	It is not yet fully understood how supply chain requirements will change when a biofilm is engineered. For example, sometimes when bacteria are genetically engineered, they gradually lose their phenotype (observable characteristics) over time. This means that a supply chain for monitoring and replacing the modified bacteria may be required. The use of genetically modified organisms may require a good partnership with the regulator. There will need to be a supply chain for enzymes and proteins with unique function. This supply chain needs to have a good understanding of the needs of the water industry and be dynamic enough to adapt to them. For example, Ecotabs was trialled by Anglian Water (Source: Internal Interview) as a solid, enzymatic solution for removing FOGs. Whilst this was effective at removing FOGs, the solid format had to be manually dosed which added maintenance time and money. This was not financially viable across all the sites. It also had unfavourable storage requirements.

Category	Impact area description
Decreased aeration costs through use of algae	The use of algae and microalgae in biological wastewater treatment is discussed in Error! Reference source not found. in the context of microbial fuel cells, however, the u se of algae and microalgae as part of secondary wastewater treatment has also been shown to reduce aeration related costs. Algae can generate enough dissolved oxygen to partially displace the mechanical aeration required – leading to 18-66% faster removal of chemical oxygen demand (COD) and offset 33% of biochemical oxygen demand (which is fulfilled by aeration) [146]. A techno-economic analysis of high rated algae ponds (HRAP) showed a 31% reduction in treatment costs, 68% reduction in CO2 equivalent and 78% reduction in electricity consumption when compared to an equivalent incumbent treatment system [126]. As activated sludge systems represent 45-75% of total operational costs in existing wastewater treatment plants [147] this technology could reduce overall treatment costs by 14-23%. Whilst this study required “sufficient sunlight”, other studies have explored algal-bacterial symbiosis within photobioreactors [147]. Furthermore, algal biomass can be sold as a feedstock for biofuels, enhancing the financial benefit (see Error! Reference source not found.).
Improved efficiency and robustness of biological wastewater treatment methods with biofilm engineering	Whilst systems level biofilm engineering is likely more than 10 years away due to the necessity for a large amount of knowledge and data, improvements to individual bacteria, algae and surfaces will likely come within the 5-10 year horizon. Current restrictions to use of genetically modified organisms (GMOs) mean these can only be used within fixed bioreactors such as anaerobic digestors or photobioreactors; biological treatment systems which are open to the environment cannot contain GMOs. Looking to other industries to explore the kinds of impacts that biotechnology could have on the water industry illustrates the efficiency gains through using this optimisation approach. For example, engineering of “plastic-eating” enzymes has made them more stable and effective at higher temperatures [148] which has been a focus area for industries that generate high levels of plastic and textile waste, whilst cereal processing enzymes have been engineered to withstand a wider variety of pH [149].

Category	Impact area description
Sludge thickening efficiency improved through engineered compounds	Anglian Water alone currently spends £5M per year dealing with sludge thickening inefficiencies, which are largely caused by polymer inefficiencies and sub-optimal dosing (Source: Internal Interview). Existing polymers which are used for flocculation (and sometimes coagulation) are slippery when wet which makes them difficult to dose. Bio-based polymers for sludge thickening are already commercially available and have half the carbon emissions of fossil-based polymers [127]. Chitosan, similar in molecular structure to the polymers currently used for sludge thickening is a further potential bio-solution. Chitosan also has adsorption properties for heavy metals, metalloids, industrial dyes and other organic pollutants and is biodegradable. Whilst chitosan is highly abundant naturally and is currently extracted from shellfish such as crabs or lobsters there are efforts to produce it using biomanufacturing [150]. For naturally occurring chitosan, prices range from \$10-\$200 per kg, compared to an estimate of \$1 per kg for the currently used sludge thickening polymers. The bioproduction or bioprocessing of chitosan could bring the cost down, but trials will need to be done with chitosan to understand whether it increases the sludge thickening efficiency and what additional benefits if any come from its further adsorption properties. It has also been hypothesised that obtaining a ubiquitous biological polymer from sludge itself might lower the costs associated with sludge thickening efficiency. An example of this would be extracting DNA from the sludge to use as a flocculant. The sludge Anglian Water treats requires approximately 750-2250 tonnes of polymer per year [151]. A rough estimate showed that 3.75 tonnes of DNA could be extracted from sludge, thus unless DNA (or other biological polymer that exists in sludge and is easily separable) is significantly more efficient at flocculation than existing polymers, it is unlikely to reduce sludge thickening costs enough to cover the required separation infrastructure investment.
Removal or prevention of FOGs using cocktails of enzymes	This application is likely to have minimal impact. An internal interview with AW revealed that FOGs need to be removed from pumps as well as sewers and pipes, and as the existing jetting system (performed on each of 6,000 sites every six months) achieves removal of FOGs in both pumps and pipes, there is minimal incentive to replace it. Moreover, there are practical challenges of getting the enzymes into the sewer. If you dose the enzymes into the wastewater, the dosing liquid needs to be topped up at a given interval. If you immobilise the enzyme on the side of a pipe, it needs to be replenished eventually. At a cost of \$1-10/kg, enzymes to remove and prevent FOGs start to have potential if their half-life can be extended such that they need replacing only once per year, rather than once per week (Source: AW Internal Interview). This is a roughly 50x improvement. Whilst estimates show that it should be possible to improve the lifetime of some enzymes by 10-100 fold, this has yet to be tested [152], [153].

Technology timeline

The expected technology timeline for bioscience solutions is shown in Table 42.

Table 42: Technology timeline for Bioscience Solutions for Wastewater Treatment

Timescale	Technology evolution and Water Industry Impact
In 0-5 Years…	**Technology evolution:** Protein engineering is widely used currently, as is metabolic engineering. These will enable many of the enzymes and proteins with unique function for removal of FOGs, microplastics and improved efficiency of sludge thickening. **Industry Impact:** Higher sludge thickening efficiency (which in turn reduces tankering costs), more efficient removal of FOGs, more efficient removal of microplastics. Currently, polymers are used to thicken sludge, but inefficiencies in thickening sludge cost approximately £5 million per year for Anglian Water (Source: Internal Interview). Biological entities that can improve the efficiency of sludge thickening could dramatically improve performance.
In 5-10 years…	**Technology evolution:** Protein engineering, metabolic engineering and surface engineering will start to be applied to biofilms – which are more complex than the single organism/protein use cases described in the short term. **Industry Impact:** Main industry impact of these technologies in the 5-10 year timeframe will be increased efficiency of wastewater treatment, which enables higher wastewater treatment capacity. This will be supported by increased robustness of biological treatment methods.
In 10-25 years…	**Technology evolution:** A systems approach (including transcription factor engineering and engineering of interactions between bacteria) to biofilm engineering is likely 10+ years away as it requires a good understanding of a very complex system. **Industry Impact:** Industry impacts will be similar to those in the 5-10 year horizon, only on a large scale.

3.9 Bioresource as a Revenue Stream

Key takeaways: The topic of 'Bioresources as a Revenue Stream' considers the diversification of revenue streams available to the water industry and to Anglian Water, improving financial resilience to changing market conditions and asset performance management. Diversifying the use cases for bioresources is important due to the potential changes to UK regulations (DEFRA and the Environment Agency) which may reduce the demand for fertilisers post 2025. The end-of-life of CHP engines - as a result of Anglian Water's Net Zero commitments - will also drive the need for new use cases and markets for bioresources. Partnerships will be critical to success in this area as it involves new markets, capabilities and customers.

Overview

Wastewater treatment presents many opportunities for revenue to be generated from bioresources. Figure 10 shows where some potential revenue streams can be created at different points in the treatment process.

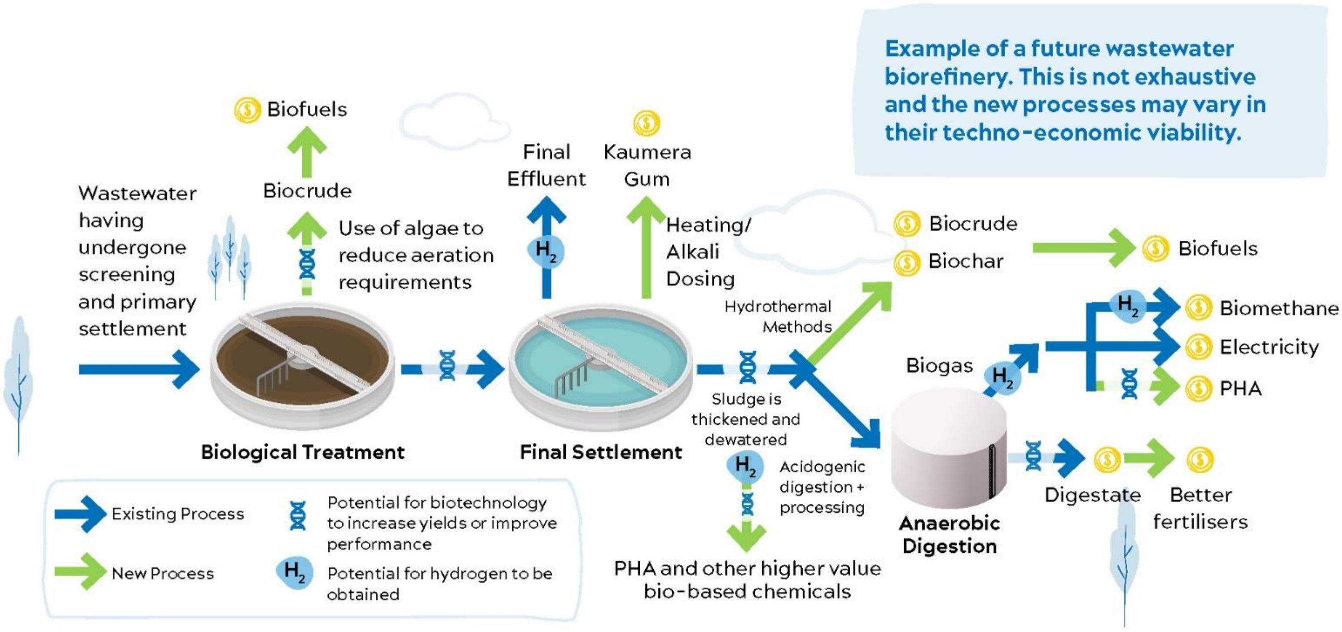

Figure 10 Bioresource revenue sources from different parts of the wastewater treatment process. Source: Cambridge Consultants

As an example, Kaumera Gum is a new bio-based material made from sludge that is sold for use as a bio-stimulant. The gum is readily extracted from granular sludge in the Nereda treatment process, which is already used in the UK including by Anglian Water. Kaumera Gum can also be used as a paper coating, a fire retardant, as a curing agent for concrete. It can also be used as part of bio-nanocomposite materials [154].

The bioplastic PHA (made from methane and/or carbon dioxide) is already commercially available from Newlight Technologies. The literature suggests the production of PHA bioplastic would be economically viable for wastewater treatment plants to as the minimum PHA cost is $1.26-$2.26 against a market price of $2.5-$5.5/kg [155].

Biomethane and biogas are also important revenue streams, as alternative energy sources are highly valued and will have an increasing role in the UK energy mix. Production has been proven at scale and is not a new revenue stream for the water sector, however there is potential to significantly improve yields through bioengineering of the microorganisms involved.

The largest biogas plant in the world is in the City of Perris, California, it has a capacity of 335,000 tons per year of organic waste [156]. Table 43 shows an estimation of the potential income from this plant. This plant had a capital cost of $55M, which could be covered in under 3.5 years by the sale of biomethane alone. Biogas can be used to replace diesel, which provides further environmental benefits. The City of Perris plant could displace an estimated 4 million gallons of diesel fuel annually, replacing it with renewable natural gas from the plant (see Table 43).

Table 43 Estimated revenue from different income source for City of Perris biogas plant

Income Source	Units	Price per unit	Income per year
Fertiliser	260,000 tons of fertiliser	$800/ton [157]	$208M
Biomethane	4,000,000 diesel gallon equivalents	$4/diesel gallon equivalent [158]	$16M
Household collection charges	17470	$2.25 /household/week	$2M

The City of Perris plant could provide an interesting template for the UK. Of further note is that whilst Anglian Water already generates £5M in revenue from biomethane, they do not currently inject it into the grid, as is the case for the City of Perris plant.

Making greater use of techniques genetic engineering can also open up new avenues for creating or growing revenue streams. One example is the potential for revenue from biomethane production. Wastewater contains various substances that can be converted to methane and carbon dioxide, as shown in Figure 11.

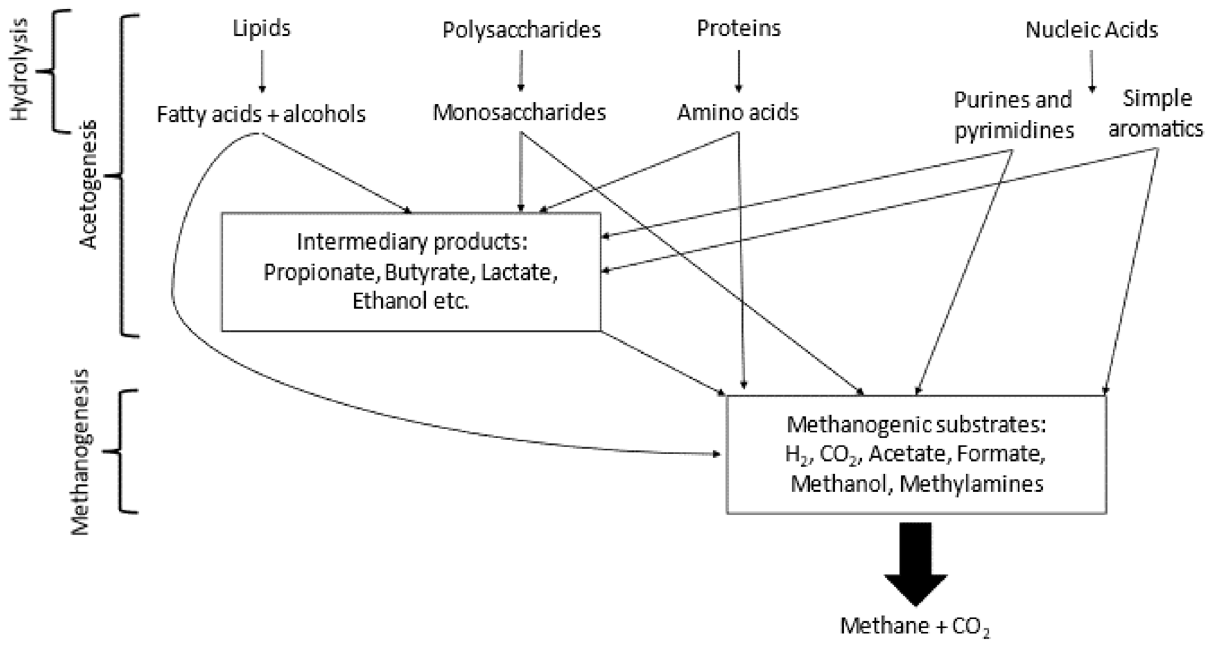

Figure 11 Diagram of methane and CO2 production using different substances

The yield of biomethane production of an anaerobic digestor could be improved through genetic engineering of microorganisms acting within these pathways, specifically methanogens and acetogens. Methanogens are micro-organisms that produce methane, many of those found in anaerobic digestors produce the methane from acetate [177]. Acetogens produce acetate from a variety of compounds including carbon dioxide and hydrogen [178].

New approaches to genetic engineering are enabling 40-200% increases in production of desired end-products [179]–[181]. If this increase in yield directly translated into increase in revenue, in total Anglian Water could be looking at £2M-£10M/year extra revenue from this genetic engineering. If the biomethane produced was additionally exported to the grid this add an additional to £8.5-19.5M.

Whilst improving the metabolism of organisms has traditionally taken a long time (it took Dupont 575 person-years to generate bio-based propanediol [159]) the advent of machine learning for genetic engineering has supercharged advancements. The main barrier to taking advantage of this technology is likely the regulation surrounding co-digestion and additives (Source: Internal Interview). As GMOs are not allowed to be released into the environment the anaerobic digestion process will need to be adapted to destroy them before they are released. Currently, sterilisation happens prior to anaerobic digestion (Source: Internal Interview), but it is feasible that this could be moved to post-digestion.

There are also a variety of lower-tech ways of increasing yield. For example, biogas yields for lignocellulosic feedstocks have also been shown to increase by 66% through ensiling (the use of lactic acid bacteria to produce acid and convert soluble substrates into organic acids) and fungal pre-treatment [182].

Relevant Technologies

The relevant technologies for realising bioresource as a revenue are shown in Table 44.

Table 44 Relevant technologies for bioresource as a revenue stream

Technology Category	Specific Technologies
Fertilisers	Whilst bioresources are already used for fertilisers, in much of the wider water industry there is still some work to be done to make them more attractive to landowners and farmers. This is achievable in the short-term and includes the removal of microplastics and heavy metals. Alongside this, there is currently some uncertainty in the use of bioresources for fertilisers post 2025, due to changes in interpretation of Environment Agency regulations by DEFRA. Specific technologies required here include extracting metals (see below), microplastic removal, disinfection technologies (e.g., pasteurisation) and synthetic biology.
Extracting metals	A possible new revenue stream for Anglian Water could be the sale of heavy metals or other valuable compounds which have been extracted from wastewater. Nonetheless, currently most water companies manage their metal discharge by managing their trader's discharge (Source: Internal Interview), so it is unlikely currently that there would be enough metals in the water to justify a business case for investment in this.
Biogas	Biogas is formed during the anaerobic digestion of organic material in wastewater. The conversion of organic content to biogas is approximately 60% efficient. This biogas can either be used in a combined heat power process (CHP) to generate electricity and heat, or it can be upgraded into biomethane via biogas upgrading.

Technology Category	Specific Technologies
	There are two main ways that future technology could improve the efficiency: optimisation of the bacteria and optimisation of digestor. Optimisation of bacteria is likely to be done via protein engineering and metabolic engineering. AI is already being used to selectively alter the genes of bacteria to make them more perform better [160]. Optimised methanogenic bacteria would be classed as GMOs and so would be subject to the GMO Contained Use regulations [161] as they would remain in the digester and surrounding system, which is as a biotechnology production facility. Whilst volatile fatty acid monitoring (VFA) is already used at Anglian Water (anecdotal, Project Workshop 1) it is likely that further advances in biosensors and photonics (see **3.4 Advanced Sensing and** Sensor Platforms) will lead to better understanding and control of digesters, thus increasing their efficiency further. CHP, methanogenic bacteria, digestors, synthetic biology (protein and metabolic engineering), AI, biosensors and photonics are all relevant technologies for biomass.
Anaerobic digestion	Pre-treatment technologies (e.g., dewatering, drying) pasteurisation, thermal hydrolysis, biological hydrolysis, HPH (developed by Anglian Water, sold to Helea), biofilm improvement (synthetic biology)
Electricity Generation	Wastewater can be used within algal and microbial fuel cells (MFCs) to produce electricity [162], [163]. In these fuel cells, nitrogen, phosphorus, organics and CO2 can be removed from wastewater whilst the electrons generated are used to generate electricity.
Tertiary feedstocks for bio-based products	Renewable, biological raw materials that can be used for biofuels, biopolymers and bio-based chemicals are collectively known as feedstocks. Sugar cane is currently used as a (primary) feedstock for biofuels and other chemicals [164], [165] but this use reduces land available for food production. Secondary feedstocks (non-food crops or waste from primary feedstocks) overcome this issue but require pre-treatment which adds expense and complexity. Tertiary feedstocks are derived from post-consumer waste, including wastewater.
Hydrogen	Hydrogen is a clean alternative to methane, also known as natural gas. . Hydrogen can be produced in many ways, including catalytic cracking from ammonia in wastewater streams and steam biogas reformation using raw biogas from anaerobic digestion of sludge. For more information on hydrogen production from bioresources see **3.6 Renewable Energy** Systems.
Synthetic biology	Synthetic biology is a specific technology that enables many of the revenue streams from bioresources through increasing the efficiency and robustness of biological entities such as biofilms. Synthetic biology is “the design and engineering of biologically based parts, novel devices and systems as well as the redesign of existing, natural biological systems” [166] . Synthetic biology encompasses various techniques and technologies including DNA sequencing (e.g., Sanger), DNA copying (e.g., polymerase chain reaction PCR), DNA editing (Crispr-Cas-9), bio-informatics, high-throughput sequencing, artificial intelligence, cell culture.

Trends

The key trends for realising bioresource as a revenue stream are shown in Table 45

Table 45 Key trends for bioresource as a revenue stream

Category	Trend
Tech Maturity	• Synthetic biology is already in use but new techniques to speed up protein and metabolic engineering are developing rapidly and improvements will likely continue for the next 5 years. • Improvements in bioreactor efficiencies and robustness is anticipated by the introduction of biosensors which are currently at TRL 3-7, depending on the type of sensor and use context (medical industry is TRL 9). • Other emerging technologies include microbial and algal fuel cells (TRL 4), wastewater as a tertiary feedstock for biofuels (TRL3) [167], extracting biopolymers (PHA) from the extracellular slime of biomass (TRL4) [168]. • Wastewater use as a tertiary feedstock for bio-based chemicals (excluding fertilisers) is likely more than 10 years away and is likely to operate within a biorefinery; this would require a multi-step process whereby low-quality feedstock accumulates a biomass in a first fermenter which can act as a primary feedstock in a separate fermentation process to produce a bio-based product.
Technology Applications	**Microbial Fuel cells:** • Synthetic biology is likely to improve the performance of MFCs beyond established approaches such as media optimisation, cell surface modification, material improvements and operation parameters validation [135]. For example, currently, the electrons generated during respiration do not transfer very well to the anode of the fuel cell. Improving the protein carriers on the cell surface, or optimising cell membrane projections that transport electrons would improve this [135], [162], [169]. • Microalgae can replace traditional aeration (a large energy requirement) in MFCs through photosynthetic aeration [163] which saves energy and thus is more sustainable and reduces cost. • Algae and microalgae can also be used in fuel cells without any microbes, and they capture carbon in the process. This technology is promising as it generates electricity, captures carbon, generates biomass, has a long lifetime, and requires relatively low levels of maintenance [170]. **Wastewater as a feedstock** It has been hypothesised that using wastewater as a feedstock could increase energy recovery by 188% and lower disposal costs by 43% [167]. As a starting point, Gross-Wen Technologies is starting to remove nitrogen and phosphorus from wastewater using algae that can be harvested to make fertilizers, bioplastics and biofuels [171]

Category	Trend
Drivers for adoption	• It is generally accepted that we will run out of fossil fuels by 2060 [172], [173]. According to current estimates, we can only burn around 20-30% of available fossil fuels before we reach catastrophic, irreversible levels of global warming [174]. It is imperative that we replace fossil fuel products (biofuels, chemicals, plastics) with sustainable alternatives. • Sugar cane is currently used as a (primary) feedstock for biofuels and other chemicals [164], [165] but this use reduces land available for food production. Secondary feedstocks (non-food crops or waste from primary feedstocks) overcome this issue but require pre-treatment which adds expense and complexity. There also may not be enough of this waste to satisfy demand. Using wastewater as a feedstock would supplement secondary feedstock supply and reduce disposal costs for sludge. It would also generate more revenue for the water industry. • Water companies in England have commenced an initiative to develop a national bioresources strategy [175] and Ofwat is producing frameworks and reports to support the adoption. Bioresources is specifically called out in the Ofwat PR24 guidance on long-term delivery strategies [60].
Barriers to adoption	• The bioresources market is still immature; clearer regulation and a better understanding of the risks involved are needed. • Uncertainty over environmental regulations was the top barrier to bioresources market development found by Ofwat in a recent report [175], followed by regulation around co-digestion and the UK's Farming Rules for Water. • Whilst schemes like the Biosolid Assurance Scheme and the Ofwat Companies market information dashboard are promising steps for the use of bioresources for fertiliser, there are currently no analogous schemes for other uses of bioresources. • Upgrading biofilms using synthetic biology approaches (GMOs) introduces new regulatory barriers and complexity. • Even with fertiliser, some issues remain in the wider water industry: fragmented data (for demand/supply forecasting of sludge), capabilities, capacity, communication and other business case factors such as regulation. Changes to Farming Rules for Water regulation may reduce the demand for fertiliser post 2025. • The reaction rates of MFCs and algal fuel cells are not high enough currently, so the currents generated are low. Currently these fuel cells are being designed to power small sensors and microprocessors [62]. Whilst this will likely be improved with synthetic biology, another way of overcoming the poor financial viability of limited power generation is through harvesting the algal biomass and refining it to use as a feedstock for biofuels, biopolymers and other bio-based chemicals. • A barrier to the sale of heavy metals or other valuable components is that currently, Anglian Water manages the discharge of traders to reduce the amount of heavy metals in the wastewater. If continuing with this model there may not be enough left in the wastewater to sell.

Category	Trend
Cost	• For existing bioresources (biogas, heavy metals, sludge for fertiliser) the cost of developing further sales infrastructure is relatively low. Where extra treatment steps are required, the cost will be higher. • Biofilm upgrade costs should be relatively low, however, genetic modification itself can have a high cost. Deployment in open beds within wastewater treatment would be contrary to UK contained use regulations. • Developing the infrastructure for microbial and algal fuel cells would likely be high due to the advanced membrane technologies required and the fact that it would be a new type of infrastructure for the water sector. Developing infrastructure for wastewater as a tertiary feedstock would be of high cost but would be a substantial new revenue stream for the water industry.
Examples from other industries	**Synthetic biology to create products from alternative feedstocks to fossil fuels:** 1,3-Propanodiol (PDO) is a key intermediate for a variety of chemicals (adhesives, solvents, plastics). It is made from sugar cane or low-cost biomass derived glycerol and now makes up 60% of the total revenue of the PDO market, emitting nearly 50% fewer greenhouse gas emissions than its fossil fuel counterpart. **Synthetic biology to improve processes to make them commercially viable or more profitable** (as would be used in improving organic content to biogas conversion efficiency and to improve microbial fuel cells etc.): Hyaluronic acid is a substance used extensively in cosmetics and the medical industry. Genetic/metabolic engineering was used to make production of it viable with fermentation. This replaced extraction from rooster combs, the previous production method. The market for finished HA products is now worth $20bn [176]. **"Waste" as a revenue stream**: Recycled plastic (i.e.. plastic waste, previously landfilled) accounts for $46.3bn of the $593bn overall plastic market (7.8%) and is growing faster than the overall plastic market. This is in addition to revenue earned from providing the waste recycling service

Category	Trend
Examples of potential future Bioresources revenue creation opportunities for the water industry	**Ttechnology transfer of PHA bioplastic production to the water industry**:analysis of the literature suggests that PHA production could be economically viable for wastewater treatment plants. The estimated minimum PHA cost produced using bioresources would be \$1.26-2.26/kg whereas the market price is \$2.5-5.5/kg [155]. Whilst this study looked at making PHA directly from sludge using acidogenic fermentation and then accumulation, PHA could also be made from methane and CO2, as described in the case studies. There is also interest in generating PHA from microalgal biomass – which could be made from wastewater using microalgae[177]. **Applying hydrothermal liquefaction to the water industry**:comparisons of hydrothermal liquefaction to produce biocrude with anaerobic digestion to produce biomethane show that in the US, this could eliminate \$3.29B across 15,000 treatment plants, increasing energy recovery by 188% and lowering disposal costs by 43% [178]. A techno-economic analysis of microalgal technology implementation in the wastewater industry showed that the production of biocrude from wastewater using algae can completely recover the operating costs (including inoculation, wastewater delivery, cultivation of microalgae, abiotic wastewater treatment, disinfection, solar drying and hydrothermal liquefaction) when the biomass price is \$0.544/kg, equivalent to \$0.9/L of biocrude [179]. Whilst biocrude prices are roughly \$0.39-\$0.48/kg currently, this may increase due to increased demand for renewable jet fuels [180] and renewable diesel [181] It is likely that using algae or microalgae could completely offset the costs of wastewater treatment within the next 5-10 years. Whilst these studies were designed with "sufficient sunlight" in mind, there are developments to photobioreactors (which would likely be required in the UK) that use algae-bacterial consortiums to achieve the benefits of algae.

Bioresources have successfully been used as a revenue stream within the water industry and other industries, examples of which are given in Table 46.

Table 46 Case studies of bio-products from wastewater

Case Study	Details	Benefits / Findings
Kaumera Gum	Kaumera Gum is the first higher-value bio-based product to be commercialised from wastewater with Royal HaskoningDHV, selling tens of tonnes of this per year currently as a bio-stimulant. The market partner is paying commercial prices comparable to those for alternative materials (alginates), with a commitment to increase purchase volumes upon completion of customer trials. The strategy for generating further demand for Kaumera Gum is to prove its value within specific applications, starting with the bio-stimulant use case (Source: Kaumera Interview). Proving value through collaboration with those closer to end users enables demand to be created. Marketplace co-ordination may then be facilitated to further increase demand. One model for this is through a broker type model;	• Removing Kaumera Gum reduces sludge volumes by 20-35% [184] • The first plant was forecast to reduce energy consumption by 30-80% and save 113 tons of CO2 each year [185]. • Commercial results have shown the retail value of Kaumera Gum to be magnitude higher than the comparable value of biogas and critically extracting Kaumera Gum does not significantly change the specific biogas yields of the remaining sludge fraction which

Case Study	Details	Benefits / Findings
	AquaMinerals has been successful with this model for in the Netherlands where they have acted as a broker for a range of waste derived products from the water sector [182] The Kaumera Gum is readily extracted from the surplus waste sludge derived from the Nereda aerobic granular sludge (AGS) treatment process. Nereda has a reduced carbon footprint (25%) and reduced energy requirement (up to 50%) compared to conventional activated sludge. The AGS has been shown to have a higher biopolymer content than sludges from other aerobic wastewater treatment processes with 20-25% of the organic material being recovered as Kaumera Gum. Kaumera Gum can also be used as a paper coating, a fire retardant, as a curing agent for concrete and can be used as part of bio-nanocomposite materials [154]. Kaumera could be used as a slow release fertiliser coating and as a flocculent, where legislation is likely to remove the use of current fossil derived products. The challenge in some applications is to build a supply chain with quality assurance. The first Kaumera Gum production site was in Zutphen in the Netherlands. A second plant was opened in 2020. As of February 2021, the UK already has 14 Nereda plants (with more under contract), so could begin to extract Kaumera Gum [183]. A biopolymer consortium including Royal HaskoningDHV and United Utilities is bidding for Ofwat Innovation funding to accelerate the adoption of Kaumera and other biopolymers in the UK. This involves UK production trials to provide further proof of value, exploring other applications and understanding the carbon and social value of the product. There is great potential from a sustainability perspective to replace fossil fuel derived materials and the consortium is exploring further ways to enhance this position considering access to global supply chains through drying the product and optimising location of the processing facilities.	is sent back into existing sludge treatment (Source: Kaumera Interview). • Trials of Kaumera Gum as a bio-stimulant have shown that 30% less inorganic fertiliser is required (Source: Kaumera interview). • AquaMinerals – a broker in the Netherlands for water treatment “waste materials” has facilitated zero waste in the clean water sector – with all WTW’s sludge and residues sold for profit.

Case Study	Details	Benefits / Findings
Nitrogen and Phosphorus	Gross-Wen Technologies uses algae to treat wastewater leading to lower energy and operational costs [186]. The system is promoted as having multiple uses within wastewater treatment: as a pre-treatment solution for industry; a secondary or tertiary treatment for the water industry or in treating effluent from agricultural anaerobic digestors. The algae system removes nitrogen and phosphorus from the water before the algae is harvested producing a slow-release fertilizer as an additional revenue stream. The company claim that this algae can also be made into bioplastics and biofuels. This could be applied as side stream treatment of the nutrient dense effluent from an anaerobic digestor or sludge thickening supernatant to maximise the value of bioresources.	• Lower energy and operational costs. • Valuable product(s) produced.
PHA	PHA is a bioplastic synthesised by many microorganisms including bacteria and archaea cells. Several companies are commercialising this production including Mango Materials and Newlight Technologies. Mango Materials use fermentation technology to produce the biopolymer PHA from methane. The pellets that are produced are biodegradable (6 weeks in the marine environment) to be readily incorporated into existing supply chains. In 2019 Newlight Technologies built the fully-integrated commercial-scale production system producing PHA from carbon dioxide using micro-organisms [187]	Biological engineering (most likely metabolic engineering specifically) increased the PHA yield for Newlight Technologies by 500%. This high yield has allowed them to outcompete oil-based commodity plastics on price, performance and sustainability. They are now partnered with Ikea and the Body Shop and fabricate branded fashion products.
Crude Oils	In the plastics industry, the hydrothermal liquefaction process is being set up and scaled up globally from New South Wales to Teesside. This hydrothermal liquefaction process enables high grade chemicals and oils to be produced from polymer waste streams. These can then be remade into plastic without the quality degradation that traditional recycling techniques often have. There are some studies looking into the development of this process for the water industry to generate "biocrude" as an alternative to anaerobic digestion. There is also research into microalgal technology to produce biocrude from wastewater.	In the plastics industry, £42M has been invested into the development and testing of hydrothermal liquefaction [188] with the company aiming for 1,000,000 tonnes of recycling capacity by 2025 [189].

Key Impact Areas for the Water Industry

Key impact areas for bioscience solutions are shown Table 47.

Table 47 Key impact areas for bioresource as a revenue stream

Category	Impact Area Description
Performance impact	• Diversification of revenues would provide financial stability and reduce business risk of companies in the water sector. • Bioresources is specifically called out in the Ofwat PR24 guidance on long-term delivery strategies [60].
Botex and Delivery Efficiency	• The conversion of bioresources into valuable products means less mass is disposed of, improving the operational efficiency of waste management. • On the other hand, extra equipment and infrastructure will need to be maintained.
Use for Operational Risk Mitigation, Resilience and Compliance	• An extra revenue stream improves the resilience to financial shocks. • Using a variety of different microbes to process bioresources means processes are more resilient.
Cybersecurity Risks from the Technology	Bio-engineering modelling, simulation of applications and ongoing monitoring will be dependent on hardware and software. That being the case cybersecurity risks will include: • Malicious introduction of errors into the models or simulation which may result in unsuitable products being created (which can cause delays, contractual problems, liability issues, insurance issues or may lead to harm depending on what the bio-product is used for) • Large scale manufacturing could also be at risk from attacks which may stop or slow down production. There could also be introduction of malicious errors here. • Risk of information leakage (which could lead to loss of IP, or sensitive information disclosure on bioengineering techniques to bad actors).
Sustainability impact	• Using waste to create new products conserves non-renewable resources and usually requires less energy and emits fewer greenhouse gases than deriving products from fossil fuels. • When algae are used to convert bioresources to saleable products carbon is captured in the process. • The use of bioresources as a revenue stream reduces the mass that needs to be disposed of thus reducing energy required for transport and disposal.

Category	Impact Area Description
Impact on supply chain and partnerships	• Partnerships will be critical to success in this area as it involves new markets, capabilities and customers. In particular, partnership with other water companies is important for setting standards and pooling resources for new innovation and infrastructure. Partnership with Ofwat will ensure regulations and price controls are fit for purpose. • Finally, where bioresources are serving a new market for the water industry, it is important that communication is clear and thorough to ensure bioresource treatments meet the needs of these new customers.

Technology Timeline

The expected 25-year timeline for bioresource as a revenue stream is shown in Table 48.

Table 48 Technology timeline for bioresource as a revenue stream

Timescales	Technology evolution and Water Industry Impact
In 0-5 Years…	**Technology evolution:** • Optimisation of methanogenic bacteria through synthetic biology approaches will dramatically increase the conversion efficiency of organic content to biomethane. • Improvements to digestors as a result of advanced sensing technology will increase efficiency. • Improvements to heavy metal and microplastic removal technologies will improve the quality of fertilisers (**3.8 Bioscience Solutions for Wastewater** Treatment**)**. • Technology for extracting phosphates (eg., accumulation with algae) will enable higher quality, and perhaps even personalised NPK fertilisers to be produced. **Industry Impact:** An additional income stream will start to be achievable from the sale of biomethane and higher quality fertilisers.
In 5-10 years…	**Technology evolution:** • Secondary and tertiary feedstocks are not yet commercially available due to a lack of a mature conversion technology, however, the rapid advances in protein and metabolic engineering are likely to enable wastewater to be used as a feedstock in around 8-10 years. • Algal fuel cells will start to be used to power sensors. **Industry Impact:** Whilst the use of wastewater as a tertiary feedstock may still be at its early stages in this timeframe, it could become a substantial revenue stream for the water industry as it replaces the function of fossil fuels. It will massively reduce greenhouse gas emissions and improve sustainability.

Timescales	Technology evolution and Water Industry Impact
In 10-25 years…	**Technology evolution:** • A wide range of bio-based chemicals, plastics, fuels and other new materials will be able to be generated from bioresources. • Microbial and algal fuel cells will likely provide significant amounts of power. **Industry Impact:** The potential of bioresources as a revenue stream will be fully realised and become one of the main activities of water companies and the surrounding ecosystem.

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4. Technologies for High-level Analysis

In addition to the top 9 technologies discussed in **Section 3,**Top Nine Technologies for Anglian Water there are a number of other important technologies that have the potential to deliver major impact to the water industry. These are discussed briefly in the section below. Many of these technologies are in relatively early development stage, but they should be closely monitored to inform AW's long term strategic decision making.

4.1 Technology Influenced Demand

Key Takeaway: The introduction and greater adoption of new energy technologies - such as green hydrogen - and new farming technologies - such as hydroponics, aquaponics and vertical farming - are likely to impact future water demand, and could potentially increase demand significantly or change the nature of market needs. The direction, pattern and extent of such impact will hugely depend on the development trajectory of these new technology areas. We recommend AW continues to closely monitor key technology development trends in this area (especially in relation to green hydrogen production) to inform its future strategic decision making.

Overview

New energy (such as hydrogen and nuclear) and farming technologies (including hydroponics, aquaponics, and vertical farming) may have a profound impact on the level and pattern of water demand.

Technologies

Hydrogen: Hydrogen fuel can be produced from a variety of petrochemical or renewable sources. The most sustainable form of hydrogen is green hydrogen, produced through the hydrolysis of high purity water using renewable energy.

Nuclear: This includes small modular reactors (SMRs), nuclear fission power plants and possibly future nuclear fusion plants by 2050. A large nuclear power plant may require up to 1 billion gallons of water a day [190] and, for this reason, they are often built next to rivers, lakes or oceans to utilise these bodies of water. The water is drawn from these sources and heated to create steam to power the turbines.

Future Farming:

- **Hydroponics**: Hydroponics is a type of horticulture and a subset of hydroculture which involves growing plants (usually crops or medicinal plants) without soil by using water-based mineral nutrient solutions in aqueous solvents.
- **Aquaponics**: A food production system that combines aquaculture (fish) with hydroponics such that the nutrient-rich aquaculture water is fed to the hydroponic plants. Nitrifying bacteria convert ammonia into nitrates.
- **Vertical farming**: the practice of growing crops in vertically stacked layers using a controlled environment. Hydroponics is widely used in vertical farming.

Trends

Global green hydrogen production is expected to expand substantially over the next two decades. In the UK, the government has placed low carbon hydrogen production as a central part of its entire energy strategy, and set an ambitious target of 10GW of low carbon hydrogen production capacity by 2030 [191].

In the UK, production cost for green hydrogen is projected to drop to ~£2 per kg [192], which would enable it to compete effectively with other renewable sources.

Hydroponics, aquaponic and vertical farming markets are all expect to grow at a relatively fast pace. In particular the global vertical farming market, which overlaps with both hydroponics and aquaponics, is expected to grow from £5 billion in 2020 to nearly £20 billion in 2026 (CAGR 24%) [193].

Potential impacts for the water industry

On the energy front, the chemistry of green hydrogen production dictates that it will consume 9 kg of water per kg of hydrogen produced; additional process (e.g., cooling) will further increase water demand. Active research is ongoing to find ways to minimise water demand in the production process [194].

It is also important to consider where the new hydrogen production will be located. On one hand, the decrease of fossil fuel-based power generation as green hydrogen takes off may reduce the overall water consumption for power generation [195]. On the other hand, the need for water to support green hydrogen production could still exacerbate water shortage in areas already with high water stress levels [195].

The impact on water demand from nuclear will depend on the types of nuclear technologies UK will adopt.

In farming, despite the significant growth projection, hydroponic, aquaponic and vertical farming will remain a small part of the overall UK agriculture sector in the foreseeable future, so are unlikely to have significant impact on overall water demand. Nevertheless, some of these techniques have reported up to a 90% decrease in water consumption [196], which could still be interesting in some sectors, particularly if climate conditions change.

Existing use cases

As of August 2022, the UK has 9 operational nuclear reactors at five locations (8 advanced gas-cooled reactors (AGR) and one pressurised water reactor (PWR)), producing 5.9 GWe. It also has nuclear reprocessing plants at Sellafield and the Tails Management Facility (TMF) operated by Urenco in Capenhurst [197]. The future of nuclear in the UK is a subject of ongoing debate, but recent surges in global energy prices as well as the need for low-carbon energy production options make it a realistic possibility that additional facilities could be developed, creating further water demand.

Green hydrogen production is in its infancy in the UK, but bp plans a major green hydrogen project in Teesside with targets of 60MWe of ‘green’ hydrogen production by 2025 [201].

Thanet Earth is currently the UK’s largest hydroponic farm that specialises in hydroponically grown tomatoes, peppers and cucumbers [198]. Aquaponics UK is an example of sustainable blend of aquaculture and hydroponics [199]. The world’s largest vertical farm is currently being built in the UK in Gloucestershire [200].

Conclusion

Water is a precious natural resource for next generation of hydrogen and nuclear power generation as well as sustainable agriculture practices, however the net impact of such new technologies on water demand is complex and will depend on how technologies evolve over the coming years; and much of these are outside of AW’s control. We recommend AW closely monitor technology demand in these areas, and proactively to be part of the relevant ecosystems to inform its future strategic decision making.

4.2 Cognitive Engagement

Key Takeaway: Cognitive engagement is the application of artificial intelligence to engaging with employees and customers using natural language processing algorithms. Common examples include chatbots, intelligent agents and machine learning. Whilst cognitive engagement is already used for engaging with customers, advances in cognitive engagement are likely to transform the employee experience.

Putting customers at the heart of service delivery, increasing levels of communication and engagement, and responding rapidly in the event of a service issue have all become critical benchmarks for water companies to meet. Advances in cognitive engagement allow for these increases, whilst minimising labour required.

From an employee perspective, cognitive engagement looks to be transformative to both the training and ongoing work of employees – particularly those involved in practical maintenance or technician type roles. Cognitive engagement can be used to train employees more effectively, using artificial intelligence to accurately assess understanding and tailor training to an employee's specific needs. It can also enable the upskilling of the workforce through augmenting their work with clear instructions or help functions. This should improve maintenance efficiency, reduce errors and enable a more flexible workforce.

Whilst cognitive engagement is an important technology, it is likely to be less impactful on AW's long term delivery strategy than other technologies discussed in this report.

4.3 Quantum Computing

Key Takeaway: Direct use cases for quantum computing may benefit the development of more complex digital twins, but the impact of this is not likely to be felt until beyond 2050. However, cryptographically relevant quantum computers (CRQCs) that are able to break public-key cryptography are likely to reach the market in the next 10-20 years, so companies involved in critical national infrastructure such as water should start planning for migration to post-quantum cryptography now. Crypto-agility (the ability to change and update cryptographic infrastructure quickly, efficiently and flexibly) will be key in maintaining sufficient cryptographic defences throughout the transition period and in the post-quantum computing era.

Overview

Quantum computing is the use of quantum mechanical properties (such as superposition or entanglement) to perform computational operations.

In classical computing, information is stored as bits (0 or 1 - binary). Quantum computing works with quantum bits or qubits (which could be 0, 1 or because of superposition, 0 and 1 at the same time). Quantum computers can therefore access an exponentially larger computational space compared to traditional computers. This makes quantum suitable for solving large scale, extremely complex problems.

Technologies

Current quantum computing approaches usually use either electrons or photons. In the case of electrons, there are quantum processors built into hardware consisting mostly of cooling equipment (which uses superfluid). The processors contain superconducting (at ultra-low temperatures) materials which allow electrons to move without resistance. With some manipulation, this quantum mechanical effect can be leveraged as a qubit to perform computation.

The other prevalent approach to quantum computing is photonic quantum computing, which uses photons as representation of qubits. This photonic approach doesn't require cooling, although other challenges remain (for example, creating logic gates at scale).

Quantum computing has important implications for cybersecurity. Critically, its compute power has the potential to render existing cybersecurity approaches ineffective, as attacks can be far more easily and comprehensively undertaken if compute power is dramatically greater.

There are two kinds of cryptography in widespread use, symmetric and asymmetric:

- Symmetric cryptography is where a secret key is used to both encrypt and decrypt a message. This secret key would need to be shared between the party or parties who need to encrypt and message and the party or parties needing to decrypt it. Once this secret key is compromised, any message protected using this key is also compromised.
- Asymmetric (or public-key) cryptography is where either a secret (private) key is used to encrypt and a mathematically related public key to decrypt (therefore authenticating the origin of the message), or where the public key is used to encrypt, and the private key is used to decrypt (therefore ensuring that the message is only accessible by its intended recipient, being the owner of the private key). In the case of key exchanges (e.g., when a symmetric key needs to be shared), public and private keys can be used in combination to form a secret key over an insecure channel.

Widespread symmetric key implementations such as AES-256 are considered quantum resistant for now [202]. There is research into the likes of Grover's algorithm (a brute force attack which reduces the time needed to break AES standards). However, the quantum computer required for this would need to be very sophisticated, and the likes of AES-256 would still need around 2^{128} iterations, which is considered quantum resistant [203]. Despite this, there are suggestions that symmetric key lengths should be doubled to ensure that it is quantum safe in the long term.

Much of the nearer term risks lie with implementations of public-key cryptography such as RSA or Elliptic Curve Cryptography (ECC). The foundations of these approaches rely on the fact that prime factors (which are used in the creation of the public and secret keys) cannot be calculated easily with current computing methods. However, the development of Shor's algorithm [204] in 1994 changed this assessment. If a quantum computer with sufficient numbers of qubits were available, Shor's algorithm would mean that public-key cryptography such as RSA and ECC would potentially be broken in days or weeks, rather than the current estimated millions, billions or trillions of years.

The implications of this are enormous, since public-key cryptography is the basis for public-key infrastructure (PKI), in which these keys are bound to identities of individuals, parties, organisations, devices, components, assets and more.

Achieving crypto-agility

To counter this threat, data and systems owners will need to develop a more agile approach to defending against cyberattacks. We refer to this as 'crypto-agility'. Crypto-agility refers to the capacity for an information security system to adopt an alternative to the original encryption method or cryptographic primitive (low-level algorithm), without significant change to system infrastructure. In other words, it is an approach that allow an organisation to adapt quickly to different cybersecurity risks depending on requirements.

For example, there are two basic approaches to ensuring quantum resistance in the cyber-security field, when looking to protect a system/network:

- ***Change the system (redesign):*** Firstly, architectures and flows could be redesigned, where appropriate, for use with symmetric cryptography. Standards such as AES-256, for example, are well established and readily supported in off-the-shelf solutions. However, there are two major drawbacks beyond the redesign and redeployment effort. Keys would need to be distributed periodically, which presents logistical challenges where areas such as IoT are involved (creating and managing different keys for millions of devices, secure storage for these keys at the edge, ready communication for key exchanges, etc). Furthermore, the most prevalent key exchange mechanisms use public-key cryptography which are not (yet) quantum safe.

- ***Update the system (migration):*** Secondly, updating through a migration to post-quantum cryptography (PQC) where required. PQC primitives already exist. However, there are challenges in backwards compatibility and potential cascading impacts with regards to performance and reliability due to differences in key or signature size, error handling, execution steps etc.

The above scenarios (whether migration or redesign or both) will require planning and the ability to adapt over a long period of time, and this is where a 'crypto-agility' approach is key.

- As with any strategic activity, the first priority will be to build or maintain a cryptographic inventory including keys, certificates, algorithms, protocols, policies and providers as well as their use and interaction in applications, devices and infrastructure.
- There would also need to be a dedicated team to map out and prioritise high-value assets, such as those that are externally facing, operationally critical, or safety related. Systems would also need to be further assessed for properties such as updateability, extensibility, reversibility and modularity of cryptographic algorithms, mechanisms, software or hardware (and the systems in which they reside or interact with) to determine changes that would need to be made to mature these areas.
- There are several schools of thought on the specific migration process, concentrated currently at the algorithm level due to the low maturity of these PQC schemes.
    - The first is a hybrid scheme where two "engines" are run: the traditional asymmetric approaches as well as the post-quantum ones. This approach may safeguard a system as long as one of the two remains unbroken.
    - The second is through combination (which takes multiple crypto-components and combines them into a new one), useful for components such as key exchange mechanisms.
    - The third is through composition, whereby multiple post-quantum algorithms are combined in one format to form a composite key structure.

Consideration of future standards is also a key part of a crypto-agility approach. Standards are being developed for specific quantum-safe algorithms, with more under investigation. However, until these are released, there are open issues to be considered, including:

- Performance: Although many algorithms have had a substantial body of work behind them, they have not been deployed in many real-world situations at scale, and therefore impact on performance is still not clear. For example, IoT devices often have size, weight and power constraints and larger key sizes, so requirements such as having to store multiple sets of keys may impact on design and communication.

- Security: These algorithms were specifically developed for quantum-resistance, but may face new challenges such as novel side-channel attacks. Again, this is an active area of research, but would remain an open consideration nonetheless in an operational environment due to low maturity of the PQC space in general.

- Implementation: Wholescale migration of entire infrastructures would remain challenging, as we have already seen in some of the digitalisation drives with regards to smart infrastructure. Since there are no standards, this may need to be managed in a different way to traditional systems (whether in IT or OT). Managing legacy systems, backwards compatibility and interoperability will likely be the biggest challenges [205].

- Monitoring: This will be an essential part of the process (especially real-time monitoring internally and externally) and will also be key in achieving agility.

Trends

Whilst there is a significant body of research on quantum computing, including quantum software and quantum algorithms, market adoption of large-scale general-purpose quantum computing is still emerging. Market barriers are summarised below.

Firstly, technology readiness level is still low, although significantly accelerated in recent years by large technology companies such as IBM. Expectations are for fault tolerant quantum computers to become available in 10-15 years, with widespread use in infrastructure applications even farther out.

Secondly, the cost of quantum computing in prohibitive for many applications, and is expected to remain so until the technology is much more mature.

Finally, the expectation is that there will never be a pure quantum computing system; such a system will always exist in tandem with classical computers. The combination of these two types of systems is also an emerging space, and there is still significant uncertainty as to the most efficient or most secure architectures.

Potential impacts for the water industry

The main area of relevance for the water industry is cybersecurity. Due to long planning periods for critical national infrastructure, crypto-agility should be considered by water companies now. Many authentication, authorisation and verification systems depend on public-key infrastructure (or asymmetric cryptography), which has the potential to be broken by quantum computing's ability to calculate large scale problems.

A second area of interest for the sector is likely to be in the area of digital twins. Realism of such 'twins' is currently limited, due to computational limitations of classical computers. This is because of the extremely large number of components that require a virtual representation, the level of fidelity infrastructure modelling requires, and the propagation of effects through time that will need to be simulated. Quantum computing could therefore be significant in ensuring faster and better digital representations of reality.

Existing use cases

There are significant activities in quantum computing, ranging from developing the hardware, to creation and development of established quantum computing simulators which can be used to prototype quantum algorithms or circuits. These simulators could be used for early investigations when exploring how quantum computing might accelerate the development and/or ongoing maintenance of digital twins.

Quantum computing can also be combined with other quantum processes (such as quantum sensing) to enhance the performance of both; for example, being able to classify in real-time without having to consider data stored on disk.

For the security use case, the most mature form of quantum computation in use is in the generation of random numbers (which are essential to cryptography). Classical computing is only pseudonymously random as they are dependent on deterministic algorithms. Quantum key distribution is also being developed as an alternative highly secure key exchange mechanism that will be essential in future cryptographic methods.

Significant ongoing global initiatives are listed below:

- Most of the effort globally is spearheaded by the US federal government, who are increasingly concerned by the long-term threat that CRQCs pose. For example, President Biden signed the Quantum Computing Cybersecurity Preparedness Act into law in December 2022. The US has adopted aggressive timelines to kickstart crypto-agility, for example, by mandating a full crypto-inventory from all federal agencies barring national security systems by May 2023 [206]. The Office of Management and

Budget must create a strategy to manage the risk posed by quantum computing within a year of the law being enacted [207]. NIST itself has in July 2022 announced four quantum resistant cryptographic algorithms for general encryption and digital signatures to be included in in post-quantum cryptographic standards, with another four under further investigation [208].

- The UK National Cyber Security Centre acknowledges the threat in the long-term of CRQCs, although advises care in migrating too quickly, due to the open challenges listed above. Furthermore, they point towards the work of the US National Institute of Standards and Technology (NIST) and the European Telecommunications Standards Institute (ETSI) as notable guidance. It is therefore likely that any UK activity will be modelled after standards that are emerging in the US and in Europe.
- There are no instances yet of critical infrastructure operators having put crypto-agility in place. This is likely due to the low maturity of the PQC space. However, with the impetus from legislation, there will also very likely be requirements emerging before the 10-20 “year-to-quantum” estimate.
- Other spaces such as banking have started to implement some of what is necessary (albeit mostly in IT rather than OT networks; some parallels could be drawn since they make use of hardware security modules or HSMs in devices such as ATMs). For example, Barclay’s have integrated a cryptography management gateway [209] which allowed them to record any vendor specific information, share information on different HSMs, allow shared use of HSMs across different projects and make it easier to audit. This centralised gateway system also allows the business to enforce policies such as key length, rotation, mode of operation and so forth. Although not a complete solution, such approaches are key components towards crypto-agility.
- We are also starting to see proliferation of services, applications and products on offer, ranging from cloud companies such as Amazon Web Services [210] who offer hybrid solutions, through to defence companies such as Thales [205], as well as a slew of security company start-ups offering solutions such as key management systems, through to licensing of PQC IP.

Conclusion

Quantum computing will likely be highly disruptive, but the technology will take time to develop fully. All indications are that fault-tolerant quantum computers will become available around 2035, although specific use cases around quantum sensing and quantum random number generation may come sooner. The wide use of quantum computing in the water industry is very likely to beyond the current planning period of 2025-2050.

Considering the long design and deployment lifecycle of critical national infrastructure such as water networks, adopting a crypto-agility approach should be considered as a way to future-proof the design of such infrastructure and the systems that manage it.

4.4 Self-healing systems

Key takeaway: Self-healing materials are an emerging class of materials. Despite their potential long-term promise for the water industry, there are significant technical, commercial, and regulatory barriers to overcome, for the technology to be adopted. It is therefore not considered likely to have a significant impact within 2025-2050.

Overview

Self-healing materials are an emerging class of smart materials that are capable of automatically repairing damage without human intervention.

Technologies

A broad range of materials include polymers, polymer composites, metal alloys, cementitious and ceramic materials have shown self-repairing capabilities through physical, chemical, and biological mechanisms [211].

Trends

Self-healing materials have been steadily attracting increasing levels of interest in the past decade. We have seen both scientific publications and patenting activities increasing significantly during that time, but the area remains largely an academic research topic, apart from some very specific high-end applications (e.g., in the aerospace industry; see existing user cases below). Project Shine under EU FP7 explored the scale-up of self-healing elastomers without noticeable success.

We expect the upward trajectory of research activities to continue, however commercialisation of such materials (especially for infrastructure related applications) will take a significant length of time and is very likely to go beyond the current planning period of 2025-2050.

Potential impacts for the water industry

Self-healing materials are being explored for a number of specific high-end applications in biomedical, aerospace/nuclear, construction and sealing applications. Examples include:

- ***Hydrogel for tissue repair and regeneration***. Despite significant research in this area, the technology is still at pre-clinical stage [212]
- ***Alloys and composites for heavy industry.*** There are reports that specialist self-healing metal alloys and composites have been used for fixing critical components in the aerospace and nuclear industry [213]. Such materials are not commercially available.
- ***Self-healing polymer elastomers.*** These have been explored for industrial applications such as dynamic seals, damping and noise reduction, but no commercial product is available yet [214].
- ***Self-healing concrete.*** This is being explored by multiple European start-ups (e.g., Basilisk, Mimicrete) for infrastructure related applications, however TRL is still very low (likely be to 4-5) [[122] [215].

Conclusion

Whilst there is a significant body of research on self-healing materials, market adoption of such materials is still nascent. There are significant technical and market barriers for the water industry to adopt self-healing systems, which include low technology maturity, high cost, difficulty of obtaining approval for drink water related applications, and inability to be retrofitted to existing infrastructure.

Nevertheless, the technology holds much potential for the water industry when the above-mentioned challenges are properly addressed. We recommend AW should monitor technology development in this area, and regularly review whether and how it should respond.

4.5 Carbon Capture Technologies

Key takeaway: The most direct area for carbon capture opportunities in the water industry is in sludge treatment. Analysis has however shown that the cost and complexity of this application is likely to be disproportionately high, compared to the carbon reduction it can achieve. Changes in process and consumption – e.g., improving energy efficiency and using renewable energy – are far likelier to achieve significant carbon reduction. In addition, the water industry can contribute to sustainability of rural areas by working with partners (e.g., farming communities) to promote regenerative agriculture, and better management of wetland and peatland)

4.6 Desalination Technologies

Key Takeaway: Desalination in the UK is usually seen as a last-resort due to the high energy requirements and waste products produced. However, as water scarcity increases, technologies that could derive drinking water from sea water at sufficiently low energy use, with significantly reduced waste, may become necessary and even attractive. The Middle East has 47% of the world's desalination capacity and been heavily investing in desalination for a long time. Alongside of this, the energy requirement for desalination has reduced over time. It is therefore recommended that the technology is monitored, ready to deploy when costs become sufficiently low.

Overview

Desalination refers to the use of technology to convert saline water into fresh water.

Technologies

Current approaches broadly use either membrane-based or thermal approaches, and require significant energy for the process. Future desalination technologies included nanotechnology enabled advances in membranes, capacitive de-ionisation, solvent-based extraction, batch/semi-batch reverse osmosis and microbial desalination cells.

Trends

For desalination to become attractive for adoption, the energy requirements need to reduce dramatically. Whilst energy requirements have come down by an estimated 60-86% in the last 50 years [216], progress has been slower recently (<10% over the last 10 years) [216]. There is a theoretical minimum amount of energy required for reverse osmosis of water (1kWh/m^3) which is higher than the current energy requirement for surface water, groundwater or reclaimed water (0.43, 0.78, 0.82kWh/m^3 respectively, figures from China) [217].

Therefore, the energy requirements for reverse osmosis will always be higher than alternative sources of water. Systems such as energy recovery devices, and approaches such as co-locating renewable energy with desalination, could assist with reducing overall costs [216] to an acceptable level. An acceptable level to attract investment is likely to be when the cost is on par with existing water supply costs (based on AW internal interview). Currently, water desalination is roughly twice as expensive as obtaining water from other sources (taking research from China as a base case) [217]. Reduction in renewable energy prices could be a factor in achieving an acceptable cost. Solar energy, in particular, could play a key role in achieving an acceptable cost level [218] as future cost estimates show costs are likely to decline by 50% by 2050.

To be truly transformative to the water industry, progress is needed on approaches to re-use or disposal of the concentrated brine. MIT claim to have developed a process for turning the concentrated brine into useful products such as sodium hydroxide, which is itself used to pre-treat seawater before desalination [219]. However this is still in early stages of development.

Potential impacts for the water industry

If the costs can be reduced and progress made on the waste products of desalination, desalination could be transformative for the water industry, as it would enable an alternative water source which would diversify the water industry's portfolio of water sources. Diversifying water sources enables greater flexibility in water resource management plans, and enables preservation of groundwater sources.

Existing use cases

The Middle East has been heavily investing in desalination for decades and provides some useful examples of approaches [220].

Conclusion

We recommend that AW should monitor this area with an eye to the impacts of climate change as well as technology trends. Innovations in technology and infrastructure related to desalination can be monitored by watching developments and adoption trends in the Middle East, so as to be ready for deployment if the trigger conditions are met.

4.7 Low Carbon Construction

Key takeaway: Low Carbon Construction will largely be driven by advancements in site management and construction techniques through the supply chain. Anglian Water can drive towards this by setting out aggressive targets for waste reduction and carbon reduction as part of its capital maintenance programs.

Overview

Low Carbon construction describes the shift in the construction industry to a more sustainable approach to construction.

Technologies

Low carbon construction encompasses a number of key behavioural, process and material changes such as:

- A circular economy approach to site management – reducing waste on site, re-using materials, re-using and re-cycling existing materials and assets.
- Reduced impact construction methods – no dig pipe repairs using unmanned pipe inspection and repair vehicles.
- Utilising low embodied carbon materials from local suppliers.
- Utilising low carbon transportation methods such as rail, hydrogen or EVs powered via renewables.
- On-site generation and energy storage.
- Reducing re-work on site by carrying out 4D-synchro planning and advance design techniques.
- Reducing time on site through off-site manufacture and modular construction.

Trends

According to the Institute of Civil Engineers, infrastructure is responsible for more than half of the UK's total carbon emissions. The ICE chairs The Carbon Project, where they are spearheading the drive towards improved carbon accounting, better site practices and improving construction techniques. This industry drive, and others, will assist in the development of improved techniques, but requires client side KPIs to drive improvement and accountability.

Potential impacts for the water industry

These techniques are highly relevant to the water industry – and some are already in widespread use. Improved stewardship on-site, better management of the natural and built environment and a reduction in the carbon-intensity of the supply chain will all contribute to a vastly less carbon intensive construction process for new water facilities.

In addition to changes in practice for new construction, there are significant challenges – and benefits to be realised – from introducing greener adaptations during the management, upgrade and refurbishment of brownfield sites in the water sector.

Existing use cases

This trend is more a general movement for the construction industry, rather than a specific transformational technology. The approaches and technologies listed above are being adopted by most leading construction firms.

However, this is likely to be a key aspect in future delivery of capital programs and a differentiator for supply chain participants.

Conclusion

Engage with the cross-sector construction industry to garner best practice in relation to low-carbon construction. With so much of Anglian Water's carbon footprint associated with construction and capital maintenance of its assets, reducing carbon intensity of these operations will be a major driving factor in the move to Net Zero Carbon.

4.8 Decentralised Infrastructure

Key takeaway: Decentralised infrastructure refers to facilities to produce, transport, and store clean water, as an alternative to (or in the absence of) existing large scale centralised water infrastructure such as water and wastewater treatment plants. Whilst decentralised infrastructure increases flexibility and resilience; it will also create efficiency and security challenges. The approach is more suited for areas where centralised infrastructure is unable to provide sufficient service, and has the potential to encourage use of local and renewable resources (e.g., microgrid energy, and greywater). Decentralised infrastructure has an important role to play for the water sector, however it is unlikely to fundamentally impact the way the water industry operates by 2050.

4.9 Open Data

Key Takeaway: Open data will play a key role in enabling long term industry improvement, as it can enable much greater transparency about water operations, customer behaviour, and infrastructure use. The broad view of operational and customer KPIs across multiple players in the sector that open data can provide should support more accurate and effective development and adoption of important improvements and best practice. There are many relevant open data and data sharing use cases both in the water industry and in other infrastructure sectors such as telecommunications and energy. Benefits include improved information to feed into long term adaptive planning, initiatives such as decarbonisation, and customer and consumer engagement. Although there are currently no specific UK regulations surrounding open data, there is a clear signal from the UK government and a strong push from Ofwat to work towards an open data ecosystem, with formal regulations not ruled out. Implementing open data policies will take time, with a number of legal, technical and logistical implications which should also be taken into account in the LTDS.

Overview

Open data is the concept of making shared data from a variety of sources available to anyone who may wish to adapt, process, collect, collate, analyse or otherwise use the data, without restrictions, to support analysis for any purpose (but at least notionally for collective benefit of some kind). The concept also encompasses enabling mechanisms such as open policies, infrastructure, standards, registers, identifiers, interfaces and so on. The sharing of good quality data is intended to promote innovation, trust and transparency. New use cases and wider trends could also be identified.

Technologies

Identity and access management (for datasets and for users) as well as transfer mechanisms including:

- Cross-sector application programming interfaces
- Interoperable systems
- Data portability e.g., machine readable transfers
- Data acquisition from IoT devices

Trends

Data in general is becoming more open, with the arrival of standardised interfaces and protocols, as well as more widespread accessibility due to prevalence of off-the-shelf solutions and connectivity.

Ofwat has recently identified the opportunities of open data in the water industry, in their report “Open data in the water industry: A case for change”, calling on water companies to make measurable progress in delivering open data to keep pace with the digital economy. 2023 will see Ofwat begin scoring and benchmarking water companies on their journey towards open data maturity.

Open data in the wider world is driving greater transparency in public services and government. The World Wide Web Foundation has recently published its 4th edition report on open data, and has taken the position that governments must make data open to enable a cascade of benefits and improved accountability. This is highly relevant to water companies, given their important role in providing critical infrastructure [142].

In the private sector, it is anticipated that more businesses will open up their data sets to enable closer and more automated relationships with their supply chains. This could be a critical aspect to improving procurement processes for the water industry, for business operations and capital programs [143].

As of now, few water companies have opened up their datasets, even though many use open data made available by others outside the industry, such as the Met Office. Digital Built Britain has taken the lead on providing a national framework for Building Information Management (BIM), and open data is a key facet of this, particularly for critical national infrastructure.

Adaptive Planning

Technology scenarios are difficult to plan for in the long-term, especially as the movement towards digitalisation and development of associated technologies accelerate. Adaptability is key to ensuring continuity in the long term, and this is where open data can have a significant role, by increasing transparency and the ability to predict trends based on much broader datasets from combining different open data sources.

This has already been shown to be the case in predicting future water demand, e.g., through the study on the impacts of weather by Affinity Water [221]. Anglian Water has also undertaken activity in this area such as the creation of open datasets regarding consumption hotspot prediction or impacts on people living at home during COVID-19.

Beyond the water industry, we are also seeing other critical national infrastructure partake in open data initiatives. For example, National Grid’s Electricity System Operator (ESO) provides an application programming interface (API) from which consumers and businesses such as car charging companies can draw and analyse data to provide better insights and services [222].

Infrastructure planning could also benefit from a multi-way open data exchange, since by its very nature this activity encompasses many different parties and requirements that need to be traded-off against one another. Open data could arguably allow for more factors to be inputted into the final decision from stakeholders including government, consumers, academia, company employees and so on.

Data sharing should also stimulate or accelerate innovation [223], [224]. For example, SymTerra's mobile app (which provided a detailed overview of London's trunk sewer network) was adopted by Thames Water [225]. This allowed the Strategic Pumping and Trunk Sewer team to record where they are and condition of assets across 1000 locations, as well as generate updates of progress and issues (such as best entry point or if traffic management is required) using 'what3words' as a location tracker. This is uploaded to a cloud-based knowledge library that integrates with Thames Water mapping and modelling systems.

Setting an open data framework early is also important, to start gathering and sharing data that identifies long term changes to the context and environment for water users and providers, whether driven by technological advancements, the demands of a growing population or the effects of climate change. Having data that is easily available enables water companies to start planning for and addressing these challenges, earlier and in a more cost-effective manner than if it is done in a purely reactive way.

Customer engagement

Customer data sharing may well have an impact on building customer engagement with water providers and the regulator. This objective is highlighted in Ofwat's H2Open document [221], which encourages consumers to report on leaks or other issues and suggests introducing efficiencies such as convenient splitting of bills. Such engagement can also be used in water conservation initiatives, especially in newer forms of water supply and demand such as decentralised water infrastructure. This was demonstrated in a recent pilot case study in Naples, Italy [226]. Data sharing may also ensure vulnerable customers' needs are met. Any insights or information that is not sensitive could also be shared with customers in a transparent manner thereby building trust and increasing engagement even more. It is of course critical to ensure consumer data privacy laws are fully respected, so compliance is key in this area.

Industrial customers with ease of access to open data could also use it to help with planning, for example to ensure that activities such as plumbing works and prevention of contamination are considered early on in their architectural or operational design.

Decentralisation

The concepts behind open data may also help with any initiatives in decentralised water. One of the most challenging aspects of decentralisation is how to ensure interoperability between decentralised sites; open data standards would ensure that data is able to flow between these sites efficiently. Furthermore, the managers of decentralised sites (which are likely to be smaller and with less resource) would be able to access data from multiple sources to build models and prediction power without having to build and maintain a repository of their own [227].

Regulation

The case for open data in an industry where there are many players in the chain from source to household is clear. Being a consumer of open data is also very likely to be highly beneficial in terms of better insights and forecasting as discussed above. But as a generator of data in the water industry, where the business handles the provision of water from end-to-end, the business case becomes less clear, since all generated data concerning water is held within the business in any case.

A key driver for open data, beyond the business case, is policy and regulation. Although there are no current regulations mandating open data in the water industry, there is a clear signal from the government to push towards such an environment. This is embodied in the final paragraph of Ofwat's H2Open report [221] , in which Ofwat states it intends to consider the extent of progress and what "formal tools" might be at its disposal to accelerate the use of open data in the sector, should progress not be sufficient.

Potential impacts for the water industry

There are opportunities through open data to stimulate more innovation, identify new business models, tackle shared challenges, and improve transparency for customers in the water industry, with the sector providers, assets and customers all able to serve as both data generators and data users.

Whilst the sector overall can benefit from having access to open data, the return on investment for Anglian Water as a data generator is more uncertain. Stakeholders may be able to use AW's data to innovate and share products and services with data generators, but the impact of such an innovation (transformative, disruptive, or incremental) cannot be predicted at this stage. Decisions on whether sharing data makes sense will likely need to be on a case-by-case basis.

Anglian Water would also benefit from having access to wider datasets, which can be used to draw insight and improve performance. Negotiating data access could also mean better management of shared assets. Companies will need to agree on a data standard and any governance processes prior to releasing data to the public, since there will likely be commercial liability for inaccurate or misleading data. Standardisation is currently being actioned via Project Stream, an Ofwat funded innovation project chaired by NWL. The aim is to build a "network of data pipes" so that industry datasets can be accessed in an efficient and secure manner.

Existing use cases

In the UK, open data frameworks exist for energy and transport, including Network Rail Abroad [228], [229].

The Agricultural Research Institute in Cyprus are utilising open data for location and type of crop to calculate the monthly water needs and economic water productivity, as published by the ARI. This allows farmers to use this data to control the use of irrigation water [144].

Engineering firm Arup has developed policy frameworks that focus on the role of open data to deliver new, better or more efficient services in cities, while responding to decreasing public sector budgets. Arup incorporates open data as part of the technical architecture required to overcome constraints in cities such as traffic and congestion and improve engagement between citizens and city leadership. The company has developed a risk information action system, The Hazard Owl, which uses real-time natural hazard information from public data feeds. It is used to alert clients to natural disasters so they can mitigate against risk and act to protect their businesses and homes.

Opensensors.io provides an IoT platform that helps users create smart products and services to build better connected systems and environments, with data shared on an open data platform. Use cases include smart car parks and optimising office HVAC systems through sensors and connected controls [145].

Additional examples of existing use cases that have potential relevance to the water industry are included in Error! Reference source not found..

Conclusion

The benefits of open data initiatives include improvements in operational efficiency and environmental impact, and can also lead to improved relationships with customers, the supply chain and the research community.

Open data usage is not without its challenges, which in turn may also require provisions in AW's LTDS. There are specific implications surrounding the use of open data that AW should consider

- Firstly, data storage and distribution issues. Cloud centres and other IT or OT infrastructure may have to be expanded significantly to deal with large numbers and volumes of data, with associated challenges such as quality management (sanitisation, aggregation, collation, upkeep etc.) and cybersecurity. Data would also need to comply with relevant regulations (such as privacy laws if datasets contain identifying data), creating an additional regulatory burden.
- There may also be liability issues, for example if the open datasets were to contain commercially sensitive or narrowly-licensed data from non-participating organisations such as suppliers.
- Furthermore, data may lead to pinpointing of vulnerabilities in what are often legacy systems, which could pose a security risk, particularly if nation state adversaries are also able to access this.
- Access to data may lead to increased complaints and negative customer engagement. This could result in reduced customer satisfaction and therefore penalties to water companies through Ofwat's Outcome Delivery Incentive mechanism. Additional public engagement to educate customers about the data may be required to counter this.
- Finally, there would also need to be capabilities in the organisation to handle the above issues. As such, if open data is to be part of the LTDS, such logistical considerations would also need to be included.

4.10 Trust & Assurance in Technologies

Key Takeaway: A high level of assurance is critical to stakeholders' trust in cyber-physical systems, the specific requirement of which will depend on the system setup and risk tolerance levels of the organisation. Anglian Water should continue exploring the integration between the necessary requirements for the level of assurance needed to support its services and operations, drawing from existing standards as well as emergent standards from analogous sectors. AW can lead the water industry in this area by having the necessary processes in place in advance of upcoming standards or legislation.

Overview

Assurance is the level of confidence that can be established in a product, service or system, backed up by a body of evidence. An appropriate level of confidence, supported by clear evidence, can give stakeholders trust in the system and encourage usage and innovation.

The body of evidence required to give this confidence (and therefore trust) is highly dependent on the system property (e.g. safety, performance, security) as well as the risk thresholds acceptable to the organisation.

Technologies

Assurance is interdependent with risk – the higher the risks, the more assurance is required (and therefore the more abundant and rigorous the body of evidence needs to be).

Technologies that support assurance come in two forms: validation and verification.

- Validation technologies aim to ensure that the system is fit for purpose, and include technologies that support stress testing, ensure adequate protection of interfaces, and ensure compliance with legal or reporting requirements (e.g., regulatory technology that helps in auditing and reporting).
- Verification technologies aim to ensure that the system meets specification. This could include use of formal verification, code inspection, sandboxing, physical testing or otherwise testing against and complying with relevant technical standards.

Trends

There is a trend towards a greater proportion of assurance cases using probabilistic risk assessments (and the associated validation and verification methods) rather than more deterministic processes. This is due to three factors:

- First, the rise in connectivity (e.g. more connected devices, IoT systems, processes, data storage and analysis), which means that a closed system now becomes part of a much more open and complex system-of-systems
- Second, the growing use of off-the-shelf components in the supply chain, where before there was a greater proportion of control since bespoke specialist hardware and software was developed in-house (particularly in heavy industrial and utilities sectors).
- Thirdly, the acceleration of digital technology development and adoption (e.g., AI, cloud computing, IoT etc.) and the subsequent speed of change in the security threat landscape which means more flexibility and agility is required.

Potential impacts for the water industry

As systems become more connected and ecosystems become more complex, with the need to consider long development and deployment lifecycles, assurance processes will need to be adjusted and new ones made to deal with the changes in the digital space.

This will need to be done across all the major factors (safety, security, and performance) as well as major new technology developments (such as AI) and assurance is also needed for the interactions between each of these areas and systems, to ensure safety, integrity, compliance and performance reliability.

Existing use cases

Existing use cases for deployment of assurance design approaches, software and processes are usually aimed at developing or refining processes (rather than focusing on specific technologies, since this varies by system and organisation) to meet assurance requirements.

For industry settings, this has been predominantly focused on how to successfully navigate the interactions between safety, performance, and security, with standards and protocols specifically created for assurance, often at the level of the specific industry sector.

For design of operational technology, there is IEC 612443 for security. In the automotive industry, this has given rise to ISO/SAE21434 (coupled tightly with the more mature ISO26262 road vehicle safety standards). For the power grid, this takes the form of IEC62351 for certain protocols.

Overarching frameworks such as the NIST Cybersecurity framework have also drawn together recommended combinations of approaches to assure security.

Conclusion

We recommend that Anglian Water continues to explore the integration between the necessary requirements for the level of assurance in different parts of operations, drawing on existing standards as well as emergent standards and protocols from analogous sectors. From there, a toolbox can be created to standardise the assurance process for Anglian Water, with the opportunity to become a leader in this area for the water sector.

4.11 Web3 Technology

Key Takeaway: Web3 is fundamentally about decentralised Internet. Why is this relevant for the water sector? In part because many of the same concepts and approaches can be applied to industrial settings, to support decentralised control and management. Applications for the water industry could include decentralised infrastructure management, and supply chain traceability. Whilst the fundamental principles of Web3 are well established, market adoption is still at early stage. AW should consider Web3 as part of its decentralisation toolbox, to help enable decentralised asset management (especially considering the broader conversation around decentralised infrastructure and community participation), as well as to help with compliance requirements in the medium to long term.

Overview

Web3, as a concept, refers to an Internet that is equally owned and controlled by its participants, rather than the more centralised forms of Internet 'asset' ownership that we see today. A key component is distributed ledger or 'blockchain' approaches to registering, storing, transacting between and sharing information about assets, activities and ownership, in a way that is fully decentralised rather than held by a central entity.

This decentralised ownership concept can equally apply to industrial settings. This approach to re-organisation of ownership, control and identification of digital assets or digital-physical information is particularly suitable where a more distributed form of service needs to take place (such as decentralised water supply) or where assets need to be tracked or monitored, such as in the supply chain.

Technologies

This concept is facilitated by decentralised mechanisms. The key technologies are the blockchain, smart contracts and non-fungible tokens.

- A **public blockchain** is a form of distributed ledger technology. It comprises a series of blocks (which can represent anything from a token to an asset, to a record, to a transaction) linked together using cryptographic methods. Private or closed blockchains can also be used, within an ecosystem or group of participants.
- A **smart contract** is a unit of pre-defined executable code stored on a blockchain. They are useful in automatically and efficiently (at machine speed) transacting an agreement when pre-conditions are met.
- **Non-fungible tokens** (or NFTs) are unique cryptographic identifiers representing an asset. The asset represented could be anything including physical equipment, locations, documents, data or currency. These are commonly used to assign and prove ownership, provenance or authenticity of an asset.

Trends

Web3 technologies and their mechanisms are well understood. Their application, and the related business case, are less mature. Many of the high profile applications (such as cryptocurrencies) have a high degree of volatility and instability – partly due to absence of regulation (although that is changing), and partly due to broader trends in (and the nature of) the financial sector and geopolitical situation.

However, there have been many other explorations of how these technologies can be used in the industrial setting. Examples include use in supply chain management and traceability, management of digital identity and credentials, as well as management of assets.

Potential impacts for the water industry

The two largest areas of potential impact are:

- **Management of decentralised assets or infrastructure**. Blockchain mechanisms could be used to manage information systems such as the data and devices surrounding supply-use-consumption-discharge at or across myriad sites, communities, and partners. Decisions and measures could be encoded as smart contracts to ensure automatic and efficient executability without having to refer to a central authority. Public blockchains (if implemented correctly) are also immutable and therefore can serve as a tool for auditing.
- **Supply chain traceability**. Since components from the supply chain can be logged and tracked (e.g. using NFTs), execution errors, such as faulty parts, duplicate payments, delayed shipments or missing inventory can be traced. Although current resource management platforms also offer similar capability, it can be hard to connect the chain of events that might have led to an erroneous situation, something which a blockchain can alleviate. Because of the way blockchains work, each participant also owns a copy of the blockchain, which means each party can review the chain of events or transactions equally. Supply chain traceability is not only important for commercial reasons; it is also key to sustainability and net zero efforts.

As ever, since this is a digital technology, there are cybersecurity threats. Risks arise from weaponising the immutability of the blockchain (if a false or malicious record makes its way onto the blockchain there is no easy way to remove or mitigate it). Smart contracts – being code – could be subverted in the same way as any other software application. Web3 presents unique considerations with regards to identity management and computing resource, which in turn requires time and resource to be spent on re-architecting existing systems if they are to interact with Web3 systems and applications.

Existing use cases

Decentralised information systems are still mostly at around technology readiness levels 3-4, with some proof-of-concepts for the water sector presented in academia. The supply chain use case is more mature, around technology readiness level 5-6 (at demonstration or pilot stages) with solutions being developed by companies such as IBM, and with implementation at some level by companies such as Walmart Canada, Cisco, Telefonica and many others. In most cases, the relevance of the technology for ensuring authenticity (eg of technology components) is a key driver of adoption.

Conclusion

Web3 would be a useful addition to the decentralisation toolbox, especially considering the larger conversation about decentralised water and community participation in serving future water needs. However, the technologies are not really mature at this point, and as with everything digital, caveats around the cybersecurity risks remain.

We conclude that if a decentralised framework were adopted by AW (eg for interactions with the supply chain), it would likely need to be managed with some oversight from a central authority (i.e., Anglian Water itself); there are complexities to this, but the decentralised technologies and approach can still be used to deliver efficiencies around management of assets, compliance requirements, sustainability and other areas.

5. Conclusion

For both the water industry and AW to build a successful future and deliver on the long-term goals laid out in PR24, a deeper understanding of and engagement with the key technologies discussed in this report will be critical. An emphasis on preparing effectively for the long-term direction of the industry, and how technology will enable this, is key to setting off on the right path for the coming 5-year period, as well as to prepare for the future over the coming 25 years.

There are several key takeaway points and recommendations we would put forward, in order for AW and the water industry to maximise the opportunities these new technologies offer:

- **Capturing data from assets will be a critical early step and managing it effectively will also be key**: Using new technologies such as advanced sensing and IoT to improve data capture from assets and turn this data in to actionable insights by the business will be at the heart of driving future value and efficiency. It will enable the business to move from a reactive to a proactive approach to challenges and shocks, and towards an ongoing cycle of asset improvement. A pro-active and thoughtful approach to data management will also be needed, in the face of ever-growing data volumes, to maximise data value and ensure its validity and verifiability. Technologies such as trust assurance architectures can be an important tool for this.
- **AI and Digital Twin technologies offer the prospect of true operational transformation** for the water industry, enabling real-time responses to change or crises. While still early stage, in time AI will be able to support a wide variety of applications requiring faster, more accurate, 'human-like' analysis of large and disparate datasets, from developing deeper customer behavioural insight to optimising water networks for maximum efficiency. Effective AI adoption will drive efficiency, quality, and customer insight, informing decision-making and eventually providing autonomous functionality throughout the water network. It will also support safety and sustainability and will help the water network to become more adaptive and resilient. This will all require significant changes to process and approach as well as to IT and OT – water companies must be ready to work in a more agile way to make best use of the insights and eventual autonomy that AI can deliver.
- **Cybersecurity will become an increasingly important consideration for the industry.** While the focus now is more on customer data protection – which will continue to be critical – digitalisation and autonomous machine-led control of operations opens water companies to significant new risks from malicious cyber activity. Any future technology strategy must plan for this from the beginning, and ensure cybersecurity is not an afterthought or something only adopted following a breach.
- **Net zero and sustainability targets urgently require adoption of renewables, changes to energy usage, and improved use of bioscience solutions:** If AW – and the broader industry - are to meet their net-zero target for 2030, then renewables adoption and alternative methods of energy usage must be adopted. Ideas, which were once novel, are now mainstream and being accelerated by a series of alarming weather and climate events. Anaerobic digestion for onsite combined heat and power, distributed energy and microgrids and the growing hydrogen industry will be major factors shaping the future of the AW business and the way assets are utilised.
- **Changes to consumer behaviour will be a key part of the puzzle:** For domestic households to achieve significant water savings, they will need new technologies within the home, to understand and control the amount of water used per day, and enable conservation and water recycling. Achieving this change will require broad adoption of new home and consumer technologies such as smart water meters, greywater reuse and other water conservation technologies, as well as corollary behavioural and service model

changes by consumers and home appliance providers. The latter may shift to new business models (e.g., appliance-as-a-service, smart home platforms) which enable faster take-up of more environmentally friendly and/or connected home appliances (that could enable reduced water usage). Water companies will need to play a more active role in promoting adoption and behaviour change.

- **There is potential for alternative revenue streams for AW and other water industry players in two areas: Bioresources and Data**. Bioresources is perhaps a more natural shift, as AW capitalises on generating revenue from sludge as fertiliser or feedstock, on producing and selling natural gas products or selling final effluent to the hydrogen industry. All of these are available over the coming 25-year period. Further, as AW gathers and analyses more and more data, it can potentially sell the insights from this data to the industry. This could be key failure indicators from vibration sensors, key process treatment parameters and so on. Some data may be shared via open data platforms instead of being monetised, which can help to develop, drive and inform relevant technology applications.

The technology-led opportunities for the water sector over the coming 5-25 years are exciting, transformational, and offer a view of a better, more resilient and sustainable future for the industry. However, none of the above opportunities can be realised through a single technology deployment. They will require a step-by-step approach, which will be enabled by a number of different and interconnecting technology initiatives over a period of years and decades.

This is why a systemic approach to technology planning, and a clear understanding of technology interdependencies, are as important as the selection of the correct technology to invest in. In addition, the right organisational support at all levels will be a prerequisite for success. Understanding where the critical paths lie within a system, now and in the future, is a critical insight which should be used to guide investment and avoid stranded assets or unexploited capacity. It has been the case too often that a technology has failed to be successfully implemented and scaled due to a lack of the supporting structures required, whether these are technical, process or organisational in nature.

We look forward to supporting Anglian Water and the broader water industry on the next steps in the journey of preparing for a brighter, more technology-enabled future, with benefits for all.

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Appendix

Technology area selection

The following 14 topic areas, shown in Figure 12 were used as a lens with which to view technologies. This list consists of a combination of topics that are core to AW operations and currently being explored under its Smart Program (SMART Topic Areas) and topics that have the potential to significantly impact the future of water demand and service demand in areas served by AW (Wider Topic Areas).

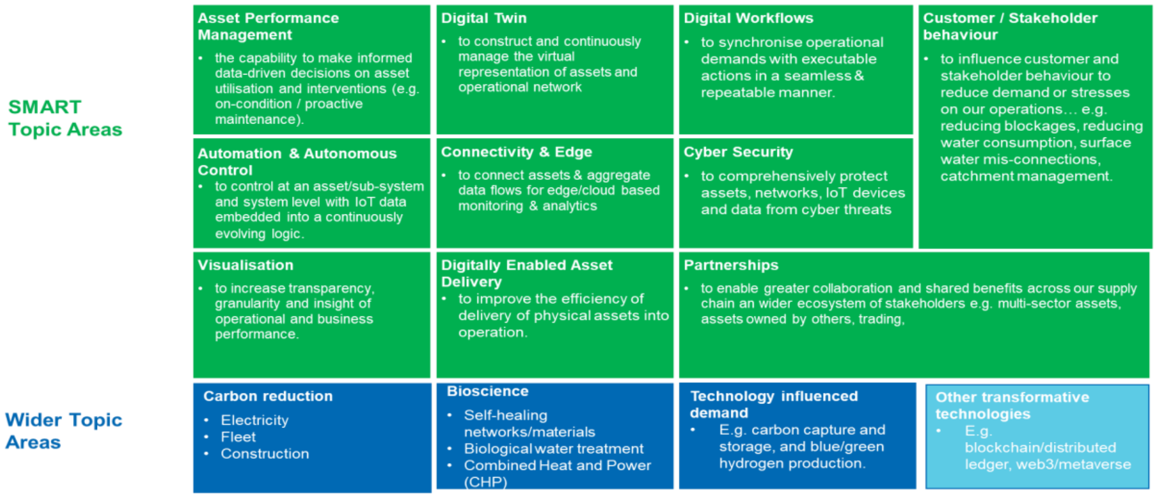

Figure 12: Topic Areas identified by AW as of long-term importance to its business

Theses 14 topic areas have been fully taken into consideration in the analysis of the technologies within this document. For a technology to be truly transformational to Anglian Water, it must impact the majority of these topics, or be exceptionally impactful on a chosen few.

Smart Topic Coverage

The following figures give a summary of which Smart Topics apply to each of the technologies covered within this report:

Figure 13 details the AW Topic Areas that are impacted by or relevant to **IoT Enabled Assets and Infrastructure** (greyed out boxes are not relevant for this technology).

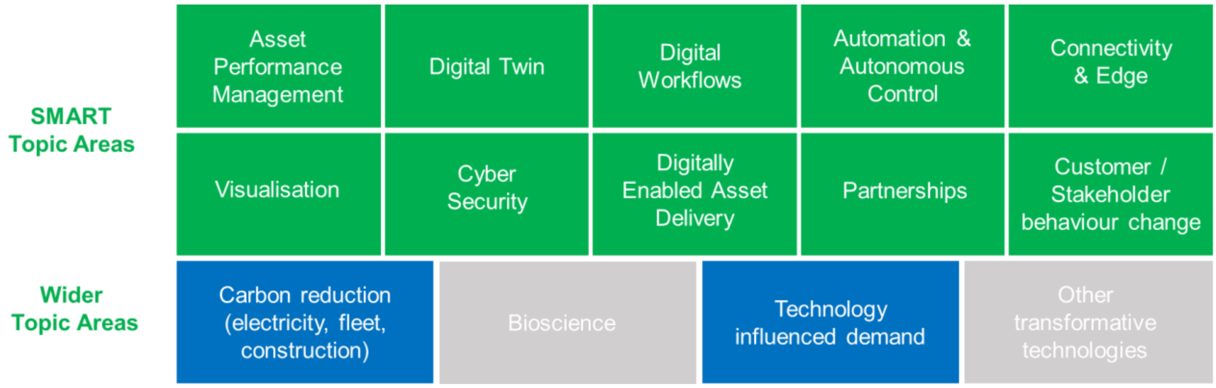

Figure 13: Relevant Topic Areas – IoT Enabled Assets and Infrastructure

Figure 14 details the AW Topic Areas that are impacted by or relevant to **Renewable Energy Systems** (greyed out boxes are not relevant for this technology).

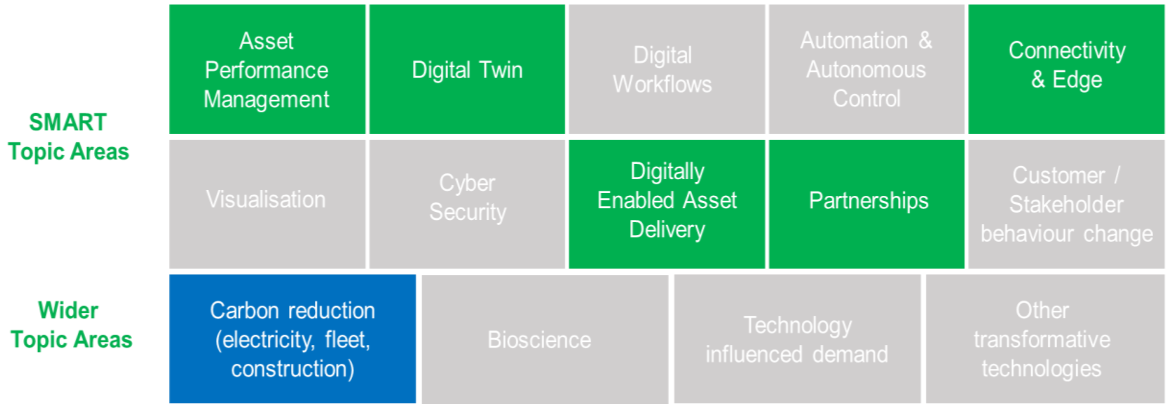

Figure 14: Relevant Topic Areas – Renewable Energy Systems

Figure 15 details the AW Topic Areas that are impacted by or relevant to **Household and Consumer Technology** (greyed out boxes are not relevant for this technology).

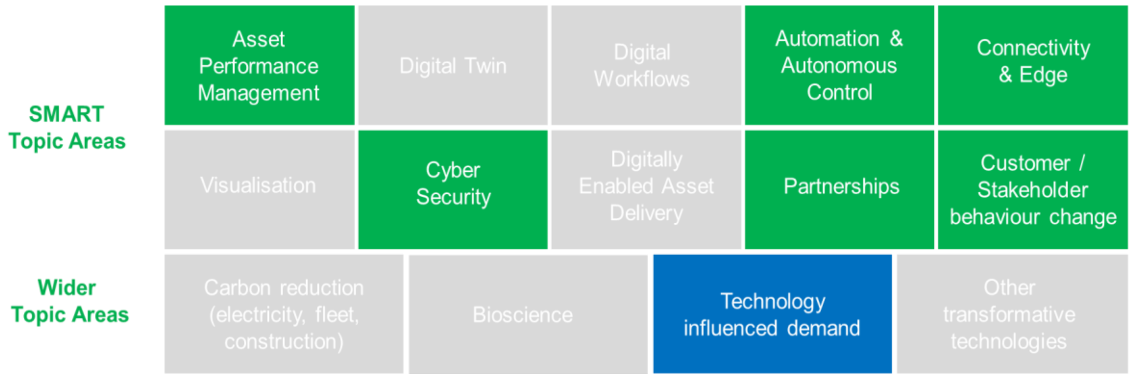

Figure 15: Relevant Topic Areas – Household and Consumer Technology

Figure 16 details the AW Topic Areas that are impacted by or relevant to **Advanced Sensing and Sensor Platforms** (greyed out boxes are not relevant for this technology).

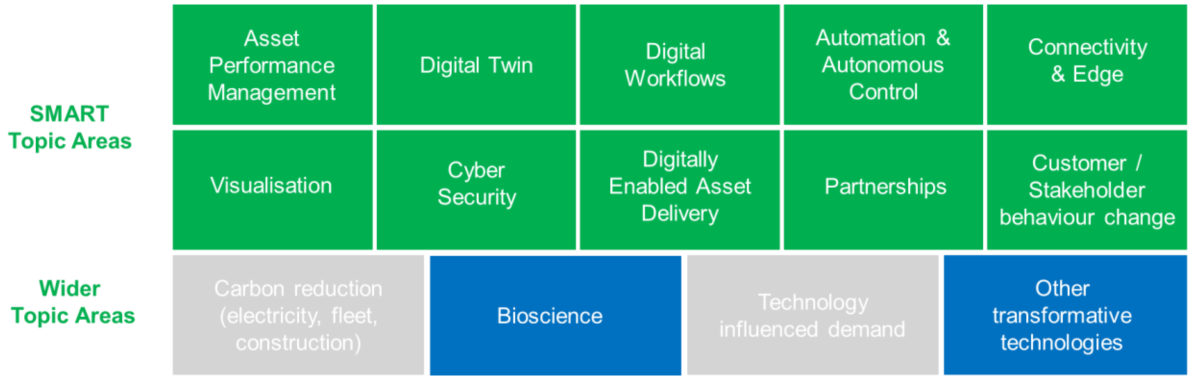

Figure 16: Relevant Topic Areas – Advanced Sensing and Sensor Platforms

Figure 17 outlines the AW Topic areas that are impacted by or relevant to **Scaling Nature-Based Solutions** (greyed out boxes are not relevant for this technology).

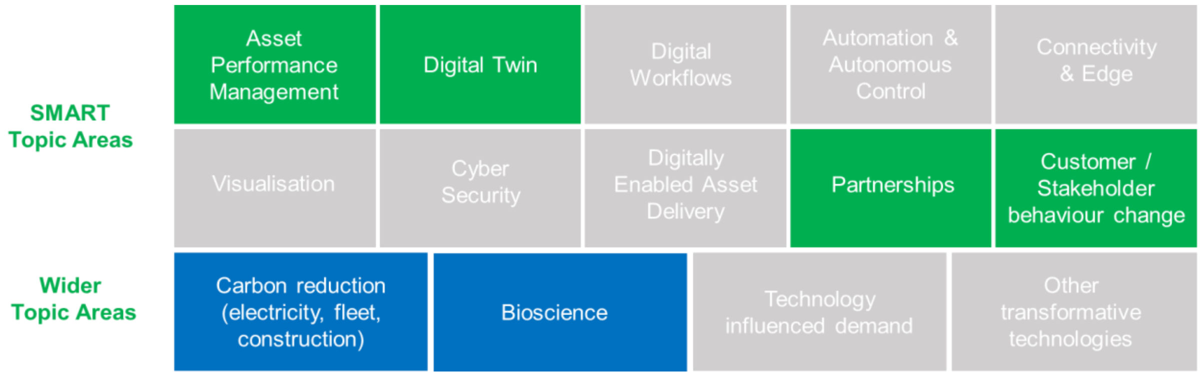

Figure 17: Relevant Topic Areas – Scaling Nature-Based Solutions

Figure 18 details the AW Topic Areas that are impacted by or relevant to **Artificial Intelligence & Machine Learning** (greyed out boxes are not relevant for this technology).

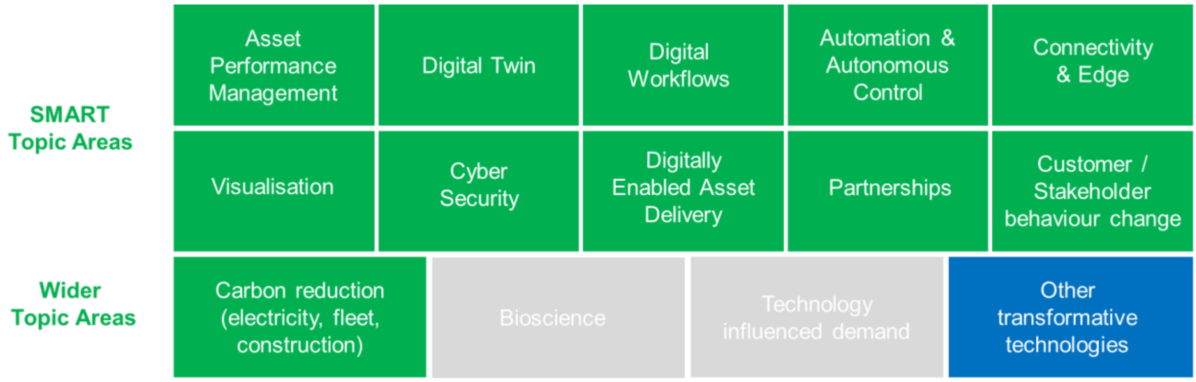

Figure 18: Related Topic Areas – Artificial Intelligence & Machine Learning

Figure 19 details the AW Topic Areas that are impacted by or relevant to **Digital Twin** (greyed out boxes are not relevant for this technology).

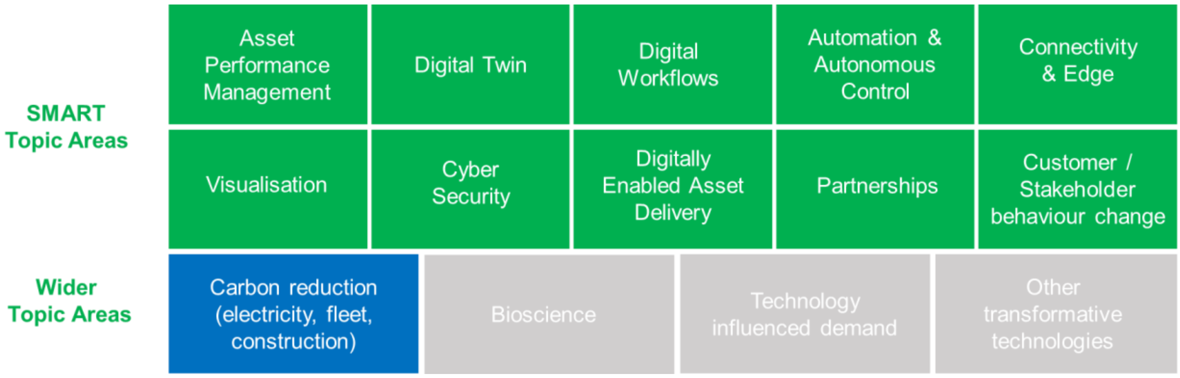

Figure 19 - Related Topic Areas - Digital Twin

Figure 20 details the AW Topic Areas that are impacted by or relevant to **Bioresources as a Revenue Stream** (greyed out boxes are not relevant for this technology).

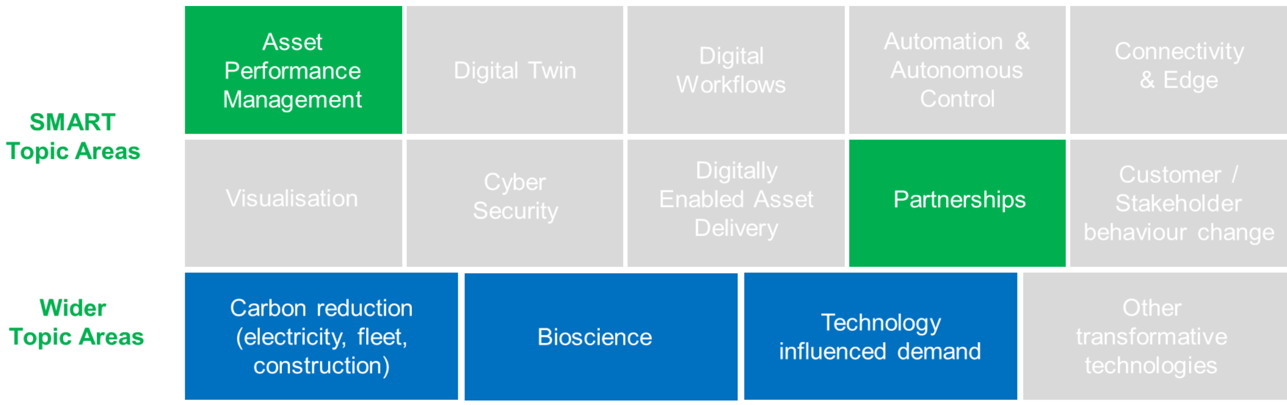

Figure 20: Related Topic Areas – Bioresources as a Revenue Stream

Technology ranking criteria

Figure 21 shows the ranking criteria that were used to evaluate and prioritise the 40 transformative technologies identified (out of the long list of 92 technologies).

	Criteria	Definition	Score		
			3	2	1
Adoption (propensity for tech to be adopted)	Tech Maturity	The likelihood of the technology being successfully developed and implemented in the water industry during the planning period (2025-2050)	Next 5 years	Next 5-15 years	15+ years
	Alignment to AWS Purpose	Does the adoption of this technology support AW's stated purpose ""To bring environmental and social prosperity to the region we serve through our commitment to Love Every Drop"?	High	Medium	Low
	Barrier to adoption	Will the technology require significant regultory change, and cultural and behavioural changes (from both internal operations and external customer behaviour perspective) which can become an adoption barrier?	Minimum	Medium	Large
	Cost	Is the investment required to implement the technology likely to be affordable for water companies?	Low	Medium	High
Impact (that tech is likely to have on the industry)	Performance & Compliance	Scale of impact to outcome performance (e.g. leakage, pollutions, river water quality, customer experience, drinking water quality).	High	Medium	Low
	Risk & resilience	Scale of impact to increasing 'resilience in the round' (including water resource resilience, financial resilience, operational resilience, cyber resilience)	High	Medium	Low
	Botex efficiency	Scale of impact to operational or capital maintenance efficiency / efficacy.	High	Medium	Low
	Delivery efficiency	Scale of impact to efficient delivery of capital schemes	High	Medium	Low
	Sustainability	Impact on additional 6 capital benefits not captured above	High	Medium	Low

Figure 21 Technologies and dependencies