Net Zero Technology Review

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Executive summary

This project was commissioned by Ofwat to identify technologies and interventions likely to be capable of reducing greenhouse gas (GHG) emissions during the investment period (2025 – 2030) covered by PR24. In particular, the project focused on identifying and reviewing the applicability, readiness and scalability of GHG reduction technologies and interventions applicable to water companies in England and Wales. It does not evaluate those same technologies or interventions through other possible drivers, e.g. provision of capacity or environmental compliance. This project was set in the context of significant uncertainty on how companies may meet Net Zero targets and the likely costs and benefits of Net Zero technologies. While recognising the scope of emerging technologies and the role of innovation looking at the medium to long term, this project focusses on Net Zero solutions that can likely be implemented during the investment period covered by PR24. Important areas for further work are indicated for promising but less developed solutions. While it is important to reduce both operational and embedded carbon emissions, a greater focus on operational emissions is borne out through the technologies identified and shortlisted in this project.

The assessment undertaken included a global literature review to identify possible Net Zero technologies and gather information for analysis - e.g. any data around costs and carbon emissions. This also included input from Jacobs' extensive global network of subject matter experts and from Ofwat. A compiled longlist of identified technologies was refined into an ultimate shortlist through a detailed Multi Criteria Analysis (MCA) assessment exercise. There has been very little work undertaken to assess what Net Zero technologies are available and whether technologies being proposed by water companies and referenced in sectoral route maps are actually aligned with Net Zero principles[1]. As such this project represents an important step in the water sectors understanding of the scope, challenges and opportunities in achieving Net Zero.

As a result of the review undertaken, it was identified that:

- A range of GHG reduction technologies and interventions are currently available to Water only Companies (WoCs) and Water and Sewerage Companies (WaSCs) to reduce their GHG emissions and are shortlisted in Table 1. Methodologies to show their alignment with GHG management hierarchies and Net Zero principles are available;
- All shortlisted technologies, applicable to WoCs and WaSCs respectively, will be applicable to all such companies. However, the extent of their applicability could vary. For example, differences in geography and population distributions will plausibly impact the applicability or size of some opportunities across the sector;
- Technologies and interventions focused on the improved monitoring and mitigation of process emissions, in particular nitrous oxide and methane, have the potential to reduce overall greenhouse gas emissions the most (see Figure 1);
- After mitigation of process emissions, other technologies which scored highly in the MCA included renewable electricity procurement through Power Purchase Agreements (PPAs, used here as shorthand to group behind-the-meter and private-wire renewables and corporate PPAs via the grid), pump efficiency, vacuum methane recovery, advanced digestion technologies with energy recovery, low energy sludge drying and leakage and water efficiency measures;

1 E.g. those set out by Ofwat and by the Science Based Targets ™ Net-Zero Standard.

- A wider range of viable options exist for WaSCs to reduce GHG emissions, particularly when such emission are viewed from an overall and sector wider perspective;

- The viable options for WoCs to reduce GHG identified through this analysis were fewer by number than for WaSCs due to much lower direct process emissions. However, as most of the GHG emissions for WoCs are from scope 2 and 3 emissions, in particular power consumption (see Figure 7), large reductions are feasible from reducing electricity consumption through reducing overall water demand (e.g. leakage reduction, water efficiency), improving asset energy efficiency, and power purchase agreements;

- Grid electricity remains the largest reported source of GHG emissions in the water sector. Water UK's Net Zero 2030 Routemap (see Figure 7 in main report) shows that 85% of negative emissions reported are from electricity purchase via Green tariffs. Transition to Net Zero should align with renewable electricity hierarchies;

- Energy recovery from wastewater residuals is already undertaken at scale through advanced or conventional anaerobic digestion. However, upgrading of biogas to biomethane for grid injection, where companies require a reciprocal increase in the import of fossil (also termed natural) gas does not offer alignment with Net Zero principles as set out by Ofwat;

- Resource recovery technologies, beyond production and local reuse of biogas, may not actually reduce emissions in alignment with Net Zero Principles as set out by Ofwat and as per science-based frameworks (e.g. where these require additional imports of fossil gas and increase in Scope 1 emissions). Where companies embrace such technologies, they will need to show alignment with Net Zero principles and carbon reduction hierarchies through the use of life cycle carbon assessment and substantiate and verify claimed emissions reductions;

- Offsetting to achieve Net Zero is not aligned with Net Zero principles but the carbon benefits of resource recovery (e.g. biomethane, heat recovery from final effluent, nitrogen stripping and recovery) may offer the opportunity to reduce emissions in agriculture or industry (e.g. nitrogen recovery to substitute fossil-based fertilisers or heat recovery to substitute fossil gas derived heating). Strong cross-sector collaboration will support development of associated technologies and solutions. Key barriers will exist during AMP8 – for example resource recovery technologies lack end of waste status;

- Existing technology solutions are likely to offer substantial mitigation opportunities. These are also likely to have multiple additional benefits, such as greater water efficiency helping to reduce home energy usage (and costs) which in turn leads to reduced GHG emissions . However, to reach their full potential, some technologies will require further innovation development to reach their net zero potential – e.g. low energy ammonia recovery without the need to import additional fossil based gas which would otherwise increase Scope 1 emissions; and

- There is a lack of evidence for the carbon impact of or alignment of technologies in relation to allowing companies to mitigate GHG emissions in line with Net Zero principles. This was subsequently identified as a gap requiring further work such as needing to focus on providing sector specific case studies and apply existing methodologies – e.g. to show life cycle analysis (LCA) with respect to carbon impacts to support whether technology solutions are aligned with Net Zero principles.

Whilst company emission reduction plans are likely to be accredited through third party schemes such as Science Based Targets Initiative (SBTi™), substantive work is still required to improve understanding and knowledge base of the Net Zero attributes of technologies. Additionally, business cases need to be built upon recognised protocols and methodologies, Ofwat guidance and use site specific assessments which align with recognised GHG inventory assessment frameworks. This will enable them to demonstrate transparency, accuracy, completeness, comparability and consistency.

In approaching the project aims we made two important considerations:

1. Shortlisted technologies are likely to allow a net emissions reduction at a technology/solution level. However, evaluation of their Net Zero credentials requires consideration of their integration at the wider systems level and the possibility this negatively impacts their decarbonising potential or even results in a net positive carbon emission. An example could be biomethane to grid, if this results in a reciprocal increased import of fossil (natural) gas and grid electricity (see section 3.1.7.).

2. The project recognises that companies who have signed up to science-based targets, aligned with the Paris Agreement, cannot 'net off' emissions through carbon offsets. This also aligns with Ofwat's Net Zero principles position paper[2] expectation that reducing emissions should be water companies' focus before offsets are considered.

2 Ofwat, Net Zero principles position paper, January 2022

Table 1. Shortlist of Net Zero technologies (not in ranked order)

Technology or solution	Description	Applicability within sector	Activity
Water efficiency across urban water cycle	Reduced losses of treated water in networks	WaSCs & WoCs	Treated water distribution
Pump efficiency	Refurbish and optimise pumps.	WaSCs & WoCs	Treated water distribution
Power Purchase Agreements (PPAs)	Onsite, behind the meter renewables, or private wire or corporate PPAs for offsite renewables	WaSCs & WoCs	Applicable to all
CH_4 monitoring & mitigation	Site wide monitoring and proactive methane mitigation.	WaSCs	Sewage treatment
Membrane aerated biofilm reactor (MABR)	Membrane aerated biofilm reactor (MABR) for secondary wastewater treatment.	WaSCs	Sewage treatment
Conversion to nitrifying/ denitrifying	Conversion of secondary nitrifying treatment to nitrifying/denitrifying	WaSCs	Sewage treatment
N_2O setpoint optimisation	Process set point optimisation for N_2O	WaSCs	Sewage treatment
Real-time N_2O control	Real time control for optimisation of nitrous oxide.	WaSCs	Sewage treatment
AAD THP	Advanced AD - thermal hydrolysis	WaSCs	Sludge treatment
AAD EH or APD	Advanced AD - enzymatic hydrolysis	WaSCs	Sludge treatment
ITHP	Intermediate thermal hydrolysis (ITHP)	WaSCs	Sludge treatment
Codigestion	Codigestion of sewage sludge with other organic materials	WaSCs	Sludge treatment
Gasification/pyrolysis (sludge)	Thermal treatment of sludge or biosolids by gasification or pyrolysis	WaSCs	Sludge disposal
Biodrying (sludge)	Biodrying of sludge or biosolids	WaSCs	Sludge treatment
Low-energy drying (sludge)	Other low energy drying methods for sludge or biosolids	WaSCs	Sludge treatment
N stripping (liquors)	Stripping ammonia from sludge liquors	WaSCs	Sludge treatment
Tanker (biomethane)	Heavy transport (e.g. sludge tanker) fuelled by biomethane	WaSCs	Sewage collection/ sludge disposal
Heat recovery (onsite)	Heat recovery from onsite influents/effluents	WaSCs	Sewage treatment
Biomethane to grid	Biomethane to grid (where this does not increase import of fossil gas)	WaSCs	Sludge treatment
Stormwater separation & treatment with NBS	Stormwater separation and treatment with nature based solutions (e.g. SuDS).	WaSCs	Sewage collection/ sewage treatment

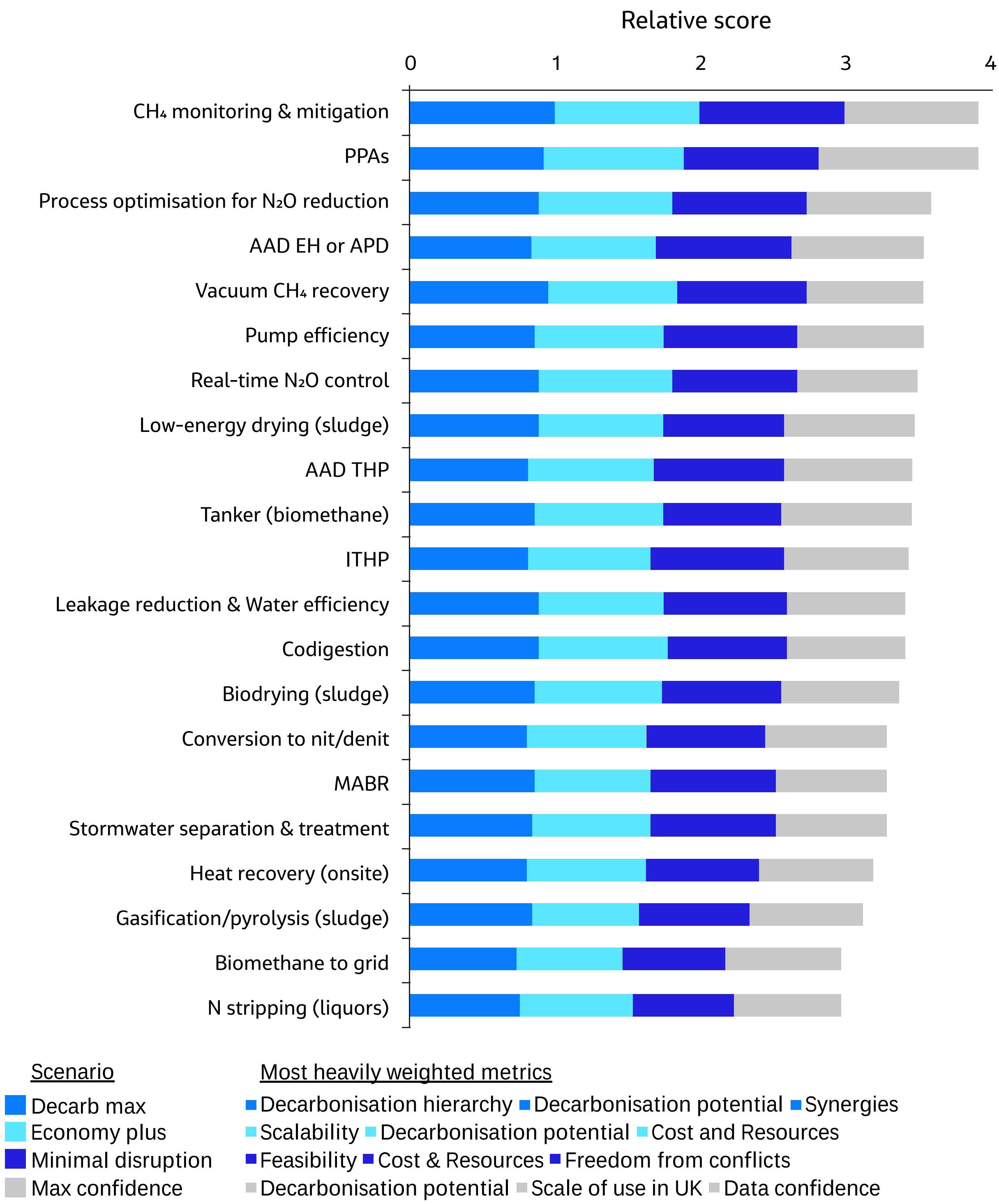

Figure 1. Overall scores from the MCA subjected to four differently weighted scenarios

The MCA scores each technology across ten metrics (details provided in Table 2 of main text):

- Decarbonisation hierarchy
- Feasibility
- Scalability
- Decarbonisation potential
- Cost and resources
- Scale of use in UK
- Scale of use outside UK
- Synergies
- Freedom from conflicts
- Data confidence

The individual metric scores were then differently weighted across four scenarios as a way of viewing the Net Zero attributes of the technologies from different perspectives. Finally, the cumulative scores for all scenarios gives an indicative assessment of the relative Net Zero performance of the shortlisted technologies against one another.

Contents

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Introduction

1 Introduction

1.1 Background

In its Net Zero 2030 Routemap, Water UK has set out a framework for how water companies in the UK are aiming to achieve Net Zero operational carbon emissions across Scopes 1 and 2 by 2030[3]. Ofwat is supportive of the ambition this Routemap signals. However, Ofwat also recognises that this needs to be balanced with longer term national government targets on net zero, meaning that both operational and embedded emissions (including Scopes 1, 2 and 3) need to be tackled in parallel if these targets are to be achieved[4]. Decarbonising in line with national interim and final targets on net zero is not without its challenges, but neither is it without significant opportunities for the water sector. Action on net zero has potential to trigger further innovation and investment in new technologies and interventions.

Ofwat's role will be to test and challenge companies' business plans to ensure fairness for current and future customers. To support this, Ofwat have expressed their expectation to see proposals which are aligned with national decarbonisation targets and which will also support other funded outcomes.

To evaluate efficiency, Ofwat will also need to test the validity of interventions water companies promote, understanding their potential impacts on GHG emissions, cost, and scalability for instance. Water companies will need to prioritise interventions which reduce emissions over those which offset them. In doing so, companies need to ensure alignment with science-based and industry recognised assessment methods for carbon management, carbon life cycle assessment and protocols for carbon neutrality and offsetting.

This project was commissioned by Ofwat to identify technologies with the potential to support Net Zero in the water sector for PR24 and review their applicability, likely benefits and scalability.

1.2 Methodology

We approached this task by undertaking a review of current and emerging technologies or solutions based on a literature review, conversations with global technologists within Jacobs, and our team's experience of working alongside UK and foreign water companies and research bodies such as UKWIR. We also drew on the Ofwat team's knowledge of technologies and a complete list of Ofwat innovation competition entries, identifying approximately one hundred distinct technologies and solutions.

Using our professional judgement, we evaluated the technology readiness level of all the technologies we identified. We used this as a 'coarse screen' to the technology list and removed from further consideration any which had a technology readiness level of 6 or below. In a small number of exceptional cases, technologies that might have a nominal Technology Readiness Level (TRL) below 7 but are subject to significant sector interest and rapid acceleration through the TRLs were also progressed for further consideration. This helped us to focus on technologies which are more likely to be ready for use at large scale at PR24.

Using a workshop approach, we evaluated each technology across nine metrics designed to identify those likely to offer greatest benefit if included in PR24 business plans. This was in effect a forecasting exercise and used a strong element of professional judgement. Therefore, our findings and recommendations are not definitive, but are intended to be an initial guide for Ofwat and water sector on decarbonisation opportunities. Metrics included assessment of feasibility and scalability, representing fundamental considerations such as technical readiness and footprint but also integration with established ways of works, regulatory alignment, risk of stranding assets and asset write-off, implications

3 https://www.water.org.uk/routemap2030/wp-content/uploads/2020/11/Water-UK-Net-Zero-2030-Routemap.pdf

4 https://www.ofwat.gov.uk/wp-content/uploads/2022/01/Net_Zero_Principles_Position_Paper_Jan_2022.pdf

for resilient operations (including resilience of supply chains) and relevant timelines for implementation.

To assess the likely relative Net Zero impacts of identified technologies, we ran an MCA with a semi-quantitative scoring methodology. This allowed us to further shortlist technologies and formed the basis of our final review. These base scores were further tested through a series of scenarios or lenses that allowed the technologies to be viewed from different perspectives by weighting the base scores differently, thereby shifting emphasis. This included different weightings towards absolute decarbonisation potential, value, practical and regulatory disruption in the sector and level of confidence in supporting data.

For the technologies which were shortlisted, we documented what they comprise, their potential carbon impacts and how they may contribute in accordance with the carbon reduction hierarchy, considerations for implementing them, and the synergies and conflicts that require consideration. We undertook a high-level costing exercise and have categorised technologies in terms of their Net Zero potential and likely cost.

Finally, we produced recommendations to highlight the technologies which, on the basis of our assessment, show the greatest potential for decarbonisation if included in PR24 business planning and implemented in AMP8.

1.3 Defining Net Zero technologies

This project requires an assessment of Net Zero technologies which are available in the near term to water only companies (WoCs) and water and sewerage companies (WaSCs). In this section we set out our considerations for what this means in terms of Net Zero alignment:

- Net Zero technologies are defined by the project team as technologies and solutions (we use technologies to refer to both technologies and other solutions – e.g. process optimisation – which isn't itself a technology) which will move the sector and the UK toward the Net Zero goals. This means technologies and solutions will need to either reduce Greenhouse Gas (GHG) emissions below current standard industry practice in the short term, or in the longer term will result in zero (or near zero) GHG emissions or atmospheric GHG removals.

- We further define these as available to WoCs and WaSCs for business planning in PR24, able to be delivered in 2025 – 2030. Section 2 provides further information on our review methodology and shortlisting based on TRL.

- Such technologies we define as Net Zero when they are likely, in our assessment, to allow an overall balance between emissions produced and emissions taken out of the atmosphere at a technology/solution level or a systems level depending on company business plan proposals.

- We consider all emissions including Scope 1, 2 and 3 supply chain emissions to permit whole value chain solutions to be considered. This will align to Net Zero methodologies adopted by the SBTi™. Emission scopes are defined further in section 1.5.1.

- We recognise the need for Net Zero alignment with the Paris Agreement, as ratified by the UK Government – and as referenced by Ofwat in terms of the need to consider both operational and embedded emissions. This requires Net Zero to be achieved before 2050 to keep global average temperature increases below 2 degrees centigrade.

- We further consider Net Zero technologies in alignment to Ofwat's recent Net Zero Principles Position Paper which requires solutions from companies which prioritise driving GHG emissions down rather than offsetting (or neutralising) them.

- When a technology is likely to rely on offsetting to achieve a claimed Net Zero alignment, we have considered technologies which recognise the carbon management hierarchy[5] but which reflect Ofwat and best practice guidance here too – considering the quality of offsets in terms of industry standards and guidance (e.g. PAS 2060, Oxford Offsetting Principles, Gold Standard). As Ofwat has referenced in the Net Zero Principles Paper, this requires considerations of the locality of offsets, direct community benefits and customer engagement and support for such offsets. This would mean a

5 E.g. 'Avoid, reduce, replace, offset' as originally developed by Forum for the Future – see link or 'Eliminate, Reduce, Substitute, Compensate' as per the IEMA GHG Management Hierarchy

preference to offsets within the value chain of the water sector (i.e. "insetting"). We note this enhanced carbon management hierarchy is well reflected in the update Figure 2 below, proposed in work from Piper & Longhurst in Bristol University of the West of England in 2021[6].

- Net Zero technologies cannot be considered such through purchase of green energy – e.g. this cannot be netted off.

- We have also considered alignment with CCC sectoral decarbonisation pathways for the UK where possible.

It is also important to note that companies who have signed up to the Science Based Targets initiative (SBTi™) cannot offset emissions to achieve Net Zero – they must have a pathway defined to reduce emissions in alignment with the pathway for 1.5 degrees Celsius[7] and can consider removal mechanisms for only a small proportion of their baseline carbon emissions (e.g. 10% of emissions). Whilst this doesn't apply at a project level for particular technology solutions, it does apply at a company level and should be considered at a business plan level.

We also note the new SBTi™ Net Zero standard[8] which companies are committing to also requires long term (2050) emissions reduction targets in addition to short term reduction targets - with emissions reduction of Scopes 1, 2 and 3 by at least 90 – 95% by 2050 and only then residual emissions able to be 'neutralised' by carbon removals. This standard, which United Utilities has committed to[9] does not allow Net Zero to be claimed by a company until such time that long term targets have been met and remaining residual emissions have been neutralised. As above, whilst this doesn't apply at a project level for particular technologies, it does apply at a company level and should be considered at business plan level.

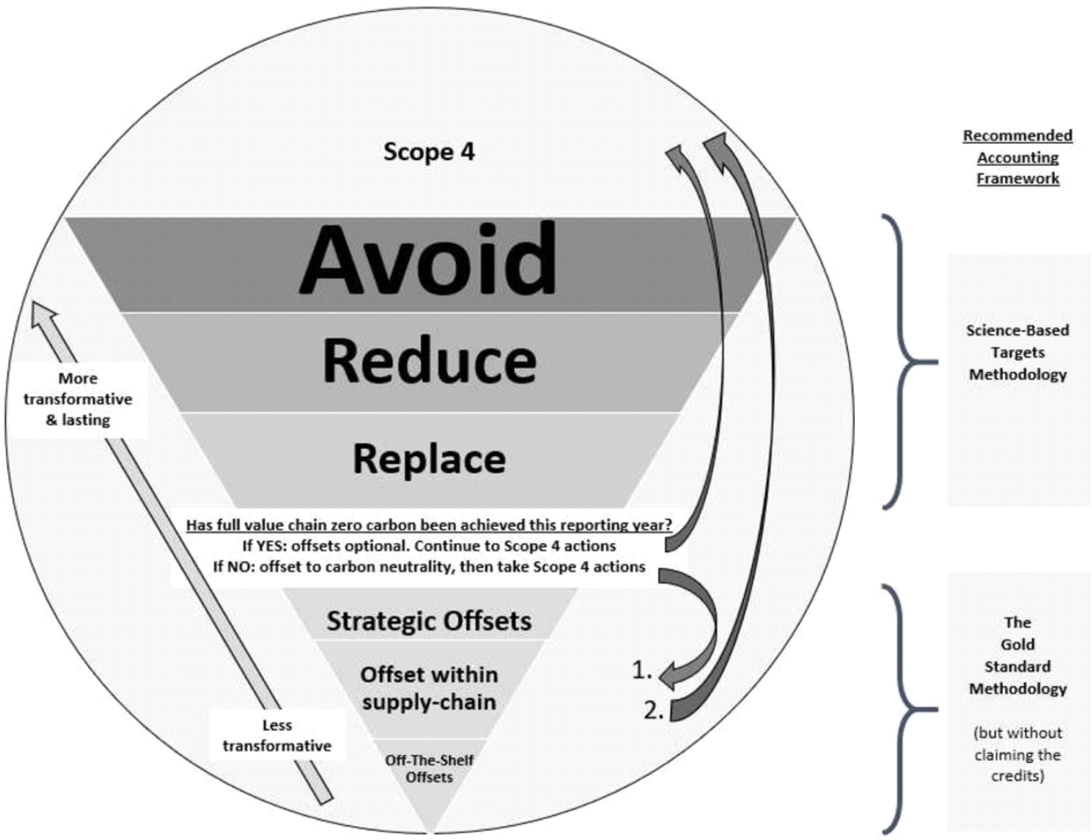


Figure 2. Carbon Management Hierarchy proposed by Piper & Longhurst (2021), *Exploring Corporate Engagement with Carbon Management Techniques*[6]**.**

6 https://emeraldopenresearch.com/articles/3-9

7 Whilst previously the SBTi™ accepted targets aligned with 'well below 2degrees Celsius this is no longer the case and all reduction targets must be aligned with 1.5 degrees Celsius - https://sciencebasedtargets.org/news/sbti-raises-the-bar-to-1-5-c

8 https://sciencebasedtargets.org/net-zero

9 https://tricarbon.co.uk/portfolio-item/setting-a-science-based-net-zero-target-at-united-utilities/

1.4 Company definition of Net Zero technologies

Our assessment in this work, as set out in Section 1.2 above, relies on subject matter expertise and our judgement based upon existing available evidence – recognising that there has been very little work undertaken to assess what Net Zero technologies are and whether technologies being proposed by companies and in the sector's route map are actually Net Zero technologies.

We would expect Companies to be undertaking substantive work to assess the Net Zero attributes of technologies put forward in accordance with recognised protocols and methodologies in addition to Ofwat guidance to date.

This section provides an overview of the assessment required to justify emission reductions based upon accepted industry methods.

Whilst some technologies are likely to be well aligned with Net Zero in all cases, others will be very case specific. We provide two examples below:

- Process optimisation of activated sludge plants (ASPs) to reduce emissions of nitrous oxide from wastewater treatment facilities and leak detection and repair (LDAR) for reduction of fugitive (leaking) methane from bioresources facilities are likely to be well aligned with Net Zero in the case of all companies treating wastewater at medium and large sites in England and Wales.

- Conversely, upgrading biogas to grid is likely to be highly site specific. Where a bioresources facility achieves a sufficient energy balance to allow export of surplus biogas without the need for import of fuels for heating this is likely to be well aligned with Net Zero. However, in the vast majority of UK cases - in particular where advanced digestion is utilised (e.g. hydrolysis of sludge upstream of mesophilic anaerobic digestion) – the energy balance may require import of fossil (natural) gas to sustain required heating for digestion to enable the export of biogas to grid. Where fossil gas is imported at site(s) this cannot be considered a Net Zero technology. We provide further discussion of this and other case studies.

For these reasons, companies will need to provide site specific assessment where a Net Zero alignment or benefit is claimed. This should align with recognised GHG inventory assessment – demonstrating transparency, accuracy, completeness, relevance and consistency.

Some examples of how companies should be expected to demonstrate these aspects are discussed further.

1.4.1 Providing an accurate, comparable baseline

Assessment of a Net Zero technology for a particular site or sites requires an assessment of baseline – this can be undertaken using life cycle carbon assessment and recognised industry standards described below.

Consideration of 'additionality' is important for existing practices – for example applying biosolids to land may have soil carbon sequestration benefits (though the permanence of this remains questioned in research and practice) but as this practice would have 'happened anyway' using this carbon benefit to offset emissions from a newly proposed enhanced drying or production process for dewatered sewage sludges would not meet the requirement for additionality.

1.4.2 Assessment of life cycle carbon

Whilst the technologies considered within the scope of this report have been evaluated and compared on the basis of their decarbonisation potential based on available literature and/or likely outcomes based on professional judgement, it is important to note that alignment with Net Zero principles requires a case specific assessment.

If a Net Zero aligned technology (e.g. carbon capture from CHP exhaust) or product (e.g. fertiliser produced from sewage and other inputs) is proposed, this requires life cycle carbon assessment approaches to evidence Net Zero alignment. Consideration of life cycle stages (see Figure 3) and boundaries should be clear and could be aligned with other (e.g. financial) assessment to ensure that the whole life cycle of the technology/solution is considered, and that a proposal does not cherry pick the benefits and ignore the disbenefits. For example – a solution may reduce operational GHG emissions but require construction of assets which results in significant capital carbon emissions (or vice versa where a capital carbon reduction results in an increase of operational carbon). Therefore, the basis for any reduction claims should be clearly explained to allow proper assessment.

In order to align with Ofwat's Net Zero principles position paper[10], which outlines the expectation that individual company action on Net Zero should encompass both operational and embedded emissions, it is recommended that any carbon assessment conducted in support of a significant investment decision should include whole life cycle analysis (LCA) within its methodology. An assessment of this type will ensure that one source of emissions is not acted and reported on to the detriment of the wider environment.

Various assessment frameworks are recognised internationally to support this – for example PAS 2050:2011 – which provides guidance for the consideration of GHG emissions across the life cycle of a product. Companies could also consider specifications for the assessment of the life cycle greenhouse gas emissions of goods and services within the GHG Protocol Product Standard. In addition, environmental product declarations (EPDs) would be expected to be developed for any claimed Net Zero, carbon neutral or carbon positive products or solutions.

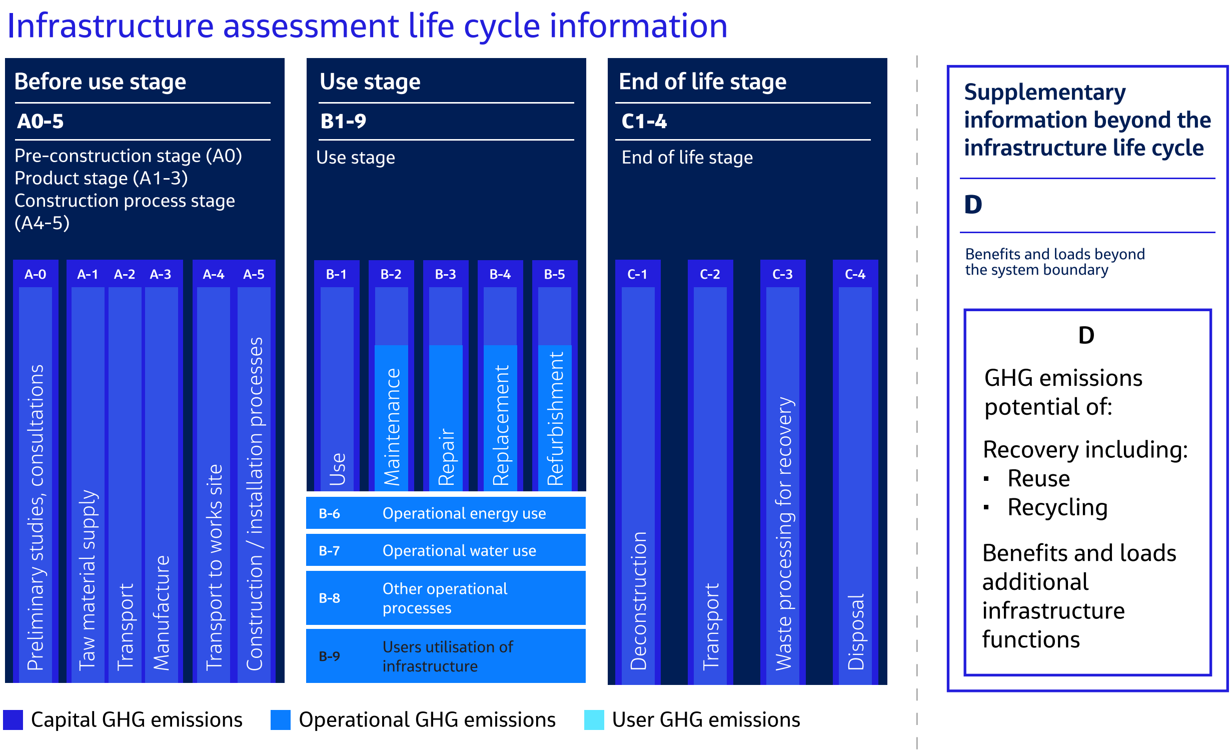


Figure 3. Life cycle stages from PAS 2050 showing GHG emissions for capital, operational and user considerations[11].

In addition to asset investment based life cycle assessment to determine alignment with emissions management and Net Zero principles, companies should adopt a recognisable international standard to inform their programme and company approaches such as BSI PAS 2080:2016.

The scope of PAS 2080 is broader than whole life cycle analysis and considers individual value chain requirements in the carbon management process including the following applicable components:

- Determining baselines against which to assess carbon reduction performance
- Establishing metrics (e.g. Key Performance Indicators) for credible carbon emissions quantification and reporting
- Selecting carbon emissions quantification methodologies (to include defining boundaries and cut off rules)

10 https://www.ofwat.gov.uk/wp-content/uploads/2022/01/Net_Zero_Principles_Position_Paper_Jan_2022.pdf

11 https://shop.bsigroup.com/products/carbon-management-in-infrastructure/standard

1.4.3 Assurance of quality

Company assessments undertaken to support Net Zero proposals should be assured in accordance with accepted water industry standards and the above specific carbon impact and Net Zero standards.

Whilst companies may be signatories to the SBTi™ or PAS 2080:2018 Carbon management in infrastructure – these apply at Company Level and do not provide evidence at technology level in terms of Net Zero.

1.5 Overview of GHG emissions in the water sector

As discussed in sections 1.3 and 1.4, the focus for Net Zero technologies needs to be mitigation of Scope 1, 2 and 3 emissions and that reduction emissions cannot be offset against purchase of green energy to achieve Net Zero. This section provides an overview of GHG emissions and some discussion of their relevance and significant issues in terms of process emissions quantification.

1.5.1 Emission scopes

GHG emissions can be quantified and reported, whether by country, company or other organization/ individual, by Scope. The commonly accepted definitions of emissions Scopes 1, 2 and 3 were introduced by the GHG Protocol of the World Business Council for Sustainable Development (WBCSD)/World Resources Institute (WRI) to categorize emissions by ownership levels, i.e. direct (Scope 1) and indirect (Scope 2 and 3) emissions (Greenhouse Gas Protocol, 2020). These are shown below in Figure 4.

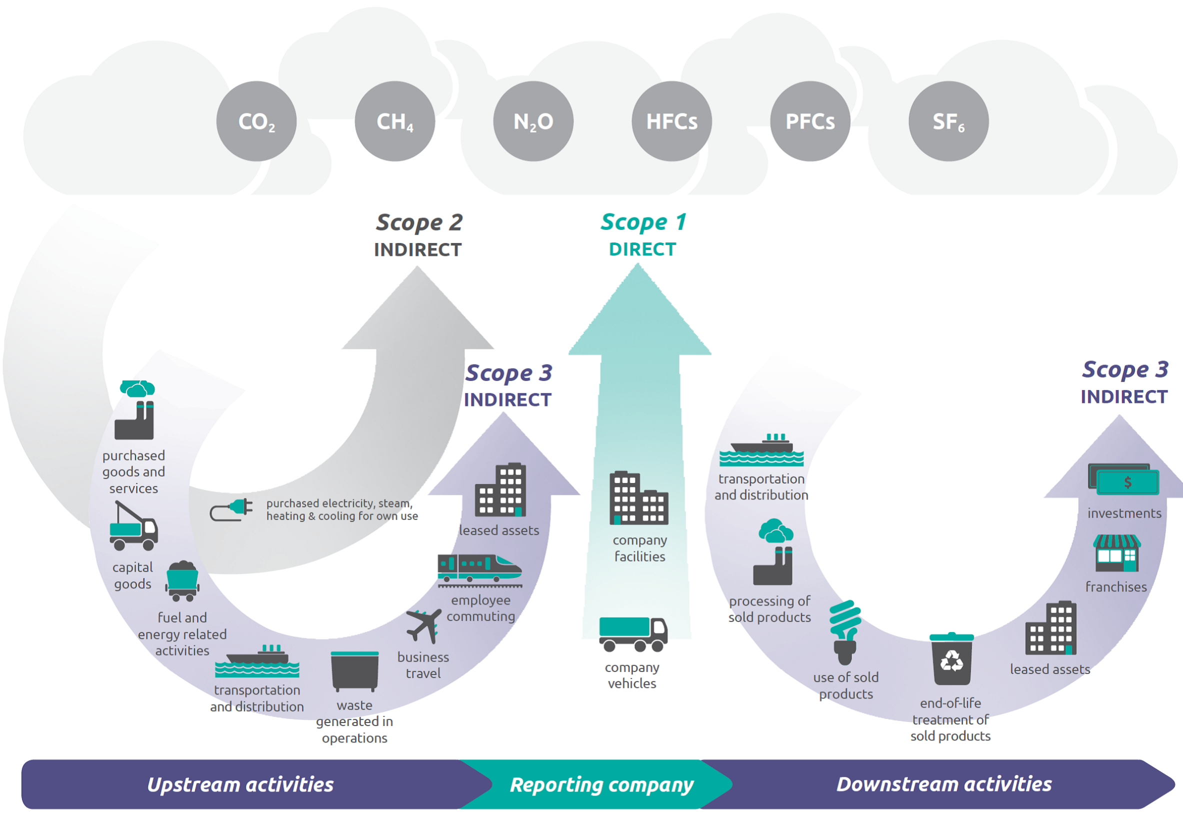


Figure 4. Sources and categories of GHG emissions for corporate reporting (Greenhouse Gas Protocol, 2020).

The GHG Protocol defines scopes and examples for the Waste Sector (with respect to water and wastewater treatment) as follows (Greenhouse Gas Protocol, 2015):

Scope 1: direct GHG emissions from sources owned or controlled by the company from stationary combustion (incinerators, boilers, flaring), process emissions from the transformation of raw materials (for example N_2O emissions from the nitrogen species (i.e. ammonia and nitrate) in wastewater treatment), and CH_4 emissions from the anaerobic treatment of wastewater and/or sludges). Direct GHG emissions from the water sector also include CO_2 emissions from wastewater treatment and emissions from mobile combustion (for example from gas boilers or owned or leased cars, vans and lorries for transportation of waste/products).

Scope 2: indirect emissions from the generation of purchased electricity, heat or steam that is consumed in its owned or controlled equipment or operations.

Scope 3: indirect GHG emissions which, based on the selected consolidation approach (e.g. control) used in setting its organizational boundaries, are not owned, or controlled by the company. There are 15 Scope 3 categories as shown in the GHG Protocol. With respect to the water sector, upstream Scope 3 emissions would include materials and consumables for the treatment of water and wastewater – for example chemicals manufacture and transport and the emissions associated with purchased goods and services, including those for capital infrastructure works, waste generated by company operations, as well as employee travel and commuting. Examples of downstream Scope 3 emissions for the water sector include emissions associated with the use of treated water or wastewater, use of products sold, transportation and distribution of drinking water, biosolids recycled to land or sludge products used as fuel at off-site processes.

Figure 5 below provides an overview of emissions by Scope which was created for the UK water sector in previous work and shows what is currently accounted for by the sector – though as discussed in section 1.3 and 1.4, companies will need to account for further emissions in order to disclose Scope 3 embodied carbon emissions as required by Ofwat and where relevant, to align with their adopted SBTi™ commitments.

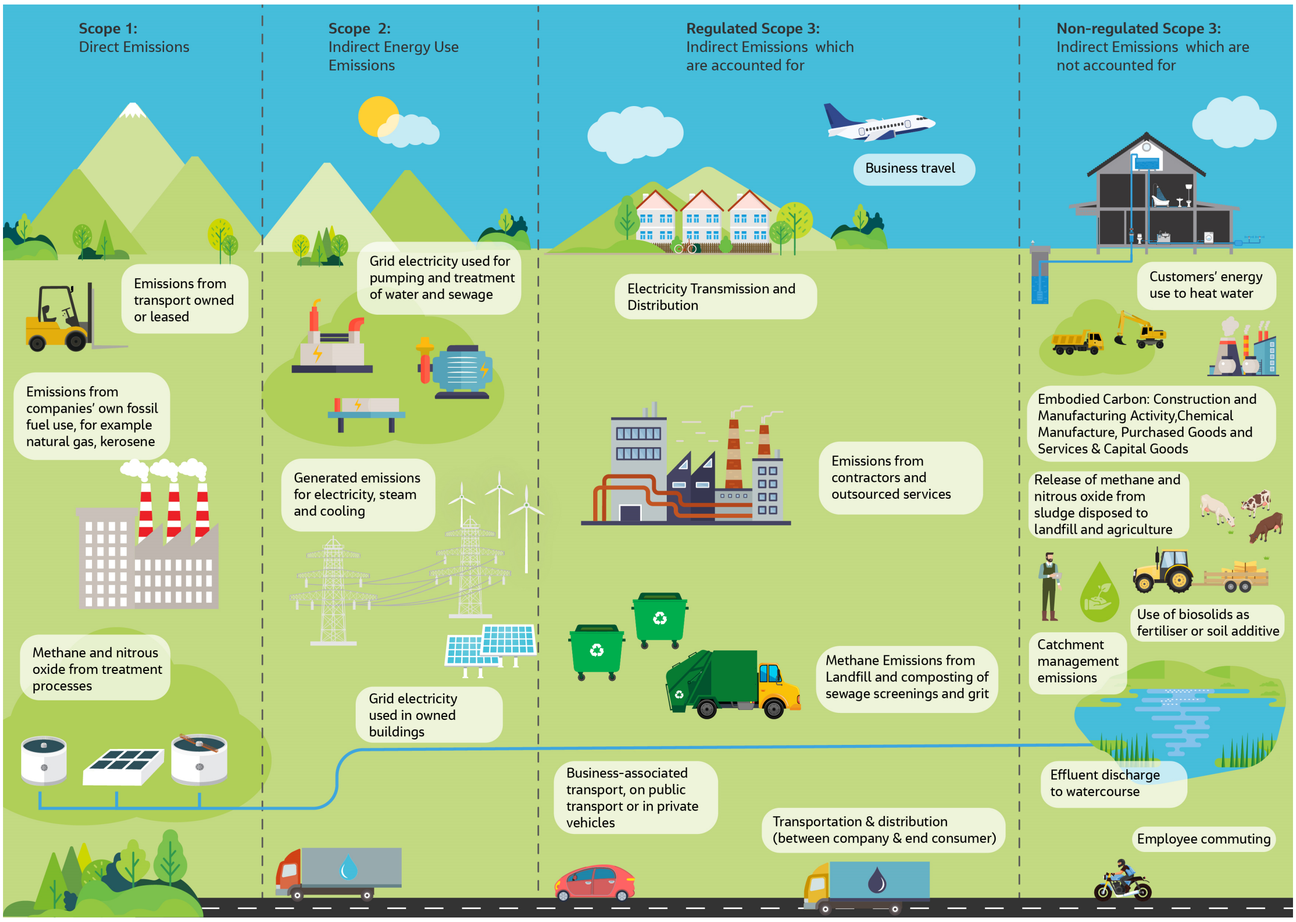


Figure 5. UK water sector emissions reporting[12].

12 UKWIR, 2019

Each greenhouse gas has a different global warming potential (GWP) over its lifetime, as shown in Figure 6 below from the IPCC's most recent 6th assessment report. This highlights the relative global warming potential – highlighting the GWP of N_2O (GWP 273) versus methane (GWP 29.8) versus carbon dioxide (GWP 1).

Species	Species (years)	Radiative Efficiency (Wm-2 ppb-1)	GWP-20	GWP-100	GWP-500	GTP-50	GTP-100	CGTP-50 (years)	CGTP-100 (years)
CO_2	Multiple	1.33 ± 0.16x10-5	1.	1.000	1.000	1.000	1.000		
CH_4 - fossil	11.8 ± 1.8	5.7 ± 1.4 x 10-4	82.5 ± 25.8	29.8 ± 11	10.0 ± 3.8	13.2 ± 6.1	7.5 ± 2.9	2832 ± 1060	3731 ± 1385
CH_4 -non fossil	11.8 ± 1.8	5.7 ± 1.4 x 10-4	79.7 ± 25.8	27.0 ± 11	7.2 ± 3.8	10.4 ± 6.1	4.7 ± 2.9	2675 ± 1057	3228 ± 1364
N_2O	109 ± 1.8	2.8 ± 1.1 x 10-3	273 ± 118	273 ± 130	130 ± 64	290 ± 140	233 ± 110		
HFC-32	5.4 ± 1.1	1.1 ± 0.2 x 10-1	2693 ± 842	771 ± 292	220 ± 87	181 ± 83	142 ± 51	78,175 ± 29,402	92,888 ± 36,534
HFC-134a	14.0 ± 2.8	1.67 ± 0.32 x 10-1	4155 ± 1160	1526 ± 577	436 ± 173	733 ± 410	306 ± 119	146,670 ± 53,318	181,408 ± 71,365
CFC-11	52.0 ± 10.4	2.91 ± 0.65 x 10-1	8321 ± 2419	6226 ± 2297	2093 ± 865	6351 ± 2342	3536 ± 1511		
PFC-14	5050,000	9.89 ± 0.19 x 10-2	5301 ± 1395	7380 ± 2430	10,587 ± 3692	7760 ± 2464	9055 ± 3128		

Figure 6. Emissions metrics for GHG species – global water potential (GWP) and global temperature-change potential (GTP)[13].

1.5.2 Water UK Net Zero 2030 Routemap gross emissions

The UK Route Map considers only Scope 1 and 2 emissions at present. Companies will need to consider all Scope 1, 2 and 3 emissions to align with regulatory and science-based climate action requirements and are unable to net these off through green energy purchase as currently illustrated in the route map.

When we consider the gross reported Scope 1 and 2 emissions, reported in the Water UK Net Zero 2030 Routemap, grid electricity for water and wastewater accounts for the highest existing emissions, followed by emissions of nitrous oxide and methane which are produced in the treatment of wastewater through aerobic and anoxic (non-aerated) biological processes (of all types) which remove nitrogen and when we treat wastewater and sludge in processes which provide for anaerobic treatment conditions, resulting in methane generation and emissions.

Under international accounting protocols (IPCC), biogenic carbon dioxide emissions produced during wastewater treatment are not reported. The rationale for this is that these form part of the short cycle carbon cycle which is released and reabsorbed by plants, consumed by animals and people etc. Whilst the CO_2 still has a global warming potential and in particular fossil-based carbon (e.g. personal care products) is recognised to be significant from wastewater sources, these emissions are not as substantiable or actionable as process emissions of N_2O and CH_4 and do not form part of national reporting at present. Irrespective of this, there may be opportunity to capture and store this and use for long term (permanent) storage (e.g. from existing separation stages of biogas upgrading) however, the transport and supply infrastructure for carbon capture and storage (CCS) does not yet exist for this and it is recognised that there are far greater needs for CCS than the water sector, based on UK Gov advisory from the Committee on Climate Change (CCC).

13 https://www.sciencedirect.com/science/article/pii/S0048969722034192?dgcid=raven_sd_search_email

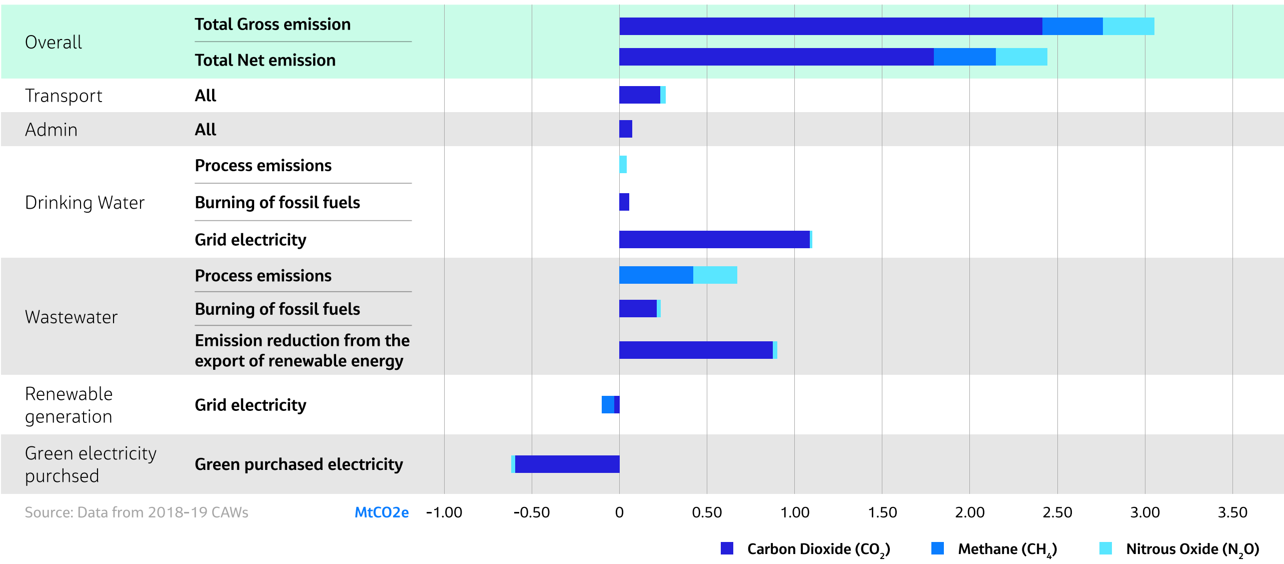


Figure 7 - Water UK GHG emissions summary for 2018-2019 operational carbon accounting workbook (CAW) reporting[14].

1.5.3 Importance of process emissions to achieve Net Zero

Importantly, ongoing industry research has highlighted that Scope 1 emissions of nitrous oxide seen in the Water UK route map, above Figure 7, are likely under-estimated by a factor of at least 4 and more likely by factor of 6-8 based on experience elsewhere and ongoing work by water companies in the UK – for example see Jacobs summary on process emissions[15] and the Phase 1 UKWIR report [16] evaluating existing Carbon Accounting Workbook (CAW) emission factors. This would significantly raise their relative impact, the sector baseline and potentially surpass even total grid electricity emissions. To accurately estimate process emissions of nitrous oxide and methane, sector level monitoring across multiple treatment facilities is required – improved accuracy of these emissions cannot be quantified without a robust national monitoring programme, as has been established in other countries (e.g. Denmark, Netherlands, Switzerland, and others).

This aspect, highlighted to a degree in the Water UK Route Map is covered in more detail in company level considerations – such as Anglian Water in their 2030 Route Map[17] which highlights the increased importance of mitigation of process emissions to achieving Net Zero and the likelihood of these emissions increasing due to under-estimated emission factors (Figure 8).

A recent review of the European wastewater sector GHG emissions[18] used variable emission factors based on the degree of secondary treatment which an emerging approach to improve on national inventory reporting – this used three emission factors for N_2O which spanned a factor of 16 (with “extended aeration without primary settlement” emitting just 0.1% of incoming total nitrogen load whilst “nitrifying only processes with PST” were estimated with an EF of 1.6% of incoming total nitrogen and “processes achieving between 70-85% total nitrogen removal” having an EF of 0.8% incoming TN ; for reference the current CAW EF is equivalent to 0.3% influent TN[19]).

14 https://www.water.org.uk/routemap2030/wp-content/uploads/2020/11/Water-UK-Net-Zero-2030-Routemap.pdf

15 https://www.jacobs.com/newsroom/news/climate-action-water-industry-embracing-challenges-n2o

16 https://ukwir.org/quantifying-and-reducing-direct-greenhouse-gas-emissions-from-waste-and-water-treatment-processes-1

17 https://www.anglianwater.co.uk/siteassets/household/environment/net-zero-2030-strategy-2021.pdf

18 https://www.sciencedirect.com/science/article/pii/S0048969722034192?dgcid=raven_sd_search_email

19 Based on the CAW EF of 0.4% N_2O per TN load to secondary treatment, assuming 8gTN/PE/d load to secondary treatment which is likely to be an under-estimate in term of both the EF and the assumed TN load to secondary treatment which would be assumed to be more like 10gTN/PE/d.

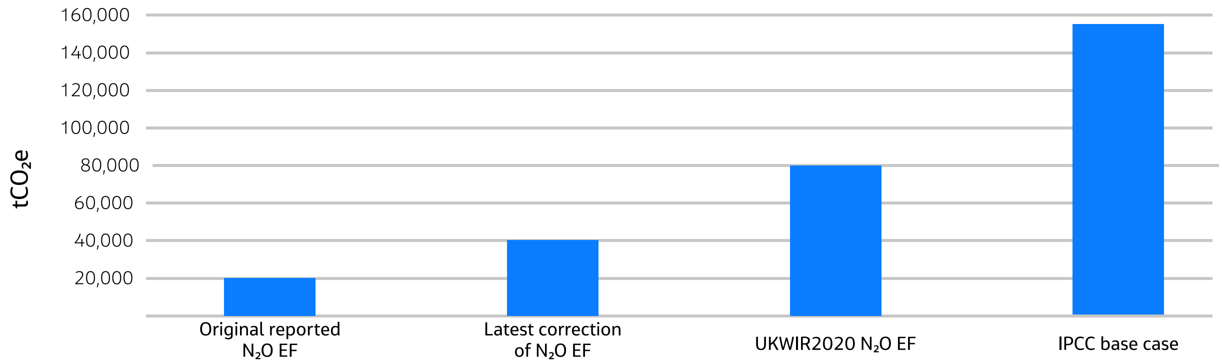


Figure 8 - Water recycling process emissions from N_2O based on different emission scenarios (as reported by Anglian Water).

Methane emissions may be presently under or over-estimated – with recent work in Denmark which found some 7.5% of produced biogas was lost through fugitive leaks at anaerobic digestion facilities for municipal wastewater[20]. Further recent analysis by researchers in the UK indicates CH_4 loss rates in the biomethane and biogas supply chain exceed those in oil and natural gas and are currently underestimated[21]. Multiple studies have highlighted the fact that fugitive methane emissions can negate the benefits of biogas[22].

1.5.4 Electrical energy emissions

When we consider grid energy usage, Figure 9 provides an idea of the relative energy usage across WoCs and WaSCs. These are dominated by pumping in water treatment and aeration in wastewater treatment.

When we consider the split of energy consumption from disaggregated data across 60 sites analysed by researchers, wastewater energy use is dominated by mechanical aeration - comprising 45 – 75% of plant energy expenditure[23]. Sites without mechanical aeration (e.g. percolating filters or other fixed film processes) will have significantly lower electrical energy demand – this is likely to be applicable to c.22%[24] of the total load treated in England and Wales by biological filtration means (though a number of these plants are likely to still have relatively high energy demands from pumping and tertiary treatment).

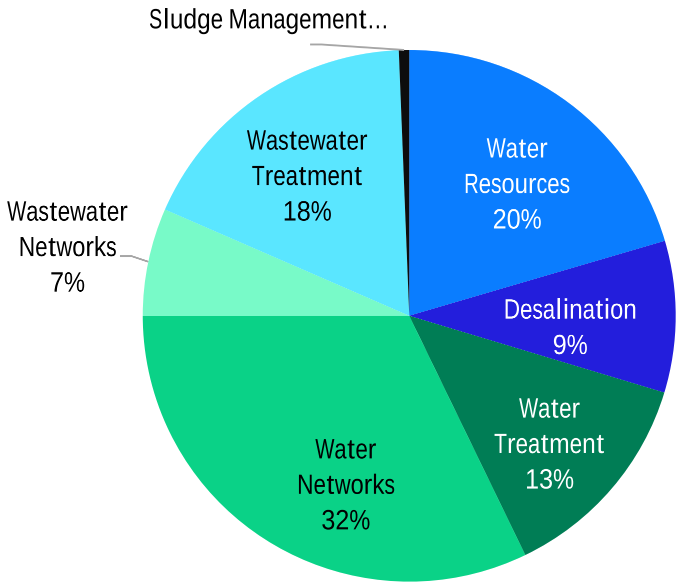


Figure 9. Energy Consumption Breakdown in Water Sector[25].

20 https://doi.org/10.1016/j.wasman.2019.07.029

21 https://doi.org/10.1016/j.oneear.2022.05.012

22 https://www.sciencedirect.com/science/article/abs/pii/S0043135412002795

23 Longo et al., 2016 – Monitoring and diagnosis of energy consumption in wastewater treatment plants. A state of the art and proposals for improvement. _ (cranfield.ac.uk)

24 Refer Figure 7 in UKWIR Phase 1 report (Jacobs, 2019). https://ukwir.org/quantifying-and-reducing-direct-greenhouse-gas-emissions-from-waste-and-water-treatment-processes-1

25 https://www.globalwaterintel.com/news/2021/32/is-net-zero-now-water-s-biggest-priority. Water resources includes abstraction and transfer of raw water upstream of treatment. Inclusion of heat energy is unclear and requires clarification.

Technology review and shortlisting

2 Technology review and shortlisting

2.1 Literature review and longlist

Technologies were collated into a longlist of technologies as seen in Appendix A.

A literature review was conducted to identify Net Zero technologies and solutions applicable to the UK water sector and gather key information for analysis.

Literature resources with greatest reliability were preferred and selected based on the hierarchical methodology described in Appendix B. Technologies and solutions submitted to Ofwat's Innovation competitions to date were identified and assessed.

Where possible literature review included cost and carbon information – however it is important to note that there is a lack of evidence base in both of these areas – and particularly in terms of life cycle carbon (e.g. considering Scope 1, 2 and 3 emissions). This lack of net zero technologies evidence base is identified as a gap which requires further work.

The longlist was filtered to produce an ultimate shortlist of technologies that would progress for further analysis.

2.2 Mid-list

Technologies progressed from the long list to a mid-list and finally to the shortlist via the procedure illustrated in Figure 10.

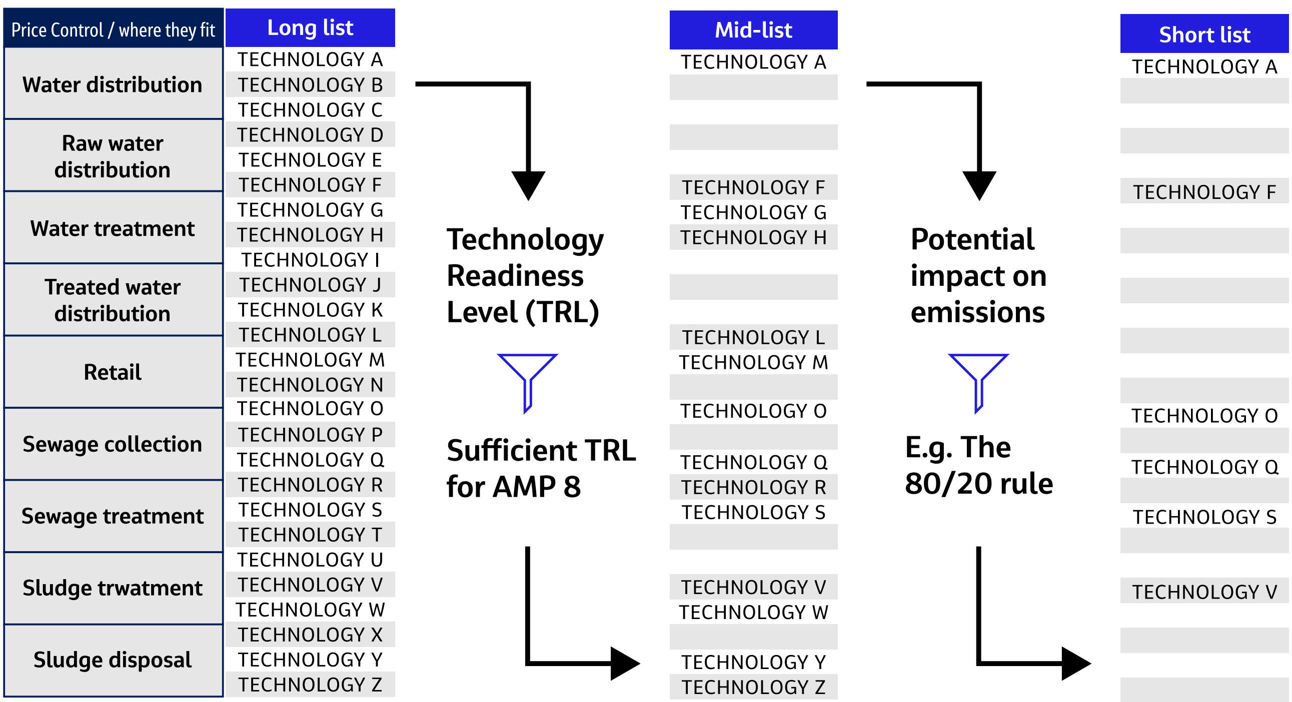


Figure 10. Characterisation of procedure used to identify a shortlist of technologies and solutions from the initial long list.

Technologies progressed from the long list to the mid-list on the basis of our estimate of their TRL. We selected TRL 7 as the minimum threshold for progression to the mid-list. We reasoned that technologies and solutions below TRL 7 are unlikely to be put forward by water companies for widespread implementation in AMP 8. A list of technologies below TRL 7 that did not progress to the mid-list, along with rationale for their TRL assessment, is included in Appendix A.

2.3 Shortlisting

Technologies progressed from the mid-list to the shortlist on the basis of our assessment of their potential impact on emissions – recognising the considerations we make in sections 1.3 and 1.4 in addition to the potential significance of the reduction – with current company carbon accounts which highlight where most emissions arise (e.g. circa 80% from electrical energy and grid emissions from pumping and treating water and wastewater).

This shortlisting assessment was broadly aligned to the 80/20 concept (also known as the Pareto principle), a concept which suggests that 80% of emissions benefits are likely to come from 20% of technologies or solutions. This was necessary due to the large number of plausibly deployable technologies and solutions remaining on the mid-list and to better discern between technologies and solutions that may be driven primarily by Net Zero and those with only minor Net Zero aspects. This assessment was on the basis of the likely scale of emissions the technology can target, and its effectiveness in targeting them.

Application of the 80/20 rule at this stage requires a significant degree of professional judgement and is more subjective than the TRL assessment. A full list of technologies and solutions that did not progress from the mid-list to the shortlist and corresponding rationale is included in Appendix A.
The application of this rule was appropriate for a relatively short timescale review project but should not be applied by companies who should robustly review technologies and their impacts and likely use in both the short term and long term.

Our assessment of the relative potential importance of each technology for decarbonisation relied on several assessments for each technology. We used a multi-criteria analysis to identify the technologies which were strongest across a range of assessments.

2.3.1 Technology assessment

We assessed the technologies across 10 categories (Table 2). Our category definitions and rationale behind allocation of scores can be found in Appendix C. These were informed by professional judgement and literature review.

Table 2. Scoring categories, description and score ranges.

Scoring category	Description	Score range
Decarbonisation hierarchy	Technology categorised based on recognised best practice for GHG management hierarchy, including Ofwat guidance and scored accordingly.	1-5
Feasibility	Feasibility for UK water sector, including applicability to prevalent existing technologies, ways of working and regulation.	0-3
Scalability	Scalability. Includes the cost, resource and personnel requirements, and potential impact on net emissions. We will seek to quantify the potential decarbonisation impact of the technology if deployed at the fullest possible scale.	0-3
Decarbonisation potential	Likely scale of net carbon benefit, taking into account any trade-offs, energy use or carbon emitted through use of the technology.	0-3
Cost and resources	Technology, solution or intervention cost and resource requirements, taking into account the Pareto Principle (80% of consequences come from 20% of causes).	0-3
Scale of use in UK	Readiness of given technology, solution or intervention for full and working operation in the UK.	0-3
Scale of use outside UK	Readiness of given technology, solution or intervention for full and working operation outside the UK.	0-3
Synergies	Potential for the suggested technology, solution, or intervention to work in tandem with another technology, solution, or intervention to achieve further solutions (e.g. increased efficiency, less waste).	0-3
Freedom from conflicts	Avoiding impact on outcomes of other suggested technologies (e.g. use of waste heat already consumed in the wider system).	0-3
Data confidence	Reliability of cost and carbon information available at time of review. Literature judged via an information resource hierarchy.	0-3

2.3.2 Weighting scenarios

After assessing the technologies, we created four scenarios with different weightings attached to each scoring category. This allowed the relative importance of categories to be increased or decreased. Category weightings were characterised within a series of scenarios (Figure 11):

1. **Decarb Max –** Decarbonisation is prioritised above other considerations. Decarbonisation hierarchy, decarbonisation potential and synergies are given the greatest weighting.
2. **Economy Plus –** Demands on resources and costs are weighted heavily with a view to delivering cost-efficient decarbonisation. Scalability, decarbonisation potential and cost and resources are given the greatest weighting.
3. **Minimal Disruption –** Technologies and ways of working that decarbonise while aligning most closely to business-as-usual are prioritised. Feasibility, cost and resources and freedom from conflicts are given the greatest weighting.
4. **Max Confidence –** Technologies with greatest information, experience and understanding in the UK water sector are prioritised. Decarbonisation potential, scale of use in UK and data confidence are given the greatest weighting.

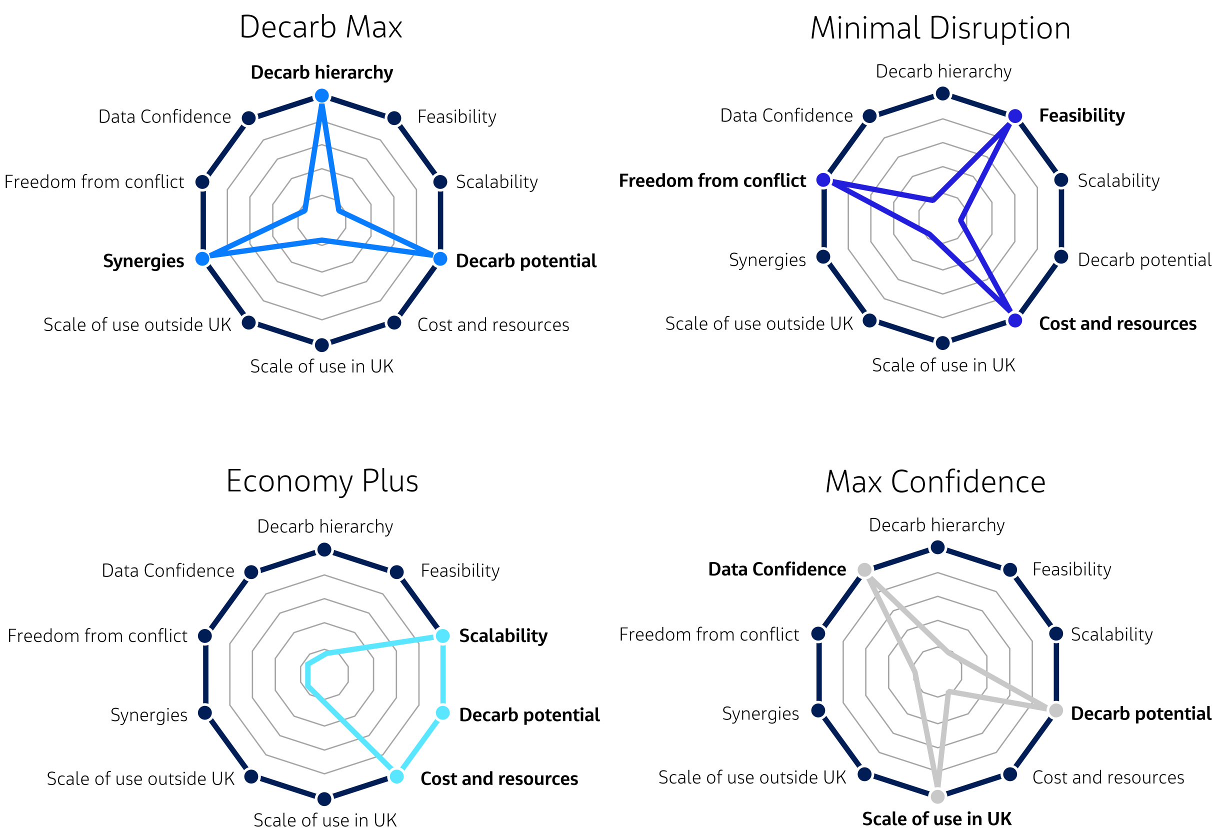


Figure 11 - Scenarios used to characterise weightings in MCA.

2.3.3 Shortlisting outputs

The multi criteria analysis ranked the technologies. A total of 21 technologies were subjected to the MCA and given more in-depth review. This resulted in a set of technologies which we consider have strong decarbonisation potential (at least in some circumstances) and a balance of other desirable features (Figure 12).

Each technology was given a relative score between 0-1 for each weighted scenario, giving a maximum possible overall relative score of 4. Methane monitoring and mitigation gave the highest overall score across the scenarios (3.91), while N stripping returned the lowest overall score (2.97). There were some minor differences in the ordering of the shortlist between differently weighted scenarios (see Appendix A). However, this was generally not extensive. One notable exception was for Biomethane to grid under the Max confidence scenario, where it was elevated to 10th in the list by virtue of its relatively extensive use already in the UK water sector.

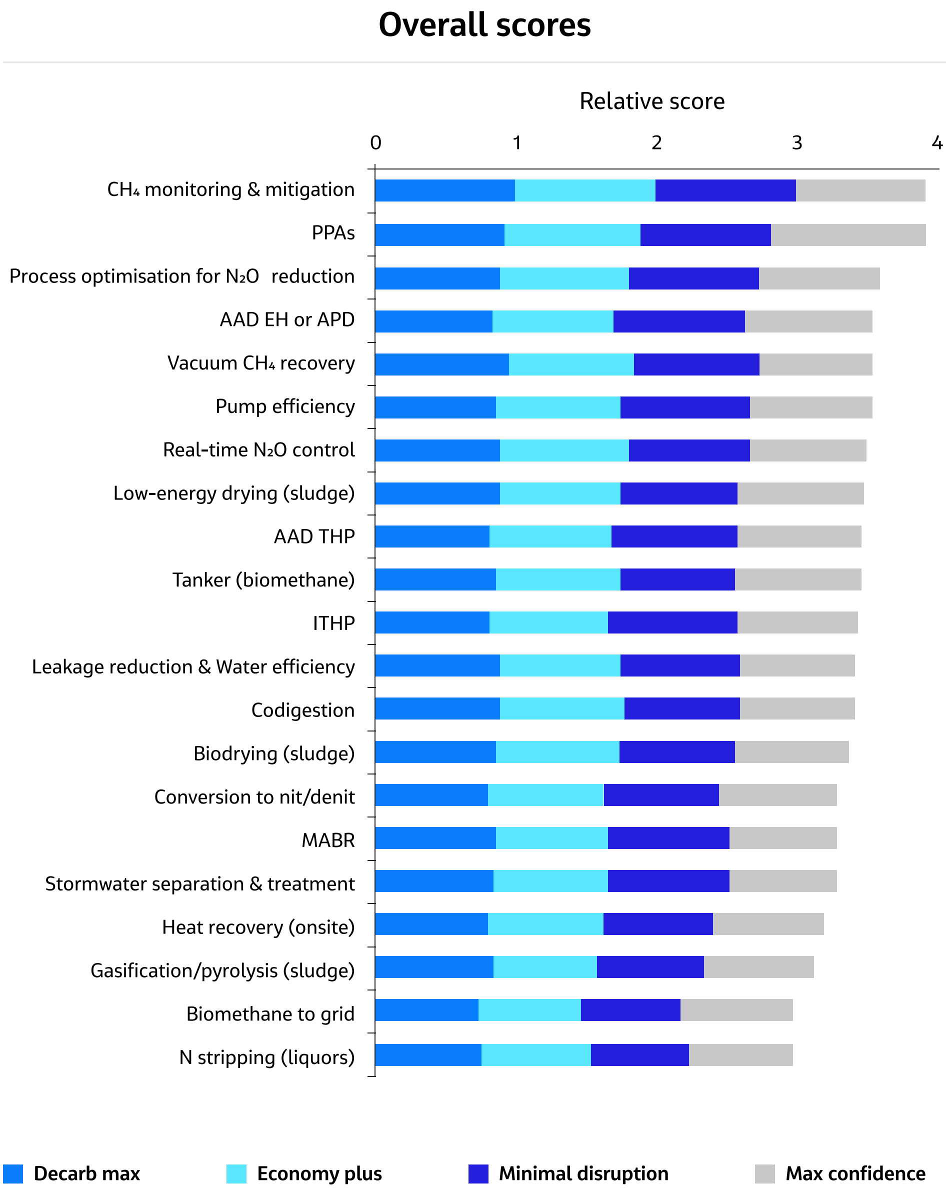


Figure 12 - Overall scores from the MCA subjected to four differently weighted scenarios

The base (unweighted) scores are given in Table 3 for each technology, listed in the order of their overall score given in Figure 12

Table 3. Base (unweighted) scores for technologies across the nine metric categories

Technology or solution (in order given in Figure 11)	WaSC or WoC applicability	Feasibility	Scalability	Decarb potential	Cost & resources	Scale of use in the UK	Scale of use outside UK	Synergies	Freedom from conflicts	Data confidence
CH_4 monitoring & mitigation	WaSC	3	3	3	2	2	3	3	3	2
PPAs	WaSC & WoC	2	2	2	1	2	2	1	2	3
Process optimisation for N_2O reduction	WaSC	2	2	3	2	0	1	2	3	3
AAD EH or APD	WaSC	3	2	1	2	3	3	2	2	3
Vacuum CH_4 recovery	WaSC	3	2	3	1	1	1	3	3	1
Pump efficiency	WaSC & WoC	3	2	2	2	2	2	2	2	2
Real-time N_2O control	WaSC	1	2	3	2	0	1	2	3	3
Low-energy drying (sludge)	WaSC	2	2	2	2	2	3	2	1	3
AAD THP	WaSC	3	2	1	2	3	3	2	1	3
Tanker (biomethane)	WaSC	2	2	2	2	2	2	2	1	3
ITHP	WaSC	3	2	1	2	3	2	2	2	2
Leakage reduction & Water efficiency	WaSC & WoC	2	2	2	1	2	2	3	3	1
Codigestion	WaSC	1	2	2	2	1	3	3	2	2
Biodrying (sludge)	WaSC	1	3	2	1	0	3	2	3	3
Conversion to nit/denit	WaSC	2	2	2	1	2	2	1	2	3
MABR	WaSC	2	1	2	2	1	2	2	2	2
Stormwater separation & treatment	WaSC	2	2	1	1	2	3	3	3	1
Heat recovery (onsite)	WaSC	2	2	3	2	2	2	2	3	2
Gasification/pyrolysis (sludge)	WaSC	1	1	2	1	1	2	2	2	2
Biomethane to grid	WaSC	2	1	2	2	3	3	2	1	3
N stripping (liquors)	WaSC	1	1	2	2	1	1	1	0	2

There are no very strong trends for the higher scoring technologies versus the lower scoring technologies across the nine metrics. However, the lower scoring technologies tend to be characterised by low feasibility and scalability, while the higher scoring technologies tend to be characterised by high-levels of synergy with other outcomes and high freedom from conflicts with other outcomes. The decarbonising potential of these technologies were broadly considered to be achievable without resulting in increased carbon emissions elsewhere in the wider system (e.g. at wastewater treatment works or national level).

As a general rule of thumb, while all shortlisted technologies have potential to contribute to the delivery of Net Zero, the decarbonising potential of technologies further down the shortlist may be determined on a case-by-case basis. Where low scoring technologies are feasible in isolation, there is a higher likelihood of wider system conflicts that jeopardises their Net Zero credentials. This could even result in a net carbon emission from the wider system. Specific details for each shortlisted technology are discussed in section 3.1.

An indicative cost band ranking in Figure 12 was undertaken based on broad bands representing the potential cost of implementing the shortlisted technologies at a Band 6 [26] wastewater treatment works – e.g. per 100,000 population or per 100,000 consumers. This assumes retrofit of Net Zero technologies and has not been validated with supplier quotations but based on high level engineering judgement intended to show indicatively a spectrum for cost/carbon considerations and to highlight the potential spread both in terms of cost and net zero potential. It is important to note that published literature is extremely limited for both cost and carbon benefit and that this may be highly site specific. Figure 13 below focuses on technology solutions and their implementation impacts - Power Purchase Agreements (PPA) are not included in this.

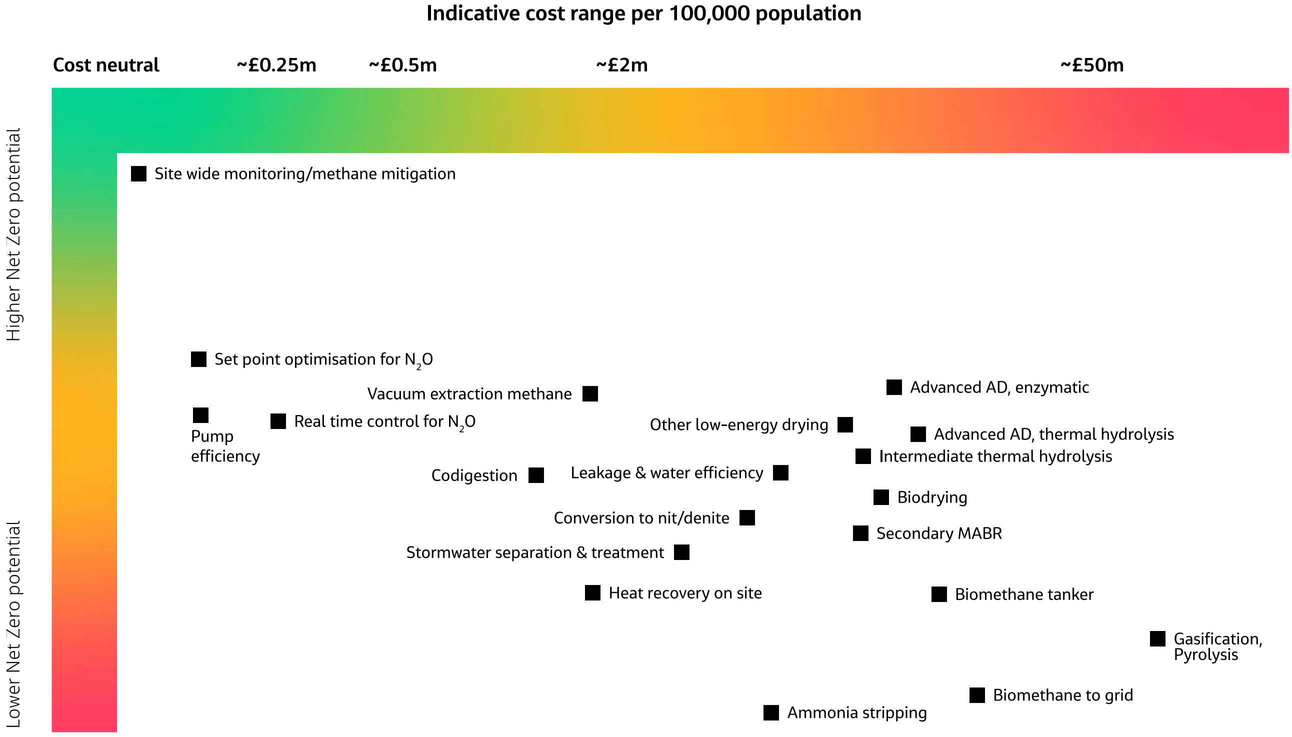


Figure 13 - Indicative cost/carbon comparison.

26 Band 6 is the Ofwat categorisation for wastewater treatment works which receive a load >1,500 kg BOD5/day, equivalent to 25k population equivalents (PE) at 60 gBOD5/day per PE.

Technology review

3. Technology review

The following sections provide an overview of shortlisted technologies and selected technologies that were not shortlisted but which may be known to Ofwat from ongoing work, e.g. in innovation projects.

In each case we provide a discussion[27] of the technology and rationale.

3.1 Shortlisted technologies

Shortlisted technologies were deemed to meet alignment with Net Zero in their likely application for upcoming business planning and AMP8 across WoCs and WaSCs. In some cases, significant blockers (e.g. lack of policy or regulatory impediments) exist which may make their implementation unlikely without rapid change to existing policy frameworks. We comment on this where required.

3.1.1 Site wide monitoring and proactive methane mitigation

Process monitoring and optimisation for nitrous oxide reduction TRL 9	Water resources Raw water distribution Water treatment Treated water distribution Retail Sewage collection Sewage treatment **Sludge treatment** Sludge disposal	Scope	**1**
		Kind	**Operational**
		Effect	**Reduce**

Low-tech reduction of fugitive methane emissions - which based on recent European evidence is imperative to provide Net Zero alignment of existing biogas production and utilisation.

Methanogenic bacteria thrive in anaerobic conditions in sludge. Anaerobic digestion makes use of this phenomenon by capturing the methane produced for beneficial use, but not all methane is retained. Sources of uncontrolled methane emissions include open-topped secondary digestion tanks, sludge holding silos, faulty pressure release valves on digestors, loss of methane through processing of biogas and use of biogas (CHP combustion and upgrading plants) and losses through pipe joints.

This solution seeks to identify and eliminate individual leaks of methane using regular (not continuous on-line) monitoring of fugitive methane emissions through structured leak detection and repair (LDAR) approaches. Presently, companies do not monitor fugitive methane emissions routinely or annually - though are starting to investigate programmes to do so in order to address net zero and also potential future Industrial Emissions Directive (IED) drivers.

Identification typically includes detection using hand-held or ground based facility level methane monitors which utilise a range of established technologies. Site level and process unit level approaches are widely published and applied in voluntary monitoring programmes in Europe – with some countries giving legislative focus to methane mitigation given the recent Global methane pledge which has seen countries including the UK commit to 30% reduction from 2020 levels by 2030[28].

Recent work in Denmark by the Danish Energy Agency, reviewing losses from 60 biogas plants showed biogas losses for sewage derived biogas of 7.7% - a significantly higher percentage than for

27 We have not provided an indicative magnitude of GHG reduction or net zero alignment because this is the evidence base from literature is poor and remains emerging on this topic. A good example is. process emissions where the sector is unclear on the current baseline and global work to date is insufficient to confirm a potential range of cost/carbon reductions. Companies will need to support proposals and decision making with science based evaluation approaches (e.g. life cycle analysis as discussed in Section 1.4) to support net zero alignment of their plans.

28 https://www.globalmethanepledge.org/

non-wastewater AD facilities. This 2021 study[29] highlighted the potential for existing high losses to negate the climate benefits of biogas.

Reduction of individual sources of methane requires proactive maintenance which aligns well with site health and safety procedures and a third party verification process – drawing on evidence from such programmes in Sweden and elsewhere in Europe.Elimination of fugitive methane from open secondary digestion tanks requires either covering the secondary digestion tanks or converting the site to advanced digestion, which requires only one stage and is fully covered. Covering secondary digestion tanks is a complex undertaking and may bring safety implications, as it will create a new enclosed space where methane will build up, creating an explosion hazard unless adequate control measures are used.

Each additional step of biogas utilisation and processing (e.g. combustion in CHP, flaring, upgrading to biomethane and export to fossil gas grid) introduces additional opportunity for fugitive methane emissions. Local capture and utilisation of biogas on site with less unit processes offers the potential for lower emissions- e.g. no methane loss (also known as slip) through upgrading plants (Scope 1) and subsequent losses in the existing gas network (Scope 3).

Funded activity synergies:

- Depending on permit conditions, compliance with the Industrial Emissions Directive, which requires management of fugitive emissions.
- Any other requirements to cover sludge stockpiles.
- Installation of further sludge drying/composting which would require enclosure/emissions control
- Renewable energy generation and on-site usage for heat and power demands, which will benefit from additional gas being available. This may require additional generation capacity to avoid increasing flaring where facilities are limited.

Decarbonisation conflicts:

- Similar to leakage, there will be a point at which it becomes uneconomical and unsustainable to continue tracking and repairing smaller and smaller leakage of biogas containing methane. Regard will need to be had to the net benefit of doing the work and the length of time over which the cost/benefit assessment is made, recognising asset age and maintenance requirements. Significant experience in European countries offers many existing considerations (e.g. the EgMet scheme in Sweden[30]) though published mitigation work remains limited.

Applicability: All anaerobic digestion sites, whether these are conventional or advanced. Opportunities exist to undertake leakage detection and repair at non-AD sites and in sewer networks but cost-effective management options likely to be minimal. Some AD site LDAR may be cost neutral.

Summary: Leaks from existing AD facilities have been shown to negate the benefit of biogas utilisation and to vary significantly – from 1% to over 7% of produced biogas. LDAR to identify and address fugitive methane emissions offers significant potential as a Net Zero technology. Proactive maintenance and third-party survey and quantification of methane leakage, as is practised elsewhere in Europe offers a key Net Zero technology solution for the sector in addition to addressing health and safety and cost benefit of increased biogas capture and beneficial use. In addition, regulatory requirements for compliance with the Industrial Emissions Directive and to meet the UK's commitment to the Global Methane Pledge by 2030 will require such action.

29 New report on methane loss from Danish biogas plants | Dea (ens.dk)

30 As discussed in the recent International Water Association Masterclass - https://iwa-network.org/learn/process-emissions-masterclass-3/

3.1.2 Process monitoring and optimisation for nitrous oxide reduction

Process monitoring and optimisation for nitrous oxide reduction **TRL 8**	Water resources Raw water distribution Water treatment Treated water distribution Retail Sewage collection **Sewage treatment** Sludge treatment Sludge disposal	Scope	**1**
		Kind	**Operational**
		Effect	**Reduce**

Monitoring of N_2O and optimisation of existing treatment process to reduce emissions through modifications to existing process control set points such as dissolved oxygen (DO) concentration or mixed liquor suspended solids (MLSS), coupled with real time nitrous oxide monitoring to demonstrate reduction from a defined baseline.

A recognised key mitigation solution for nitrous oxide formation and emission from aerated activated sludge WwTWs is the implementation of continuous monitoring of nitrous oxide. This is required to understand existing emissions and to implement emerging process control methods which have been demonstrated at full scale to minimise N_2O formation and emission. Currently these approaches, as supported by published studies[31], have been considered for fine bubble diffused aeration (FBDA) activated sludge WwTWs and have not been implemented for surface aerated ASPs, forced aeration biofilm processes[32] or percolating/ trickling filters, where quantification of emissions can be more problematic to support mitigation work. Research remains ongoing in these areas in both how to monitor and what levers are available for mitigation.

Such approaches might or might not result in any process treatment cost impacts (e.g. cost increase in treatment due to changes in aeration energy) and in some countries (e.g. Denmark) the recognised carbon pricing regime which will be introduced will further support cost benefit. However, capital outlay is required to begin monitoring emissions of N_2O to provide the evidence required to prioritise sites and take action to mitigate emissions. Baselining of N_2O emissions on a site-by-site basis is required to demonstrate any Net Zero benefits/alignment given the substantial variability in the emissions of nitrous oxide across treatment sites (even of similar process type) – as highlighted in the 2019 Phase 1 UKWIR study 'Quantifying and reducing direct greenhouse gas emissions from waste and water treatment processes'[33], undertaken by Jacobs and ongoing Phase 2 work which Jacobs is also delivering.

Multiple factors can lead to increased N_2O emissions from biological processes including the concentration of ammonia, high and low dissolved oxygen (DO) concentration, incomplete nitrification and accumulation of nitrite, carbon to nitrogen ratio (for WwTW requiring to remove total nitrogen), short sludge age and low wastewater temperatures.

Recent work on resource recovery in Denmark recognises process optimisation for N_2O mitigation as the single most important carbon impact relative to other resource recovery options[34]. This has been achieved in full scale mitigation work to date through the implementation of online monitoring of N_2O and modifying existing process control of dissolved oxygen within secondary treatment in activated sludge treatment plants through:

1. Modifications to enhance anoxic treatment through control of dissolved oxygen (DO) set points and cycle durations – based on full scale trial work in Denmark[35] (which led to the first mentioned process enhancement in further work).

2. Simple DO set point changes to reduce N_2O – increasing DO where levels are too low and

31 E.g. industry paper and published review of mitigation approaches and the first globally peer reviewed full scale mitigation study by Duan et al. (2021)

32 Quantification work for BAF plants has been undertaken in France - https://pubs.acs.org/doi/10.1021/acs.est.1c00840 and https://bg.copernicus.org/articles/17/979/2020/ though has not focused on mitigation approaches.

33 https://ukwir.org/water-research-reports-publications-viewer/$9tT09zO!

34 https://www.sciencedirect.com/science/article/pii/S0043135421007508?via%3Dihub

35 https://pubs.acs.org/doi/pdf/10.1021/acs.est.9b04889

reducing DO where levels are too high[36] as estimated using N_2O risk approaches with knowledge-based risk assessment and machine learning, characterised with short term before and after monitoring[37] and using long term monitoring and mitigation including mechanistic process modelling in academic work with an Australian water utility[38].

3. More involved process set point changes to reduce N_2O including the increase in mixed liquor suspended solids which provides more treatment capacity for ammonia loads and has been shown through Danish full-scale trials to reduce N_2O emissions[39] through creating a more stable, less highly loaded system.

4. Implement real time N_2O control and promotion of simultaneous nitrification/denitrification through coupling of process control with liquid phase N_2O measurement – which has been linked to ammonia and nitrate control and hence DO set points and length of anoxic treatment – in recent full scale Danish case study[40] (see section 3.1.3 below for real time solutions).

Recent work in Denmark evaluating five resource recovery/process optimisation technologies highlights the significance of N_2O mitigation relative to other resource recovery when considering a WwTW plant retrofit. As part of the VARGA project, Farago et al. (2021)[41], five technology alternatives were evaluated against the current performance of a WWTP which comprised conventional nitrogen removal and chemical phosphorus removal and anaerobic digestion with biogas upgrading.

The five alternatives were:

1. Real-time N_2O control.
2. Biological biogas upgrading coupled with power-to-hydrogen.
3. Phosphorous recovery.
4. Pre-filtration carbon harvest.
5. Enhanced nitrogen removal.

Their results show that real-time N_2O control, biological biogas upgrading (without advanced digestion thermal or enzymatic hydrolysis) and pre-filtration lead to a decrease in climate change and fossil resource depletion impacts. The implementation of the real-time measurement and control of N_2O achieved the highest reduction in direct CO_2-eq emissions (-35%), with no significant impacts in other environmental categories.

Funded activity synergies:

- Refurbishment of existing works.
- Capacity upgrades.

Decarbonisation conflicts:

- DO set point changes may require increased or decreased aeration energy – subject to site baselining and assessment. Where increased grid energy is required, this will increase Scope 2 emissions based on current grid energy mix.
- Enhanced nitrification/denitrification conflicts with potential wider system opportunities for reactive nitrogen (ammonia) recovery and reuse for agricultural or other benefits – however the technology solutions and Net Zero benefits of N recovery are not yet sufficiently developed for AMP8.

Applicability: As a first step, set-point optimisation is likely to target larger works that operate specific treatment processes identified as being particularly high risk for N_2O emissions as demonstrated through continuous on-line monitoring. It is important to note that existing industry emission factors in the Carbon Accounting Workbook (CAW) or IPCC guidelines for N_2O emissions are not able to be used to demonstrate potential baseline/reduction toward Net Zero. Site level monitoring across all sites of interest will be required to take steps towards mitigation of these emissions.

36 E.g. a typical DO set point range for nitrifying ASP may be 1.5-2mg/l.; l ower and higher values than this might lead to risk of N_2O but this is not categoric and N_2O production and emission will vary within and across sites due to biological pathways, greatly influenced by operational conditions.

37 http://www.cobaltwater-global.com/uploads/2/8/2/1/28215105/porro_etal_weftec_2017.pdf - this is not peer reviewed published literature.

38 https://pubmed.ncbi.nlm.nih.gov/32738601/

39 Presentation at IWA Digital World Congress, provided to Jacobs by authors – programme here

40 https://www2.mst.dk/Udgiv/publikationer/2022/01/978-87-7038-374-5.pdf (machine translated from Danish)

41 https://www.sciencedirect.com/science/article/pii/S0043135421007508?via%3Dihub

Despite approaches which utilise simple (e.g. STOWA)[42] and more complex risk-based modelling approaches for N_2O formation[43], evidence from peer reviewed publications to date highlights the need for continuous online (liquid or gas phase) monitoring for N_2O to allow such prioritisation of sites and Companies will need to show evidence of this if taking science-based approaches.

Summary: Monitoring of N_2O is key to this mitigation solution. Upon establishing a reliable a site baseline for N_2O, relatively simple (e.g. DO set point changes) and more complex (e.g. process changes to biomass through MLSS or degree of anoxic denitrification treatment) process optimisation for nitrous oxide mitigation may support mitigation and such interventions are likely to be the most significant Net Zero solution companies can take at existing assets during AMP8. Currently, establishing a reliable site baseline requires online (liquid or gas phase) N_2O monitoring, which is imperative (with emerging opportunities for data driven and soft sensor/digital approaches not yet market ready to offer surrogate alternatives to continuous N_2O monitoring).

3.1.3 Monitoring and real time control for nitrous oxide reduction

Monitoring and real time control for optimisation of nitrous oxide **TRL 7**	Water resources Raw water distribution Water treatment Treated water distribution Retail Sewage collection **Sewage treatment** Sludge treatment Sludge disposal	Scope	**1**
		Kind	**Operational**
		Effect	**Reduce**

Real time N_2O control to reduce emissions through additional monitoring instruments used to optimise existing process control strategies.

The context for this intervention is presented in section 3.1.1. Real time process control of N_2O is one of a number of process interventions/ optimisation opportunities to mitigate N_2O. It is not a pre-requisite for N_2O mitigation, though full-scale monitoring of N_2O is required to baseline each site given present science-based understanding of N_2O production and emission and variation across sites and with seasonal variation (e.g. 12 months monitoring to understand how emissions vary) with greatest emissions observed during springtime at some sites but not others.

In the context of monitoring for process control, online N_2O monitoring is feasible through liquid phase sensors (a single instrument is currently available off-the-shelf to the market) or through gas phase monitoring (multiple off-the shelf solutions exist though these are most widely used in academic research given the additional operational input required). Continuous online monitoring offers the opportunity to link this to process control – e.g. controlling N_2O emissions by manipulating set points of air flow via DO-based control, ammonia-based aeration control (ABAC) or a combination of nitrate and ABAC (which provides the only full-scale demonstration case to date from work in Denmark[44]).

Funded activity synergies:

- Refurbishment of existing works.
- Capacity upgrades.

Decarbonisation conflicts:

- The impacts of real time control using N_2O where this results in changes to aeration supplied may require increased or decreased aeration energy – subject to site baselining and assessment. Where increased grid energy is required, this will increase Scope 2 emissions based on current grid energy mix
- Where RTC is used for enhanced nitrification/ denitrification this conflicts with potential wider system opportunities for reactive nitrogen

42 https://www.stowa.nl/sites/default/files/assets/PUBLICATIES/Publicaties%202011/STOWA%202011-30.pdf

43 http://www.cobaltwater-global.com/uploads/2/8/2/1/28215105/porro_etal_weftec_2017.pdf

44 https://www2.mst.dk/Udgiv/publikationer/2022/01/978-87-7038-374-5.pdf (in Danish)

(ammonia) recovery and reuse for agricultural or other benefits – however the technology solutions and Net Zero benefits of N recovery are not yet sufficiently developed for AMP8.

Applicability: Similar to section 3.1.1.

Summary: Given online N_2O monitoring is required to understand emissions at a site level sufficiently to take science-based action to reduce these, implementing real time control may be viable at sites where sufficient infrastructure (e.g. SCADA or alternative) exists to integrate this into existing site controls. This is likely to be possible for all WaSCs - though site to site, requirements for integration and communications needs will differ.

3.1.4 Optimisation of nitrifying/denitrifying treatment stages to achieve nitrous oxide reduction

Process upgrade to achieve nitrous oxide reduction **TRL 9**	Water resources Raw water distribution Water treatment Treated water distribution Retail Sewage collection **Sewage treatment** Sludge treatment Sludge disposal	Scope	**1**
		Kind	**Operational**
		Effect	**Reduce**

Provide real time N_2O monitoring and process modifications to enhance denitrification which allows reduction of nitrous oxide for activated sludge treatment plants.

The context for this intervention is presented in section 3.1.1. Given evidence which supports the potential for lower N_2O emissions by enhancing denitrification, an opportunity for companies is to enhance the denitrification processes within existing ASPs or provide denitrification process treatment at new or upgraded ASPs.

Long term online N_2O is currently required to provide sufficient understanding of site emissions baseline and mitigation options and efficacy as with all N_2O mitigation opportunities and as discussed previously. This is currently feasible through existing methods for fine bubble diffused aerated (FBDA) ASPs and not surface aerated plants or fixed film plants (e.g. trickling filters).

Limited published full scale studies highlight that increased anoxic cycle times in sequencing batch reactors or enhanced denitrification through simultaneous nitrification and denitrification is feasible. A majority of ASPs in England and Wales are not enabled for denitrification through sufficiently sized anoxic (non-aerated) treatment zones. Some companies (e.g. Severn Trent) undertake denitrification to support other processes on site (e.g. to minimise risk of rising sludge in final settlement tanks and/or support biological phosphorus removal) whilst others (e.g. Southern Water) have a large number of consented treatment sites which require denitrification to meet coastal discharges with total nitrogen (TN) standards. This is further discussed in the 2019 UKWIR publication[45].

It is possible that optimisation of existing sites within existing tankage may allow increased denitrification - e.g. through simultaneous nitrification and denitrification or enhanced settlement through continuous flow granulation or through augmentation technologies to allow intensification of treatment. In other cases, capital infrastructure (additional tankage, mixers and process recycles) would likely be required.

Processes which denitrify require reduced aeration input overall and other process benefits (e.g. no need for alkalinity dosing, improved settlement) may also exist. Optimisation of aerobic treatment may still be beneficial for N_2O mitigation.

Funded activity synergies:

- Refurbishment of existing works.
- Capacity upgrades.

45 https://ukwir.org/quantifying-and-reducing-direct-greenhouse-gas-emissions-from-waste-and-water-treatment-processes-1

Decarbonisation conflicts:

- The impacts of real time control using N_2O where this results in changes to aeration supplied may require increased or decreased aeration energy – subject to site baselining and assessment though where TN reduction is introduced, this will reduce net aeration demand.
- Where process upgrades to remove nitrogen are implemented this conflicts with potential wider system opportunities for reactive nitrogen (ammonia) recovery and reuse for agricultural or other benefits – however the technology solutions and Net Zero benefits of N recovery are not yet sufficiently developed for AMP8.

Applicability: Similar to section 3.1.1 – though where additional tankage is required this is likely to limit opportunities in terms of space and cost.

Summary: Optimisation of nitrification and denitrification, coupled with process optimisation of aeration stages is likely to offer significant opportunities for N_2O mitigation. This is likely to be site specific though we consider opportunities are likely to exist for most Companies with existing FBDA ASPs. There may be opportunities to augment or enhance existing assets (e.g. through further innovation in promoting augmentation and/or simultaneous nitrification/denitrification or short cut processes in mainstream) but where additional tankage is required (e.g. with the addition of an anoxic zone which could comprise up to 40% of ASP tankage) - in addition to cost implications - the net carbon impacts must be weighed up against potential operational benefits. This should also include considerations for future N recovery which is likely to offer greater system benefits for Net Zero (where this does not require net increase in natural gas imports on sites).

3.1.5 Process energy efficiency in wastewater treatment

Process energy efficiency in wastewater treatment **TRL 7**	Water resources Raw water distribution Water treatment Treated water distribution Retail Sewage collection **Sewage treatment** Sludge treatment Sludge disposal	Scope	**2**
		Kind	**Operational**
		Effect	**Reduce**

Process optimisation to improve aeration efficiency which is the most significant source of energy for site treatment at WwTWs offers high potential for Net Zero alignment through mitigation of Scope 2 emissions.

Examples of process optimisation with potential low investment and rapid payback are outlined by Longo et al. (2016)[46] and include optimisation of active mixers, improved control of MLSS concentrations and resulting aeration inputs, applying variable frequency drives and adopting energy efficient pumps, diffusers and aerators and improved, more advanced DO control. In specific examples illustrated in this comprehensive study, up to 30-35% energy savings across a number of these areas were demonstrated. The authors suggest overall energy savings between 5 – 30% seem reasonable with the most potential in aeration systems.

Simple actions such as keeping dissolved oxygen monitoring instruments cleaned and accurate and revising sites to optimise aeration plant/adjust for seasonal variation are also likely to offer companies with programmatic approaches to improved process and energy efficiency.

Funded activity synergies:

- Quality and capital maintenance upgrades

Decarbonisation conflicts:

- Energy efficiency requires to be considered in conjunction with N_2O production and emission – in some cases energy efficiency in aeration systems may increase N_2O emissions without these being monitored in real time and assessed in terms of variation across process changes and seasonal variation.

Applicability: Widely applicable.

46 https://dspace.lib.cranfield.ac.uk/bitstream/handle/1826/10871/energy_consumption_wastewater_treatment_plants-2016.pdf?sequence=3

Summary: Whilst many companies have undergone energy efficiency programmes over recent and historic AMPs, further focus on energy efficiency – in particular for largest uses such as aeration plant on wastewater treatment – is aligned with Net Zero principles to reduce Scope 2 emissions. Such interventions may offer wider or parallel benefits when undertaken in conjunction (e.g. reduced N_2O emissions if optimisation for energy, N_2O and quality is undertaken holistically).

3.1.6 Membrane aerated biofilm reactor

Membrane aerated biofilm reactor (MABR) for secondary wastewater treatment TRL 7	Water resources Raw water distribution Water treatment Treated water distribution Retail Sewage collection **Sewage treatment** Sludge treatment Sludge disposal	Scope	**1**
		Kind	**Operational + Embodied**
		Effect	**Reduce**

A reinvention of air/oxygen delivery for aerobic secondary wastewater treatment.

MABRs can be deployed as the principal method of treatment in a dedicated MABR plant or can be retro-fitted within existing treatment infrastructure to support or add capacity to an activated sludge process (ASP), effectively converting it in to an Integrated Fixed film Activated Sludge (IFAS) system. Demonstration scale trials so far have explored the latter format of MABR implementation[47].

The Activated Sludge Process (ASP) is ubiquitous throughout the world in a variety of forms as a principal biological method for removal of carbon and nutrients nitrogen and phosphorus. While effective, the ASP is incredibly energy intensive. Energy is demanded by high-pressure air blowers that blow air bubbles into the wastewater or surface mounted aerators which provide agitation to introduce air – these aeration technologies supply the activated sludge microorganisms in tanks with dissolved oxygen for respiration and biological transformation of the wastewater. Typically, 50% of the electrical demand of a wastewater treatment works is estimated to be from aeration of activated sludge plants. Oxygen Transfer Efficiency (OTE) is also low, meaning most of the oxygen dissolved into the wastewater does not reach the microbes that need it to perform their treatment function.

MABRs reduce the relative energy demand for treatment compared to ASP by supplying air at a lower pressure and with a much-improved OTE. It does this using hollow-fibre membranes, where air is fed through the membrane bore and a biofilm containing the necessary microbial community for treatment is grown on the outside of the membrane. Unlike for ASP, the air supply isn't pushing against a head of water and so a lower pressure (and lower energy) air supply can be used. Oxygen permeates through the membrane where it encounters the aerobic biofilm. This direct oxygen supply mechanism is much more efficient than for the ASP, where microbial communities must scavenge dissolved oxygen from the surrounding wastewater. This efficiency further lowers the relative energy demand for treatment versus ASP.

MABRs impact Net Zero by reducing energy demand of forced aeration treatments but could also be associated with significantly reduced nitrous oxide (N_2O) process emissions. Monitoring of a single ASP and full-scale demonstration MABR facility in Denmark[48] has suggested an order of magnitude reduction in N_2O for MABR plants – though this evidence base remains limited. The importance of action on nitrous oxide emissions is key - Water UK's Net Zero 2030 Routemap has highlighted N_2O process emissions as remaining high. Finally, MABRs can be retro-fitted within existing ASP tankage to expand the treatment capacity of existing works without a significant increase in infrastructure and pouring of concrete. This allows MABR to influence both operational and embodied carbon as part of the Net Zero agenda.

47 https://www.oxymem.com/blog/severn-trent-commissions-the-uks-largest-mabr-plant-during-lockdown

48 https://www2.mst.dk/Udgiv/publications/2020/08/978-87-7038-216-8.pdf

Funded activity synergies:

- Refurbishment of existing works.
- Capacity upgrades.

Decarbonisation conflicts:

- No major conflicts.

Applicability: Existing and new activated sludge plants, although may be site-specific depending on operational hydraulic retention time.

Evidence base: There are no reported studies which provide evidence for Net Zero alignment.

Summary: MABR may be the only market-ready solution with the potential to tackle process emissions of nitrous oxide, energy consumption and embodied carbon emissions. Full scale trials with UK water companies (e.g. Scottish Water and Severn Trent) appear to be giving promising results. Other water companies (e.g. Anglian Water) also looking at MABR within their published Net Zero Strategies. Whether in augmentation of existing treatment processes or in greenfield installation (e.g. as being considered by Anglian Water at Cambridge), MABR would appear a promising Net Zero technology.

3.1.7 Biogas upgrading – biomethane to grid

Biomethane to grid TRL 9	Water resources Raw water distribution Water treatment Treated water distribution Retail Sewage collection Sewage treatment **Sludge treatment** Sludge disposal	Scope	3
		Kind	**Operational**
		Effect	**Substitute**

Injection of upgraded biogas (biomethane) into the gas grid as a renewable substitute for natural gas.

WaSCs generate biogas through the treatment of sewage sludge by anaerobic digestion. In recent decades the majority of this gas has been combusted in combined heat and power (CHP) engines to generate renewable electricity and heat, which can be used onsite (e.g. heating digesters, creating steam for thermal hydrolysis). However, full scale biogas upgrading plants at a number of UK treatment works are able to treat biogas to a standard that makes it analogous to natural gas, biomethane. This allows it to be injected into the national gas grid (instead of CHP), thereby lowering the gas grid carbon intensity and gaining commercial benefits for companies due to renewables certification.

In some cases, e.g. where a site receives large sludge imports, application of all biogas to CHP generates more energy than can be consumed onsite and it must be exported[49]. In this case, diverting the excess biogas to the gas grid might not impact the wider wastewater treatment system. However, at other sites there is not an excess of electricity and heat. For example, a number of sites already report the need for natural gas support to generate steam for thermal hydrolysis[50], indicating that all high-grade heat from CHP has already been consumed onsite. In this case, shifting more biogas away from CHP towards grid injection is likely to result in a reciprocal increase in natural gas and grid electricity imports into the wider system, undermining the carbon benefit of biomethane to grid. It is not clear from readily available public information what proportion of Bioresources sites would require significant import of natural gas to balance the export of biomethane. However, peer-reviewed study has suggested that sites with thermal hydrolysis would see a large net carbon emission from shifting their biogas end-use from CHP fully to grid injection[51].

It is possible this is already happening at sites with existing biomethane to grid. Based on Ofwat's

49 https://conferences.aquaenviro.co.uk/wp-content/uploads/sites/7/2018/08/30-Steve-Riches.pdf (Figure 8)

50 https://www.aquaenviro.co.uk/wp-content/uploads/2015/06/Thermal-Hydrolysis-at-Davyhulme-WWTW-%E2%80%93-One-Year-On-Edgington-R..pdf (Table 6)

51 https://doi.org/10.1016/j.wasman.2013.08.024

Bioresources Market information[52], approximately 28% of sludge in England and Wales is treated at sites with thermal hydrolysis and 16% of sludge at sites with thermal hydrolysis and biogas upgrading. It is possible that thermal hydrolysis will expand even further to satisfy treatment capacity and increase solids destruction in anticipation of constrained outlets for biosolids to land. Biogas upgrading plants could also expand as financial subsidies for CHP drop-off, with 85% of Renewables Obligation Certificates (ROCs) due to expire by 2030[53]. This shows the existing scale of risk of reciprocal importing of natural gas, a risk that might increase over the next AMP period and beyond. This practice is not aligned with Net Zero principles given it increases company Scope 1 emissions due to necessary import of natural gas, in addition to other increased emissions associated with combusting natural gas (Scope 1), increased emissions associated with upgrading biogas to biomethane (Scope 1), associated embodied (Scope 3) infrastructure and resulting downstream fugitive emissions from longer transit in gas networks (Scope 3).

Decarbonisation conflicts:

- Moving biogas away from CHP towards grid injection is likely to reduce the availability of high-grade renewable heat and could increase imports of natural gas and grid electricity to readdress the energy balance.
- Reduced availability of renewable heat onsite could be problematic for the introduction of new heat-intensive processes, such as ammonia recovery by thermal stripping and sludge drying.

Applicability: Can be technically implemented anywhere biogas is generated and there is a practical point of access for injection of biomethane into the gas grid.

Summary: Water UK's Net Zero 2030 Routemap indicates a target for 70% of biogas to be injected into the grid and a number of company strategies appear to be aligning with this, forgoing local use of biogas for onsite heat and power generation. Where Company strategies require new or increased import of fossil (natural) gas this will increase their Scope 1 emissions and cannot be considered Net Zero aligned.

While biomethane can decarbonise the gas grid (and reduce emissions for other third parties – this is not able to be accounted for by companies pursuing science-based emissions targets or aligning with Net Zero emissions principles set out by Ofwat) there is a significant risk of increased carbon emissions elsewhere in the treatment system by a reciprocal increase in imported natural gas to provide the heat no-longer provided by CHP. To align with Net Zero and science-based trajectories for the UK, decarbonisation across the whole system needs to be demonstrated by carbon and energy balances for every case of biomethane to grid.

More work must be done to:

Substantiate the carbon benefit of new biomethane to grid plants through energy and carbon balances, accounting for any increased import of natural gas and grid electricity. Where grid electricity is obstensively procured from renewable sources, this should follow the hierarchy detailed below in Section 3.1.8.

3.1.8 Power Purchase Agreements (PPAs)

Power Purchase Agreements TRL 9	Water resources Raw water distribution Water treatment Treated water distribution Retail Sewage collection Sewage treatment Sludge treatment Sludge disposal	Scope	2
		Kind	Operational
		Effect	Reduce

Renewable electricity procured directly through onsite renewables or corporate PPAs

The use of grid electricity is a major source of emissions for both water and wastewater treatment. While the grid is likely to decarbonise gradually over time, this is outside of the water sector's control and is likely to remain relatively carbon intensive by the end of AMP 8.

52 https://www.ofwat.gov.uk/wp-content/uploads/2021/11/Bioresources_Dashboard_Data-2020-21.xlsx

53 https://renewablesandchp.ofgem.gov.uk/

Water UK's Net Zero 2030 Routemap reveals that 85% of the UK water sector's reported negative emissions came from purchase of Green electricity tariffs, with only 15% as renewable energy exported by the sector.

However, several sources[54] [55] place use of Green electricity tariffs at the bottom of the decarbonisation hierarchy regarding corporate procurement of renewable electricity (Figure 14). In simple terms this is about demonstrating the immediate additionality of renewable electricity generated.

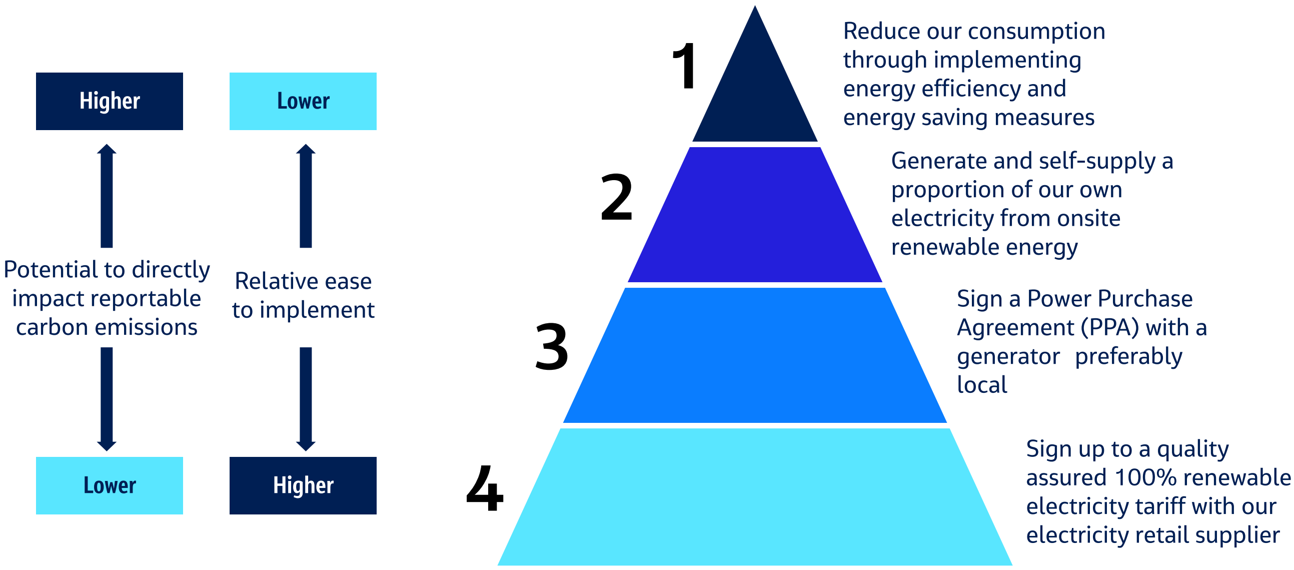


Figure 14 - Hierarchy of renewable electricity procurement. Figure based on article by Ray Arrell, Regen, (25/6/2021)[56].

Reducing consumption of electricity in the first place is always at the top of this hierarchy. Where electricity use cannot be avoided there should be preference for onsite, behind the meter renewables to materially reduce grid electricity imports with demonstrably additional renewable electricity. Opportunities to do this behind the meter may be restricted on WaSC/WoC land for practical or planning reasons. A private-wire to adjacent off-site renewables may be similarly preferable from an additionality perspective, although the unit price of electricity to WaSCs/WoCs might be higher as they are not providing the land and there could be external competition to secure the electricity. However, without storage (e.g. batteries) there is risk that electricity generation has periods of low output and intermittency. WaSCs/WoCs are large consumers of electricity, and it is probable that sites will need to import electricity via the grid during these periods.

PPAs are next in the hierarchy. The grid is used to import electricity from specific renewable sources, with typically long-term contracts. Additionality is still straightforwardly demonstrated. However, there are high levels of competition for securing electricity generated at these sites – particularly at the scale of consumption relevant to WaSCs/WoCs. For example, from government issued Contracts for Difference (CfDs). Therefore, the challenge for PPAs will be availability of new renewables and the ability of WaSCs/WoCs to secure long-term contracts as new production comes online.

By contrast, Green tariffs are at the bottom of the hierarchy. While increased demand for Green tariffs can generally stimulate future renewables development, opting for a Green tariff does not directly result in the introduction of new, additional renewable electricity. As a result, they don't provide a verifiable additional source of renewable electricity at the national level.

54 https://www.jll.co.uk/en/views/is-all-renewable-electricity-procurement-equally-as-green

55 https://www.theccc.org.uk/wp-content/uploads/2020/12/Corporate-Procurement-of-Renewable-Energy-Implications-and-Considerations-Terri-Wills.pdf

56 https://www.regen.co.uk/the-race-to-zero-our-electricity-use-and-green-tariffs/

Summary: Onsite, behind the meter or private wire renewables and PPAs represent the greatest impact for decarbonisation of electricity. Wherever possible WaSCs and WoCs should opt for these solutions as per established hierarchies as illustrated in Figure 14. Only where onsite renewables are not possible due to footprint or planning constraints, geographies do not readily allow for private wires, and once securing corporate PPAs has been fully explored, should Green tariffs be considered (via further hierarchy set out in Section 3.2.14).

This philosophy could be counter to the UK water sector's approach to date, based on the significant apparent preference for reporting negative emissions via Green tariffs as detailed in the Net Zero 2030 Routemap. However, we don't expect this approach to date will deliver additional decarbonisation at the national level and shouldn't continue to comprise the sector's primary strategy to decarbonise its electricity use. Companies aligned to frameworks such as the Science Based Targets initiative are likely to need to demonstrate additionality for their renewable electricity sources.

3.1.9 Vacuum extraction of methane

Vacuum extraction of methane **TRL 7**	Water resources Raw water distribution Water treatment Treated water distribution Retail Sewage collection Sewage treatment **Sludge treatment** Sludge disposal	Scope	**2**
		Kind	**Operational**
		Effect	**Reduce**

Removal and recovery of dissolved methane from digested sludge as it exits the anaerobic digester or from downstream sludge storage.

Sludge exiting the anaerobic digester comprises mainly water along with remaining solids that have not been converted into biogas (mix of mainly methane and carbon dioxide). The water fraction of sludge will be saturated by dissolved methane, while methane gas bubbles can be attached to the solid fraction and dragged out of the digester, rather than being collected with the bulk of the biogas. This methane will be emitted upon contact with the atmosphere, e.g. in an open secondary digester or during downstream sludge processing such as dewatering.

Commercial systems are capable of recovering the methane in sludge post-digestion or from storage by subjecting it to a vacuum within an enclosed tank before it is exposed to the atmosphere[57]. This methane can then be recovered and reunited with the bulk biogas that has been collected from the digester.

Vacuum extraction avoids the emission of methane that diminishes the carbon benefit and energy yield of biogas and the digestion process. Process vendors note that the additional methane captured is approximately equal to the energy required to sustain the process – allowing for an energy neutral technology solution whilst offering reduced fugitive methane emissions. The scale of fugitive methane emissions reduction has not been quantified in published studies and will be site dependent – affected by the processes downstream and release of methane from these. Recent work in Denmark is providing vacuum extraction on sludge storage tanks rather than immediately downstream of digestion.

Funded activity synergies:

- Can be implemented to complement site-wide monitoring and proactive methane mitigation
- Improve biogas recovery yield for Combined Heat and Power (CHP) or biomethane to grid

Applicability:

- Applicable at all sites using anaerobic digestion of sludge

Summary: Commercial systems are relatively new and the magnitude of methane emissions reduction, net of the energy requirement to run the system remains yet to be published by commercial vendors who to date claim that the increased biogas yield through system installation is sufficient for operation of the

57 https://www.eliquo-we.com/en/elovac.html

plant and equipment. There are trials at UK Sludge Treatment Centres[58 59]. The technology has reported synergistic benefits, such as the prevention of foaming and reduction in anti-foaming chemicals. Impacts on dewaterability are not clearly positive or negative with both outcomes observed in (large scale) pilot work to date. It remains to be seen how big an impact vacuum extraction will have on methane emissions as a component of wider proactive methane mitigation measures and its cost effectiveness, e.g. versus covering secondary digester tanks. It is likely such assessments will be site-specific and best informed through initiation of a programme of methane emissions quantification across bioresources assets and leak detection and repair (LDAR) – as discussed in section 3.1.1.

3.1.10 Advanced anaerobic treatment – thermal hydrolysis

Advanced anaerobic digestion – thermal hydrolysis **TRL 9**	Water resources Raw water distribution Water treatment Treated water distribution Retail Sewage collection Sewage treatment **Sludge treatment** Sludge disposal	Scope	**1**
		Kind	**Operational + Embodied**
		Effect	**Reduce**

Intensification of digestion process. Increases sludge to methane conversion compared with conventional mesophilic anaerobic digestion.

Anaerobic digestion converts solid organic material into methane through the action of methanogenic bacteria. Conventional anaerobic digestion leaves a substantial portion of organic material trapped within plant and microbiological cell walls. This limits methane production and creates the need for secondary digestion to complete the stabilisation of raw sludge.

Thermal hydrolysis destroys cell walls and enables the methanogens to convert a greater fraction of solid organic material into methane.

Thermal hydrolysis achieves this by elevating the temperature and pressure of liquid sludge, before releasing the pressure in a flash tank. This is an energy-intensive process. It is often paired with combined heat and power (CHP) engines to allow waste heat to be used. Where biogas is exported from site rather than used in CHP engines, fossil (natural) gas is typically imported to provide the heat required which negates the Net Zero alignment of this technology - the energy and carbon balance is less attractive in this case and company reported emissions will be significantly increased due to import of fossil gas (given upgraded and exported methane introduces additional fugitive losses and is not reportable as emissions reduction for the water company even if financial incentives exist).

Thermal hydrolysis is often used to intensify existing digestion processes. This is because the plant required is relatively small, and it has the effect of increasing the throughput of existing digestors and eliminating the need for secondary digestion. This makes it generally applicable to sites which currently use conventional digestion.

Funded activity synergies:

- Energy generation, which will benefit from additional gas being available. This may require additional generation capacity to avoid increasing flaring.
- Sludge disposal transport, which benefits from better dewaterability post-digestion and a reduction in total solids content. Estimated reduction of around 15% of transport requirements.
- Increases to capacity to meet growth drivers or rationalisation objectives.

Decarbonisation conflicts:

- Because of its high heat demand, thermal hydrolysis is a competitor for other potential waste heat uses on site such as sludge drying

58 https://www.eliquohydrok.co.uk/en/news-details/vacuum-degassing-for-digested-sludge-elovac-r-demonstration-plant-contributes-to-achieving-carbon-neutrality-in-wales-in-2030-eh.html

59 https://www.linkedin.com/posts/eliquo-water-group_netzerocarbon-wwtp-sustainable-activity-6906583372496527360-1pT3?utm_source=linkedin_share&utm_medium=member_desktop_web

and ammonia stripping. This heat demand can be met through importing fossil (natural) gas, which could undermine the technology's decarbonisation benefits.

- Not considered aligned with Net Zero principles as discussed in section 1 where biogas is upgraded and exported and as a result fossil (natural) gas imports are required to meet site energy requirements.

Applicability: Sites with conventional anaerobic digestion.

Summary: This is an appropriate technology for use where existing digestion processes need increased capacity. Particular regard should be had to where the heat for the process is derived from.

If biogas undergoes upgrade and biomethane grid injection is undertaken, such that fossil gas imports are required to meet site energy demands (e.g. increasing Scope 1 emissions from combustion of natural gas), the business case should not be considered Net Zero aligned based on principles developed by Ofwat and related guidance and methodologies, as discussed in section 1.

More work must be done to:

- Demonstrate carbon and energy balances, where THP is presented as a Net Zero technology, recognising other valid drivers around increasing cost effective treatment capacity, generating enhanced final biosolids products and increasing solids destruction and improving final biosolids dewatering.

3.1.11 Advanced anaerobic digestion – enzymatic hydrolysis

Advanced anaerobic digestion – enzymatic hydrolysis TRL 9	Water resources Raw water distribution Water treatment Treated water distribution Retail Sewage collection Sewage treatment **Sludge treatment** Sludge disposal	Scope	**1**
		Kind	**Operational + Embodied**
		Effect	**Reduce**

Lower-energy, higher-footprint intensification of digestion process. Increases sludge to methane conversion compared with conventional mesophilic anaerobic digestion.

Anaerobic digestion converts solid organic material into methane through the action of methanogenic bacteria. Conventional anaerobic digestion leaves a substantial portion of organic material trapped within plant and microbiological cell walls. This limits methane production and creates the need for secondary digestion to complete the stabilisation of raw sludge.

Enzymatic hydrolysis separates the stages of anaerobic digestion. This reduces the extent to which organic matter is locked up within inert microorganisms.

Enzymatic hydrolysis requires less energy than thermal hydrolysis because it operates at lower temperatures. However, it requires more land, because each separate stage of digestion requires its own tanks, in contrast to thermal hydrolysis systems, which have one combined stage. It is less likely than thermal hydrolysis to require imports of fossil (natural) gas and competes less for waste heat, though if biogas is upgraded and exported and fossil gas imported to meet the site heat and power requirements, this negates the Net Zero alignment of this technology - company reported greenhouse gas emissions will be significantly increased due to import of fossil gas (given upgraded and exported methane introduces additional fugitive losses and is not reportable as emissions reduction for the water company even if financial incentives exist).

The process is often used to intensify existing digestion processes, because it increases the throughput of existing digestors. It is generally applicable to sites which currently use conventional digestion.

Funded activity synergies:

- Energy generation, which will benefit from additional gas being available. This may require additional generation capacity to avoid increasing flaring.
- Sludge disposal transport, which benefits from better dewaterability post-digestion and a reduction in total solids content. Estimated reduction of around 15% of transport requirements.

- Increases to capacity to meet growth drivers or rationalisation objectives.

Decarbonisation conflicts:

- Some additional demand for heat.

- Not considered aligned with Net Zero principles as discussed in section 1 where biogas is upgraded and exported and as a result fossil (natural) gas imports are required.

Applicability: Sites with conventional anaerobic digestion.

Summary: This is an appropriate technology for use where existing digestion processes need increased capacity. Particular regard should be had to where the heat for the process is derived from. Older iterations used low-grade heat from CHP, while newer iterations use steam injection, with steam generated either directly in a biogas-boiler or from high-grade 'waste' heat from biogas CHP. However, even in this case the heat demand for enzymatic hydrolysis is expected to be lower than for thermal hydrolysis. This makes it less likely that natural gas will need to be imported as support fuel, although this could occur if the full biogas production is directed to biomethane grid injection. However, if biogas undergoes upgrade and biomethane grid injection is undertaken, such that fossil gas imports are required to meet site energy demands (e.g. increase in Scope 1 emissions from combustion of natural gas), the business case should not be considered Net Zero aligned based on principles developed by Ofwat and related guidance and methodologies, as discussed in section 1.

3.1.12 Intermediate thermal hydrolysis

Intermediate thermal hydrolysis TRL 8	Water resources Raw water distribution Water treatment Treated water distribution Retail Sewage collection Sewage treatment **Sludge treatment** Sludge disposal	Scope	**1**
		Kind	**Operational**
		Effect	**Reduce**

Rearrangement of usual thermal hydrolysis format to focus application to Surplus Activated Sludge (SAS)

Thermal hydrolysis can increase biogas yield and increases capacity of existing digester assets. It does this using temperature and pressure to force open cells in sludge's microbial biomass and increase its digestibility. However, this process is very energy intensive. In some circumstances the energy needed to generate high pressure steam for the process must be provided or at least supported by natural gas.

Intermediate Thermal Hydrolysis (iTHP) rearranges the 'traditional' format of thermal hydrolysis such that it is applied to SAS rather than a mix of SAS and primary sludge (PS). This is advantageous because the digestibility of PS is not greatly improved by thermal hydrolysis, whereas SAS observes a marked improvement. In iTHP, PS is first fed to a dedicated digester and volatile solids converted into biogas. Only then is the outlet of this digester blended with SAS, fed to thermal hydrolysis and then further digested. The advantage of this system is that the thermal hydrolysis is applied to a smaller quantity of sludge than traditional arrangements. This could reduce or even eliminate the need for natural gas, where renewable heat sources are available, e.g. from combined heat and power (CHP) of biogas.

Funded activity synergies:

- Energy generation, which will benefit from additional gas being available. This may require additional generation capacity to avoid increasing flaring.

- Sludge disposal transport, which benefits from better dewaterability post-digestion and a reduction in total solids content. Estimated reduction of around 15% of transport requirements.

- Increases to capacity to meet growth drivers or rationalisation objectives.

Decarbonisation conflicts:

- Likely to have a lower heat demand than normal THP but still expected to be large. At sites looking to install other heat-intensive processes, e.g. sludge drying, thermal stripping of ammonia from liquors, there still might not be enough waste heat to operate without natural gas imports.

- If biogas end-use is shifted away from CHP towards grid injection, this could remove the 'waste' heat resource needed to operate iTHP. This could result in increased import of natural gas

Applicability: Sites with conventional anaerobic digestion.

Summary: iTHP trials by Thames Water have reported a more efficient process than for normal THP[60], readdressing the energy balance and reportedly requiring no natural gas support fuel to operate. However, this benefit comes at the expense of an increased footprint (and possibly cost) because iTHP needs at least two digesters to operate, with one digester dedicated to SAS. This may make iTHP more difficult than THP to retrofit at sites where space is at a premium, although this will need to be determined on a site-by-site basis. iTHP is still energy intensive and a full, system-wide energy and carbon balance is needed to ensure there will not be a net carbon emission, especially if technologies like sludge drying, ammonia stripping or biomethane to grid are also introduced.

3.1.13 Co-digestion of sewage sludge and other organic wastes

Codigestion of sewage sludge and other organic wastes **TRL 8**	Water resources Raw water distribution Water treatment Treated water distribution Retail Sewage collection Sewage treatment **Sludge treatment** Sludge disposal	Scope	**1**
		Kind	**Operational + Embodied**
		Effect	**Reduce**

Additional energy generation for sewage treatment works.

Other organic wastes can be added to digestor feedstocks to increase methane production. This can contribute to decarbonisation through increased energy recovery and diversion of waste from landfill or incineration.

Codigestion technology is similar to sewage sludge digestion but requires additional preparation of feedstocks through depackaging and maceration and may require sterilisation of the digestate produced. Its use is widespread globally[61], but except for a pilot in Scotland[62], it is not practiced in the UK. This is partly due to regulations on sludge disposal which would require addressing to allow this technology to be implemented.

Funded activity synergies:

- Codigestion is synergistic with the transformation of sewage treatment works into energy generating centres through combined heat and power (electricity), gas to grid, and hydrogen production.

Decarbonisation conflicts:

- Codigestion can increase fugitive methane emissions (Scope 1) from site through increased sludges throughput and methane production, but this could be managed through good asset design, operation and maintenance.
- Codigestion would produce more digestate to recycle to land, adding to landbank pressures, contributing to company Scope 3 emissions and possibly requiring more disposal work.

Applicability: Sites with anaerobic digestion. These wilneed to have additional plant and permitting, and the safety of the digestate needs to be demonstrated to be able to recycle this to land.

60 Nick Mills PhD thesis (2015) https://openresearch.surrey.ac.uk/esploro/outputs/doctoral/Unlocking-the-full-energy-potential-of-sewage-sludge/99515301502346

61 https://doi.org/10.1016/j.rser.2015.04.129

62 https://www.scottishwater.co.uk/About-Us/News-and-Views/2022/04/070422-Nigg-co-digestion

Summary: Codigestion is likely to show the best benefits for decarbonisation when viewed as part of the entire waste system. By using existing sites and assets to a fuller extend it should be possible to avoid the need for additional plant, bringing efficiency to the waste sector as a whole. As a non-appointed activity customers would not be expected to pay for this through their water bill, but it is something Ofwat could support if any companies seek guidance on accounting for this.

More work must be done to:

- Understand the balance of benefits and possible risks, e.g. around maintaining viable outlets for biosolids and impacts on liquor quantity and strength.

3.1.14 Sludge pyrolysis or gasification

Sludge pyrolysis or gasification **TRL 7**	Water resources Raw water distribution Water treatment Treated water distribution Retail Sewage collection Sewage treatment **Sludge treatment** **Sludge disposal**	Scope	**1 + 3**
		Kind	**Operational**
		Effect	**Reduce**

Recovery of energy otherwise inaccessible via digestion. Minimises residual solids.

Advanced anaerobic digestion typically converts up to 55% of the volatile solids in sludge. Most of the rest is locked up in cellulose and other complex organic compounds, which the microorganisms present in conventional and advanced digestion are not able to efficiently break down.

The process works by heating sludge in the absence of oxygen. Pyrolysis requires temperatures upwards of 350 °C and gasification requires temperatures over 500 °C. This releases volatile solids as a combustible syngas. The pyrolysis process also creates biochar, which is a carbonaceous solid while the gasification process often produces an ash. Bio-oil can also be produced and recovered as a fuel or recycled in the process to maximise syngas production.

These processes can convert up to approximately 85% of the total volatile solids in sludge, giving a corresponding reduction in residuals for recycling or disposal. However, they require a relatively dry feedstock. Thermal drying of the sludge is likely to use most of all of the energy produced, so either low-energy drying can be used to achieve net energy production, or the technology can be used primarily for sludge destruction.

Pyrolysis and gasification[63] of biosolids have been demonstrated in the UK but have not progressed to widespread use at scale. We understand this is due to a complex mix of practical, technical and economic factors as well as historic availability of landbank as a biosolids outlet. A handful of gasification and pyrolysis plants are reported elsewhere in the world at relevant scales[64]. Current versions of the processes require a consistent feedstock, which has proven challenging to provide based solely on sewage sludge. The abrasive nature of sludge can cause high maintenance costs. Potential uses, markets and regulation of the biochar or bio-oil products are unclear.

Funded activity synergies:

- Can be synergistic with energy production on sewage treatment works, depending on the energy requirements for sludge drying.
- Reduction of sludge disposal work, depending on the end use of the product.
- Reduction of strategic cake storage requirements.

63 https://www.etgas.eu/our-projects

64 https://www.linkedin.com/feed/update/urn:li:activity:6927541454684737538/?updateEntityUrn=urn%3Ali%3Afs_feedUpdate%3A%28V2%2Curn%3Ali%3Aactivity%3A6927541454684737538%29 (Table 1)

Decarbonisation conflicts:

- Requires sludge drying, which can create additional heat demand. While syngas, biogas or other ‘waste’ heat source can be used, there is a chance increased import of natural gas will be required if these options are deployed elsewhere.

Summary: These technologies show promise for decarbonisation and landbank protection. The main driver for these is more likely to be to reduce reliance on the landbank (e.g. through the introduction of new consents on contaminants) where the main competing technology is incineration. In our view it would be preferable from a Net Zero standpoint for gasification or pyrolysis to be adopted by the sector, rather than incineration, because of their greater potential for capturing carbon in non-gaseous form (e.g. as biochar) and reported reductions in the nitrous oxide content of their exhaust gases versus incineration.

Widespread implementation of gasification or pyrolysis within the next AMP period is an ambitious expectation. However, it has been included within the shortlist as possibly the sole most developed Net Zero aligned solution for sludge disposal in the event that biosolids recycling to land becomes impractical through regulatory constraint.

More work must be done to:

- Elevate the priority of gasification or pyrolysis solutions up the research and development agenda.
- Develop a parallel research agenda around confirmation of multi-phase destruction of organic contaminants via these processes as well as end-uses and markets for residual solid outputs.
- Consider innovative business models as a way of managing the significant capital investment likely needed to implement these technologies at scale, making use of drivers to develop Bioresources markets.

3.1.15 Sludge biodrying

Sludge Biodrying TRL 8	Water resources Raw water distribution Water treatment Treated water distribution Retail Sewage collection Sewage treatment **Sludge treatment** **Sludge disposal**	Scope	**1 + 3**
		Kind	**Operational**
		Effect	**Reduce**

Low-energy sludge drying.

Sludge is transported from treatment centres to land by road. Typically, approximately ¾ of treated sludge mass is water and ¼ is dry solids. Although so much of the transported mass is water, drying sludge to enable more efficient transport is often not cost effective because many drying technologies are energy intensive and may require an increased import in natural gas to provide heat.

Biodrying is similar to composting, but it is a process for treated cake instead of raw cake and typically requires some energy input to supply air into the cake pile. This tends to make biodrying more intensive and less passive than traditional composting, giving the process a small footprint. It uses the heat generated by micro-organisms in sludge to drive out moisture and can reduce the gross weight of sludge by more than half through reducing the amount of water in sludge.

It is applicable to most digested sludges. It is an aerated process, so conditions are not favourable for methanogens and uncontrolled post-digestion methane emissions decrease accordingly.

Funded activity synergies:

- Thermal treatments which require a dry feedstock, such as pyrolysis and gasification.

Decarbonisation conflicts:

- There is energy demand to aerate the biosolids cake, but this is relatively small.
- Although aerobic, some composting-type processes are associated with the emission of methane and nitrous oxide greenhouse

gases. But these are expected to be low for an engineered biodrying process.

- Other emissions such as ammonia, bioaerosols and odour are possible and could fall under Industrial Emissions Directive requirements to control emissions. However, it might be possible to manage this through the use of negative pressure aeration to capture off-gases or by containing biodrying within a building with air extraction and abatement.

Summary: Like many drying technologies, this is likely to produce transport savings in the longer term (greater than one AMP). It is also a technology which can be used to prepare to reduce reliance on the landbank, increasing operational resilience. This solution is attractive because natural gas cannot easily be substituted into the process to provide heat, however it requires demonstration in the UK.

3.1.16 Other low energy sludge drying

Other low-energy sludge drying TRL 8	Water resources Raw water distribution Water treatment Treated water distribution Retail Sewage collection Sewage treatment **Sludge treatment** **Sludge disposal**	Scope	**1 + 3**
		Kind	**Operational**
		Effect	**Reduce**

Low-energy sludge drying.

These are methods that can enable sludge drying using relatively low-grade heat. This can be low-grade 'waste' heat from biogas CHP that might commonly be used in hot water loops or heat recovered from sewage effluent using a heat pump. Specific technologies might include low temperature belt dryers or solar drying (likely to be supported by heat from CHP or heat pump in regions of relatively low solar activity[65]). These differ from biodrying because the heat is not generated internally as part of the process. Although the temperature ranges required are relatively low (c.70-90°C), these technologies remain energy intensive – in excess of 800 kWh of heat per tonne of water evaporated[66].

Funded activity synergies:

- Thermal treatments which require a dry feedstock, such as pyrolysis and gasification.

Decarbonisation conflicts:

- May compete with other processes for lower-grade waste heat (e.g. heating digesters or liquor treatment plants, hot water loops, pre-heating boiler water
- A push towards biomethane to grid and away from CHP could remove the low-grade 'waste' heat sources the low energy dryer depends upon. It is plausible this would lead to an increased import of natural gas to provide the heat.

Summary: Low Temperature belt dryers are attractive because they are relatively low footprint compared to alternatives, such as solar dryers. They may also be less susceptible to the production of dust than drum dryers historically deployed in the UK, where dust presents a significant fire hazard. There is some limited experience with low temperature belt dryers in the UK. However, while biogas or 'waste' heat can be used for drying, it would be relatively straight forward to substitute these for natural gas. The significant energy needed for sludge drying suggests this application of natural gas would be significantly counter-productive to Net Zero. We anticipate a push away from biogas to CHP and towards biomethane grid injection could induce such a scenario by removing CHP as a renewable source of heat. A full carbon and energy balance of the whole bioresources system would be needed to demonstrate that there is not a net carbon emission in this scenario.

65 https://www.huber.co.uk/huber-report/ablage-berichte/sludge-treatment/huber-installs-its-first-combined-solar-and-regenerative-sewage-sludge-drying-project.html?L=0

66 https://www.huber.co.uk/fileadmin/01_products/04_sludge/04_trocknen/02_bt/pro_bt_en.pdf

3.1.17 Sludge liquor ammonia stripping

Sludge liquor ammonia stripping **TRL 7**	Water resources Raw water distribution Water treatment Treated water distribution Retail Sewage collection **Sewage treatment** **Sludge treatment** Sludge disposal	Scope	**1 + 3**
		Kind	**Operational**
		Effect	**Reduce**

Avoids return of ammonia to treatment. Reduces aeration energy and nitrous oxide process emissions - but Net Zero alignment depends on managing residual ammonia, source or heat and use of chemicals.

Anaerobic digestion converts the nitrogen compounds found in surplus activated sludge into ammonia. Much of this ammonia ultimately ends up in sludge liquors after digestate dewatering, particularly where advanced anaerobic digestion is used. This ammonia needs to be treated and is achieved through forced aeration biological processes, either by returning the liquor to the wastewater treatment works or by a dedicated liquor treatment plant. This is an energy intensive process, and also produces nitrous oxide, a powerful greenhouse gas.

Stripping and recovery of ammonia from wastewater was recognised as a key action required to address greenhouse gas emissions – this being one of five societal threats identified by the 2011 European Nitrogen Assessment (ENA)[67] in the global management of nitrogen. The water sector also contributes to the other 4 societal threats of excess reactive nitrogen – Water Quality (impacts of nitrate and ammonia on freshwater ecosystems), Air Quality (emissions from combustion of fuels), Terrestrial Ecosystems and Biodiversity (resilience of catchments and land systems) and Soil Quality (with application of N fertilisers and manure leading to potentially negative crop impacts, leaching and water quality issues).

This evaluation considers ammonia stripping to be an important consideration in Net Zero aligned technologies given the significance of nitrogen management and the contribution which could be made by the water sector if recovery and reuse were possible – though recognises that this is not likely to be PR24 ready.

Modern day[68] ammonia recovery plants are not utilised yet in sewage treatment but have been developed in bench and pilot work; elsewhere, removal and ammonia destruction has been undertaken (e.g. in landfill leachate management). Recovery of ammonia in wastewater treatment is considered technologically feasible though TRL for stripping and recovery for the wastewater sector is not considered to be at the considered cut-off of 7.

The technology aims to remove and recover ammonia as a product from liquors before they are returned to biological treatment. Removal can be achieved by air stripping, using a chemically induced pH swing and large air flows to liberate ammonia from liquors or thermal stripping, using high temperature steam instead of chemicals and a more modest air flow. In each case ammonia can be recovered either as an aqueous ammonia product or as a concentrated ammonium sulphate solution, via an acid scrubber.

Removal of ammonia reduces the ammonia loads sent to biological treatment, likely reducing respective nitrous oxide process emissions or freeing up treatment capacity. However, there is not yet an established market for ammonia products if they are recovered. It has been historically assumed that these can be sent to agriculture as fertiliser. However, it is unclear whether the forms that the ammonia is recovered in are useful to UK agriculture or as a manufactured fertiliser feedstock. There are also unanswered questions around whether the recovered ammonia can be classified as End of Waste.

A range of alternative uses such as feedstock in hydrogen production are being studied but are unlikely to be sufficiently ready to impact AMP8. Traditional air strippers have been associated with high energy demand to create large air flows

67 Published 2011 with two of the 8 editors from the UK NERC Centre for Ecology and Hydrology - http://www.nine-esf.org/node/360/ENA-Book.html

68 As reported in the ENA, historically, Paris recycled 50% of reactive nitrogen available in human waste for use in fertilisers – this came to an end with the advent of flushing toilets and the fossil fuel intensive Harber-Bosch fertiliser production process.

for stripping and have a high chemical demand to adjust pH, which has implications for their embodied carbon. Recent innovation work in the UK water sector appears to focus on thermal stripping techniques. However, these will need to avoid the large-scale use of natural gas in order to be Net Zero compatible. High-grade renewable heat from CHP can be used but this may already be committed to other uses, such as thermal hydrolysis or may become less available if the sector moves its biogas use away from CHP and towards grid injection. Care must therefore be taken to ensure ammonia recovery does not increase use of natural gas elsewhere in the system to an extent that is counter-productive to Net Zero.

Funded activity synergies:

- Upgrades to CHP engines to allow them to accept produced ammonia as a fuel source.
- Fate of biosolids to land which could support development of enhanced biosolids fertiliser products.

Decarbonisation conflicts:

- Requires a large amount of heat. Heat generated on site might already be committed to other uses. This could lead to the increased import of natural gas.
- Where excess, high-grade 'waste' heat is currently available, this could be made unavailable by moving biogas away from site use via CHP towards grid injection. A reciprocal increase of natural gas imports to readdress the energy balance would be counter-productive to Net Zero.

Applicability: Applicable to wastewater sites with highly concentrated liquor returns such as sites with advanced anaerobic digestion. Particularly applicable to sites with combined heat and power engines or some other source of renewable high-grade heat. May not be applicable for AMP8.

Summary: Industry attention appears to be focussed on thermal stripping techniques, rather than air stripping. This means a significant quantity of high-grade heat is required for steam generation. 'Waste' heat from CHP can be used but this is finite and there is a likelihood it will already be committed elsewhere, such as for thermal hydrolysis. This is doubly critical because sites with thermal hydrolysis are likely to have the greatest ammonia loads in their sludge liquors and therefore targets for ammonia stripping. Further, moving biogas away from CHP to grid injection will further reduce the availability of renewable heat onsite. The import of additional natural gas to realign the heat balance will undermine the carbon benefit of ammonia stripping and could result in an increased net carbon emission – from our awareness of ongoing work to date on this subject, we consider that significant further work is required to demonstrate that this technology is Net Zero aligned.

It is unclear whether the technology is AMP8 ready and its application could result in increased company emissions. However, it offers a likely N_2O mitigation pathway and the importance of N_2O mitigation (Scope 1 emissions) combined with the multiple nitrogen challenges facing companies and society highlight the importance of continued focus on ammonia removal and recovery, accompanied by careful carbon assessment.

3.1.18 Nature based solutions - Stormwater separation and treatment

NBS – Stormwater separation and treatment **TRL 9**	**Water resources** Raw water distribution Water treatment Treated water distribution Retail Sewage collection **Sewage treatment** **Sludge treatment** Sludge disposal	Scope	**1 + 2 + 3**
		Kind	**Operational**
		Effect	**Reduce**

Nature based solutions (NBS) such as sustainable urban drainage systems (SUDS) and treatment wetlands can be applied to stormwaters separated from combined sewer systems. These reduce the need for in line storage and additional treatment capacity which is likely required to address current combined sewer overflow (CSO) challenges the sector faces in AMP8.

Improvement management of CSOs is required in AMP8 and will likely require reduced spills through a combination of increased in-sewer storage and treatment as well as the removal of surface water from impermeable surfaces – with three scenarios modelled for cost, carbon and wider benefits in the Storm Overflow Evidence Project. Both infrastructure solutions (grey in-sewer storage and treatment and green nature based solutions) come with considerable Scope 3 (embodied) carbon costs. Some can also impact negatively on Scope 1 (methane) emissions from sewers and from treatment systems. Others may offer (likely minimal) carbon benefits (e.g. tree planting).

We include this 'technology' as companies are actively considering this. Increased SUDS solutions may lead to additional Scope 3 emissions relative to conventional grey infrastructure, as estimated from the recent Storm Overflow Evidence Project - but we consider that more work is required to assess this including sensitivity analysis. In addition, the wider water quality and community benefits which themselves are likely to align with Net Zero principles are relevant in addition to the trajectory and pace of sectoral (e.g. concrete) decarbonisation. This may offer alignment with Net Zero principles - though trade-offs between operational and capital carbon impacts require scrutiny. It is likely that the wider benefits of NBS (climate and flood resilience, wider community value, active travel etc) are key benefits; to date assessment of, along with their importance with wider decarbonisation transition (green spaces, active travel, climate resilience and adaptation). NBS solutions are being applied for mainstream treatment of wastewater also – but the evidence base for net zero alignment is lacking and requires further work.

Funded activity synergies:

- Managing CSO impacts – Environment Act implementation
- Capacity upgrades

Decarbonisation conflicts:

- Whilst these may lower Scope 3 emissions associated with chemical and aeration usage, additional Scope 3 emissions result from the construction of nature-based solutions and life cycle carbon assessment is key.

- Changes may be required to the regulation of water quality standards in order to recognise the capabilities and limitations of nature-based solutions e.g. inability of treatment wetlands to continue treating to the same efficiency when faced with sudden loads which have not been built into the design. Whilst the use of upstream lagoons to buffer flows to treatment wetlands is one approach which may be used to increase the resilience of treatment wetlands consideration may also be given to changes to the regulations which can reflect variability in treatment processes whilst continuing to protect any receiving waters. For example, the receipt of a slightly elevated concentration of some pollutants may have minimal impact to a receiving water when flows are elevated.

Applicability: Widely applicable.

Summary: CSOs management requires new approaches, greater monitoring, changes to water quality regulation and increased understanding of the carbon impacts.

3.1.19 Water efficiency across urban water cycle (including pumping, leakage reduction)

Water efficiency **TRL 9**	**Water resources** **Raw water distribution** **Water treatment** **Treated water distribution** Retail Sewage collection **Sewage treatment** Sludge treatment Sludge disposal	Scope	**1 + 2 + 3**
		Kind	**Operational**
		Effect	**Reduce**

Water efficiency including water use efficiency (in home), leakage reduction and associated reduced dry weather flows through water pumping efficiency.

Household water efficiency offers significant benefit in terms of reduced consumption and treatment costs, pumping and potential downstream impacts on wastewater management – particularly for separate systems not predominantly impacted by inflow and infiltration. This provides resource preservation of natural water systems and their key ecosystem and natural capital benefits through reduced abstraction.

Most UK water companies historic water efficiency programmes (Artesia Consulting, 2010) have been guided by policies such as:

- Integration of water saving messaging and water efficiency advice and assistance into all customer facing activities.
- Use of consistent water saving messaging across all media with a consistent call to action for adoption of water saving behaviour and the installation of water saving goods.
- Active engagement with selected customers and maintenance of passive water efficiency engagement for all customers.
- Contribution to the water minimisation research evidence base and fostering innovation to improve the effectiveness of customer engagement.
- Fostering a community of interest in order to develop and disseminate best practice water savings within the customer base.
- Informing the development of water saving goods providing a market for innovative products and to commission new and innovative water saving products.
- Providing leadership by consistently improving companies' own water efficiency.
- Statistical analysis of performance and customer feedback to inform improvements to any efficiency programme.
- Embedding a water efficiency culture, identifying and deploying innovative ways of working.

Separately, significant focus on leakage reduction from treated water distribution remains key for company performance commitments and delivery incentives, with existing and emerging technology and digital solutions available to detect and address leaks and more efficiently manage networks. These may offer carbon benefits also though little quantification is evident in published work.

Finally, efficiency in raw and treated water distribution and wastewater management through more efficient pumping may offer significant emissions (Scope 2) reduction – recognising that pumping of water and wastewater is the most energy intensive activity by WoCs and WASCs.

More efficient pumping through refurbishment of pumps to original manufacturer's performance specifications, fitting with high efficiency motors, pumping optimisation and data driven network optimisation all offer potential alignment with Net Zero principles.

Within household drinking water use, efficiency objectives tend to evaluate the effectiveness of retrofitting water efficient devices by using disaggregation methods to estimate water savings per property. There is also recommendation to target properties with high water usage so a campaign may provide a higher return on investment and consequently a better cost benefit analysis. Water efficiency at household level involves the installation of devices in customer homes or the support to do this for third parties.

Increased use of smart meters enables customers to be better informed about their usage, can assist in bringing about change in water use habits and can also allow the earlier identification of leaks. For example, it is recognised that flushing the toilet is not only one of the biggest water usages in domestic properties, but toilets are also one of the biggest sources of leaks. Increased monitoring of usage enables earlier identification of leaks through unusually high usage.

Funded activity synergies:

- Existing leakage ambition and targets
- Quality and capital maintenance upgrades

Decarbonisation conflicts:

- Lower per capita usage combined with increased dry spells may result in greater decomposition and fugitive methane emissions (and odour and corrosion) in sewer systems as a result of reduced water usage – whilst not well quantified it would be expected that the net benefits of reduced drinking water treatment, distribution and associated wastewater volumes would offer Net Zero alignment.

Applicability: Widely applicable though water conservation requires sufficient measurement to allow for efficiency and incentivisation.

Summary: In terms of reported Scope 1, 2 and 3 emissions, reduced drinking water treatment, treated water conveyancing, dry weather flows and associated treatment all offer potential carbon benefits to WoCs and WaSCs. Although outside of reported emissions, reduced water consumption also offers significant wider carbon and cost benefits to customers given in-home energy use for heating hot water (some 4-5% of national UK emissions[69]) and the current cost of living crisis.

3.1.20 Biomethane fuelled lorries

Biomethane fuelled lorries TRL 9	Water resources Raw water distribution Water treatment Treated water distribution Retail Sewage collection Sewage treatment Sludge treatment Sludge disposal	Scope	1
		Kind	Operational
		Effect	Reduce

Trucks fuelled by renewable biomethane instead of diesel

According to the Water UK's Net Zero 2030 Routemap, transport in the water sector emits around 0.25 Mt CO_2 equivalents per year. Zero or low emission vehicles are already widely commercially available for smaller vehicles, e.g. battery-electric cars and vans. However, heavy-duty transport, e.g. for sludge tankering, faces different challenges, in part because of specific power requirements to haul heavy loads efficiently, safety regulations around drive-times and shift patterns and duty cycles of drivers. These challenges have resulted in a number of potential low and zero emission options for large trucks, at different stages of commercial availability and with different practical advantaged and disadvantages.

Biomethane trucks are already quite widely used for the transport of freight in the UK and there are a growing number of biomethane refuelling stations at strategic points in the UK's transport network. There are also already a small number of biomethane-fuelled sludge tankers in the UK water sector. A well-to-wheel carbon assessment in the UK found an 84% reduction in carbon emissions for biomethane fuelled trucks versus their equivalent diesel-fuelled counterparts[70]. Performance is also reported to be comparable to diesel trucks.

Biomethane trucks can be fuelled by WaSC's own biomethane or biomethane produced elsewhere. They are likely similar to diesel trucks in terms of refuelling time and their modified internal combustion engine (ICE) drivetrains are unlikely to require particularly more specialist expertise to repair and maintain than equivalent diesel engines. New biomethane production by water companies could struggle to engage the new Green Gas Support Scheme (GGSS), which is currently only open to new-build digestion plants (simply installing new biogas upgrading assets to existing digesters does not qualify, currently). This leaves the Renewable Transport Fuel Obligation (RTFO) as the most likely financial support scheme available to the water sector for new biomethane production. This could influence the sector towards more biomethane-fuelled heavy duty transport of their own.

Funded activity synergies:
- Could be performed in tandem with biomethane to grid

Decarbonisation conflicts:
- Could leverage increased biomethane production, which would reduce biogas to CHP. In turn it is possible that this could reduce supply of renewable heat at Sludge Treatment Centres (e.g. used by Thermal Hydrolysis), which could result in increased imports of natural gas. In this scenario, a whole system Lifecycle Carbon Assessment will be required to demonstrate there isn't a net carbon emission.

Applicability: Can be applicable to any heavy-duty transport, even if the company doesn't produce biomethane of their own. Refuelling stations might not yet be suitably located for all companies or at all locations, which could restrict practicality, at least in the short term.

Summary: Biomethane trucks are currently the most available and practical low emission trucks in the UK. Reliable UK study has demonstrated a significant reduction in well-to-wheel carbon emissions. They

69 https://www.ciwem.org/assets/pdf/Policy/Reports/A-Blueprint-for-carbon-emissions-reductions-in-the-water-industry.pdf

70 https://www.cwu.org/wp-content/uploads/2017/10/Element-Energy-CNG-Report.pdf

are also likely to align well to existing duty cycles used in the water sector for heavy-duty transport (e.g. of sludge by diesel ICE trucks). This makes biomethane trucks a good candidate to reduce the UK water sector's heavy-duty transport carbon emissions contribute to the sector's ambitious timeline of Net Zero by 2030. However, they are not zero emission vehicles and so might not be suitable across longer timeframes (e.g. new non-Zero Emissions trucks to be banned in UK by 2040). Where biomethane is produced internally by WaSCs, care must be taken to balance carbon and energy across the whole system as it is plausible increased biomethane production could result in a reciprocal increase in natural gas imports to produce heat for use in sludge treatment. This could result in a net carbon emission across the wider system. This could be site specific depending on heat-intensive processes onsite (e.g. thermal hydrolysis, sludge drying, thermal ammonia stripping) and company specific depending on the quantity of sludge imports transported by road.

3.1.21 On-site heat recovery

On-site heat recovery **TRL 8**	Water resources Raw water distribution Water treatment Treated water distribution Retail Sewage collection **Sewage treatment** Sludge treatment Sludge disposal	Scope	**1 + 2 + 3**
		Kind	**Operational**
		Effect	**Reduce**

Recovery of heat from sewage influent or final effluent at a wastewater treatment works by heat pump

Raw sewage and treated wastewater contain small amounts of residual heat energy. However, because wastewater treatment works (WwTWs) handle large volumes of influent/effluent this residual heat can add-up to a lot of energy that can be recovered by heat pump and put to use onsite.

Heat pumps require an electrical energy input but are significantly more efficient at delivering (low-grade) heat than a dedicated water heating system (e.g. a gas boiler). This efficiency, coupled to the use of a renewable electricity source, allows heat recovery systems to contribute to the Net Zero agenda. Sewage influent arrives at WwTW at a higher temperature than final effluent and so has a greater potential for heat recovery. However final effluent is cleaner and easier to integrate with a heat pump.

The small number of heat recovery systems reported by UK water companies (e.g. Anglian Water) focus on heat recovery from final effluent. The opposite side of the heat recovery coin is that the effluent exiting the heat pump has its temperature lowered by several degrees. This could be important for outfalls in environmentally sensitive areas, where the local ecology could be adversely impacted by higher effluent temperatures. Conversely, lowering the temperature of sewage influent could reduce the performance of biological treatments. Heat pumps take heat energy and magnify the outputs to useful temperatures. High temperature heat pumps can achieve temperatures up to around 80°C.

Reported examples of heat recovery export the heat offsite, e.g. to heat neighbouring greenhouses for production of food (Anglian Water)[71] or to supply adjacent district heat networks (Thames Water)[72]. However, there can be onsite uses, such as heating digesters, liquor treatment plants or onsite hot water. It is also plausible that heat pumps could play a role in sludge drying, where the output temperatures of some heat pumps overlap with the operational range of low-temperature belt dryers. However, heat recovery systems are unlikely to be directly used for applications requiring higher-grade heat, e.g. high-pressure steam production for thermal hydrolysis or thermal stripping of ammonia from sludge liquors. Although, heat recovery could be used to pre-heat boiler water in these applications.

71 https://www.cibsejournal.com/case-studies/growing-interest-using-wastewater-to-heat-britains-giant-greenhouses/

72 https://www.cibsejournal.com/general/londons-hidden-energy-source-recovering-heat-from-sewage/

Funded activity synergies:

- Can support low-grade heat uses onsite that might otherwise require import of natural gas

Decarbonisation conflicts:

- Requires electricity that could be deployed elsewhere. The amount of power needed depends on the size and efficiency of the installation.

- Electricity from biogas CHP could be used but must demonstrate additionality (e.g. not already used onsite or exported to the grid) and heat recovery isn't technically restricted to sites co-located to Sludge Treatment Centres and CHP assets. Alternative renewable electricity sources needed if biogas end use shifted away from CHP and towards biomethane to grid.

Applicability: A handful of heat recovery projects are reported for UK WwTWs.

Summary: Heat recovery could be used to support low-grade heat requirements onsite, especially where existing low-grade heat sources (e.g. biogas CHP) could disappear if biogas end-use shifts towards biomethane grid injection. The electricity used to power heat pumps must be demonstrably from a renewable and additional source. Export of recovered heat is also possible and early examples of heat recovery at UK WwTW report this.

This carbon benefit could sit outside of water companies' boundaries and would offer emissions reduction for others – these not able to be accounted for by WaSCs adopting science based targets. Synergistic application alongside sludge drying could be possible, depending on the drying technology in question. However, heat recovery has limited applicability to other possible Net Zero technologies like Thermal Hydrolysis or thermal stripping of ammonia from liquors. These require higher-grade heat to generate high-pressure steam, although heat recovery could be used to pre-heat boiler water in this applications.

3.2 Technologies not shortlisted

The full list of technologies that did not progress from the mid-list to the shortlist and accompanying rationale is given in Appendix A. We present a select number of them here due to their relatively high level of interest within the UK water sector and also provide some general discussion.

3.2.1 Cellulose recovery

Cellulose recovery **TRL 6-7**	Water resources Raw water distribution Water treatment Treated water distribution Retail Sewage collection **Sewage treatment** Sludge treatment Sludge disposal	Scope	**1 + 2 + 3**
		Kind	**Operational**
		Effect	**Reduce**

This involves the (relatively) selective removal of cellulose by microscreen technology at the primary settlement phase as a cellulose-rich sludge. This avoids progression of cellulose to secondary treatments. It is claimed that removal of cellulosic carbonaceous load significantly reduces oxygen demand and therefore aeration energy in forced aeration treatment. The cellulose is washed and recovered as a product that can be incorporated into products, such as bioplastic composites, or used to recover energy (e.g. pyrolysis or dedicated anaerobic digestion).

Summary: Pilot studies (e.g. the EU SMART Plant project and WOW! Project, including participation by Severn Trent[73]) have not yet sufficiently demonstrated the benefit of reduced aeration specifically due to the selective removal of cellulose. We have not seen data that adequately fractionates the Chemical Oxygen Demand (COD) of settled sewage following primary settlement by conventional

73 https://www.stwater.co.uk/news/news-releases/severn-trent-is-proud-to-be-part-of-project-wow--kick-off/

gravity separation versus microscreens. In advanced models of secondary forced aeration systems, used routinely by Jacobs, cellulose is typically classified as a non-biodegradable inert component. We might not therefore expect to see a marked reduction in oxygen demand through selective removal of cellulose upstream. Although there may be other benefits, we do not consider Cellulose recovery as a Net Zero technology until further evidence is made available.

More work must be done to:

- Better demonstrate empirical reduction in energy for secondary treatment specifically related to the selective removal of cellulose at the primary stage.
- Perform a lifecycle carbon assessment taking into account possible reductions in biogas production and possible end uses for recovered cellulose (e.g. incorporation in recovered materials, biogas production through specialist developmental processes, such as micro-hydrolysis[74].

3.2.2 Sludge liquor phosphorus recovery

Sludge liquor phosphorous (P) recovery **TRL 8**	Water resources Raw water distribution Water treatment Treated water distribution Retail Sewage collection **Sewage treatment** **Sludge treatment** Sludge disposal	Scope	**1 + 2 + 3**
		Kind	**Operational**
		Effect	**Reduce**

Removal of dissolved phosphorus from sludge liquor and its recovery as a mineral product, e.g. struvite.

Phosphorus (P) can be present in sludge in a variety of forms. When in its dissolved phosphate form and under the correct conditions (e.g. sludge pH), phosphorus can precipitate into solid mineral deposits, e.g. struvite. Uncontrolled deposition of struvite can cause operational problems by forming deposits on the inside of pipes and fittings. This can cause significant maintenance demand at sites with struvite problems.

However, the conditions within the sludge treatment train can be manipulated to promote controlled precipitation of struvite within an engineered reactor. The struvite can be recovered as a mineral phosphate product. Recovery is usually performed on sludge liquors following sludge dewatering and reduces the phosphorus loads returned to wastewater treatment in liquors. Struvite recovery is most effective and efficient at treatment works that use biological phosphorus (Bio-P) removal processes.

However, the majority of P load in England and Wales is not treated by Bio-P but removed by dosing of ferric chemical instead. Based on the WwTW classification issued within Ofwat's Bioresources Market information[75] cross referenced with Annual returns data from water companies[76], just 3.6% of P load is expected to be treated at a works operating Bio-P removal. Some sites possessing elements of Bio-P treatment may not be classified as such if Bio-P represents <50% of treated flow at those sites. Inclusion of influent P load at these additional sites which would appear to undertake some Bio-P[77] the total P loads into site that might be compatible with struvite recovery to 9%. As a result, P recovery potential in the UK is likely to be low and is heavily weighted to just one water company, Severn Trent. There are technologies focussed on the recovery of P as an iron-based compound (vivianite) but these are still in development[78].

Ferric dosing makes struvite recovery less effective because much of the phosphorus is tied-up with

74 Presentation of Jacobs' development of the Micro Hydrolysis Process targeting difficult to digest organic materials, such as cellulose, using specialist C. Bescii microbes, 17th IWA World conference on Anaerobic Digestion

75 https://www.ofwat.gov.uk/wp-content/uploads/2021/11/Bioresources_Dashboard_Data-2020-21.xlsx

76 https://www.stwater.co.uk/content/dam/stw/regulatory-library/ST.%20APR%202021-single-pages.pdf

77 https://conferences.aquaenviro.co.uk/wp-content/uploads/sites/7/2015/06/Rob-Wild2.pdf

78 https://www.vivimag.nl/technology

iron and not in its dissolved phosphate form. High concentrations of iron also interfere with the chemical formation of struvite. This limits the scope of applicable sites for phosphorus recovery, to the limited number of Bio-P removal sites. Only two large scale struvite plants have been built in the UK and these are not currently in use as far as author's are aware. Struvite recovery is also chemically intensive, requiring dosing of sodium hydroxide and magnesium chloride chemicals. The embodied carbon of these chemicals could counteract at least a portion of any carbon benefit through reduced removal efforts elsewhere in the treatment system. Finally, in addition to the fact that Net Zero principles and water company climate reduction targets would not recognise 'offsetting' of any potential fertiliser product, there is no established market for struvite products in the UK, and we are not aware that any struvite products derived from wastewater have been awarded End of Waste status. Therefore, while recovered P could technically contribute to a sustainable supply of phosphate fertiliser, there remain sizeable regulatory barriers to their commercial implementation in the immediate future.

Applicability: Likely only applicable to a small percentage of P load at Band 6 sites with sludge treatment centres, served by Bio-P processes or that have an appreciable portion of their phosphorus removed by Bio-P mechanism.

Summary: As long as ferric dosing remains the primary method of P removal from wastewater, there will always be a restricted applicability of P recovery by struvite precipitate in the UK. P recovery could help to deliver reduced phosphorus content in final effluent discharges but P recovery is unlikely to contribute significantly to the Net Zero agenda at the next price review.

More work must be done to:

- Develop opportunities from the perspective of supporting compliance with WINEP outcomes and increasing circularity.
- Further develop and understand the scope for implementation at Bioresources sites in England and Wales that are Bio-P or possess Bio-P treatment elements but are not classified as fully Bio-P.
- Maintain a watching brief on technologies reporting P recovery applicable to ferric dosing sites, e.g. as vivianite.

3.2.3 Carbon capture and storage

Carbon capture and storage (CCS) **TRL 9**	Water resources Raw water distribution Water treatment Treated water distribution Retail Sewage collection Sewage treatment **Sludge treatment** Sludge disposal	Scope	**1**
		Kind	**Operational**
		Effect	**Substitute**

Capture and storage of carbon dioxide separated during biogas upgrading to biomethane

Around 40-50% of raw biogas is carbon dioxide (CO_2). This must be removed before biogas can be injected into the gas grid as biomethane. The process of removing CO_2 from biogas is known as biogas 'upgrading'. There are a number of upgrading plants in the UK, operating by water scrubber or membrane processes.

While the purified biomethane is captured for grid injection, the CO_2 fraction is typically emitted to atmosphere. Because biogas is a biogenic feedstock, this CO_2 is not considered to have a net global warming potential. However, if this CO_2 can also be captured and stored, instead of being emitted to the atmosphere, biomethane could be considered carbon negative – actively removing carbon from the atmosphere. The infrastructure to enable this and national priorities (e.g. for CCS in hard to abate sectors and the substantial transport and storage infrastructure required) may support this as a longer term focus.

There are reports of plans to deploy CCS to commercial AD in the UK[79]. The CO_2 is expected to

79 https://www.bioenergy-news.com/news/future-biogas-to-build-25-new-plants-with-ccs/

be liquefied and injected under the seabed in the North Sea[80]. However, critics of CCS argue that it has failed to deliver significant decarbonisation (e.g. in the fossil-fuel industry), despite decades of research and development. Further, individual Sludge Treatment Centres (STCs) are small and diffuse sources of CO_2 relative to other significant point sources, such as oil and gas (and other industrial) hubs. This means the practicality and economics of delivering carbon capture at STCs and transporting the CO_2 to locations for storage remain uncertain. The Climate Change Committee recognises the importance of CCS within its Sixth Carbon Budget report[81], with bioenergy using CCS at scale by 2035. However, this timeline extends beyond AMP 8 and it remains unclear if the 'scale' mentioned will be relevant to the UK water sector.

Funded activity synergies:

- Performed in tandem with biomethane to grid

Applicability: Applicable at sites with biogas upgrading to biomethane.

Summary: Although carbon from biogas is biogenic, a carbon negative process could be a useful way to net-off difficult to avoid emissions elsewhere in wastewater and sludge treatment. However, CCS still needs to be demonstrated to be technically and economically feasible - especially at the scale and geographic locations of STCs in the UK. The risk is that CCS is used as a means to justify decisions made elsewhere that are sub-optimal with respect to carbon emissions and Net Zero, but then CCS never materialises in a way that can be engaged by the water sector.

More work must be done to:

- Develop the CCS market and understand opportunities and barriers for individually small scale and collectively diffuse sources of CO_2, relative to large industrial point sources and hubs.Demonstrate the permanence of carbon sequestration and understand how and if these can be included as part of Net Zero reporting frameworks.

3.2.4 Hydrogen fuel cell lorries

Hydrogen fuel cell lorries **TRL 7**	**Water resources** **Raw water distribution** **Water treatment** **Treated water distribution** Retail **Sewage collection** **Sewage treatment** **Sludge treatment** **Sludge disposal**	Scope	**1**
		Kind	**Operational**
		Effect	**Reduce**

Trucks fuelled by hydrogen (instead of diesel) in a hydrogen fuel cell (HFC)

HFC vehicles use compressed hydrogen stored onboard to produce electricity 'on the go' to drive an electric engine. This is in contrast to battery electric vehicles (BEVs) that store electricity as chemical energy within a charged battery. Broadly, the practical benefits of HFCs are that they are as quick as diesel to refuel (and so align well to existing duty cycles for drivers), whereas BEVs require longer times for charging, and they do not need to carry around a large, heavy chemical battery that can compromise a truck's carrying capacity. On the other hand they have a lower well-to-wheel efficiency than BEVs (due to energy losses during production of hydrogen and its conversion into electricity) and their decarbonisation credentials are highly dependent upon how the hydrogen is produced (e.g. grey hydrogen from reformation of natural gas or green hydrogen from electrolysis using renewable electricity).

The commercial availability of smaller HFC trucks has been reported in parts of Europe, while development of articulated trucks (possibly most applicable to the water sector, e.g. for sludge transport) is reported in the USA. The first commercial HFC articulated tanker deployed for transport of milk was reported recently in the Netherlands.

80 https://norlights.com/news/northern-lights-signs-memorandum-of-understanding-mou-with-future-biogas/

81 https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf (p26)

Challenges for their deployment in the UK in the near future will include:

- Their unit cost compared to alternatives
- Their commercial availability, especially in formats used within the UK water sector
- The availability of green hydrogen and sufficient number and strategic location of refuelling stations
- Availability of specialist engineers to repair and maintain the novel and complex drivetrains.

Decarbonisation conflicts:

- While HFC vehicles have guaranteed zero tailpipe emissions, their well-to-wheel carbon emissions depend strongly upon how the hydrogen is produced.

Applicability: Hydrogen refuelling stations will need to be suitably located to make HFC trucks practical to use. This could be company and site specific, assuming that hydrogen refuelling stations will (at least initially) be located next to major transport hubs, rather than isolated or rural locations.

Summary: HFC trucks are a genuine zero emission vehicle in terms of tailpipe emissions and can have zero well-to-wheel emissions if green hydrogen is used. It appears unlikely that sufficient infrastructure for delivery and refuelling of green hydrogen will be in place in time to impact the water sector in AMP 8. Where hydrogen delivery and refuelling infrastructure does emerge, this is likely to be highly site and water company specific, depending upon geographic location. Until verifiable green hydrogen is readily available, we don't consider HFC trucks to necessarily be a Net Zero technology, but this is expected to change in time.

3.2.5 Hydrogen internal combustion engine powered lorries

Hydrogen internal combustion engine powered lorries **TRL 7**	**Water resources** **Raw water distribution** **Water treatment** **Treated water distribution** Retail **Sewage collection** **Sewage treatment** **Sludge treatment** **Sludge disposal**	Scope	**1**
		Kind	**Operational**
		Effect	**Reduce**

Trucks fuelled by hydrogen (instead of diesel) in an internal combustion engine (ICE)

Similar concept to HFC trucks except hydrogen is combusted within a modified ICE. This could make the unit cost for hydrogen trucking lower than for HFCs and repairs and maintenance are likely to be more straight forward and not require particularly specialist knowledge. However, hydrogen ICEs are less efficient than HFCs. This can compound the inherent well-to-wheel inefficiencies of hydrogen trucking compared to alterative zero or low emission vehicles, such as battery electric. Hydrogen ICE vehicles are also not yet considered to have zero tailpipe emissions as they do generate some nitrogen oxides, however truck manufacturers have reported solutions to this.

Truck manufactures that commonly supply conventional trucks within the UK water sector have reported ongoing development of these vehicles. A small number of diesel-hydrogen hybrid vehicles have been trialled by UK water companies and can reduce emissions by 40% versus diesel fuelled trucks. These may be attractive as a transition towards low emission transport. However, these vehicles still require practical delivery of hydrogen and risk prolonging reliance on fossil-fuel, especially as these hybrid trucks can still run on diesel fuel only.

Summary: Decarbonisation conflicts and applicability are broadly the same as for HFC vehicles. Hydrogen ICE trucks might be less technically complex and expensive than HFC trucks but suffer from significant well-to-wheel inefficiencies. They will still rely on hydrogen delivery and refuelling infrastructure that will expect will severely limit their applicability for the next AMP period. Until verifiable green hydrogen is readily available, we don't consider hydrogen ICE trucks to necessarily be a Net Zero technology, but this is expected to change in time.

3.2.6 Natural gas fuelled lorries

Natural gas fuelled lorries TRL 7	Water resources Raw water distribution Water treatment Treated water distribution Retail Sewage collection Sewage treatment Sludge treatment Sludge disposal	Scope	1
		Kind	Operational
		Effect	Reduce

Trucks fuelled by compressed or liquified natural gas instead of diesel

These trucks are likely to be very similar or identical to those operating on biomethane, although their relative carbon benefit will be significantly lower. Relative to diesel fuel they are likely to have a small carbon benefit in terms of carbon emitted per distance travelled and air quality benefits from other emissions, e.g. particulate carbon and nitrogen oxides.

Summary: Since these vehicles remain fossil-fuelled it is difficult to rationalise these as a Net Zero technology, although there are some marginal benefits versus diesel-fuelled trucks. One possible advantage could be the use of these vehicles in the transition to fleets fuelled by biomethane, because of the interchangeability between natural gas and biomethane as fuels. Conversely, having a natural gas compatible vehicle could result in the extended use of fossil-fuelled transport if biomethane projects are slow to develop.

3.2.7 Battery electric lorries

Battery electric lorries TRL 7	Water resources Raw water distribution Water treatment Treated water distribution Retail Sewage collection Sewage treatment Sludge treatment Sludge disposal	Scope	1
		Kind	Operational
		Effect	Reduce

Use of battery electric vehicles (BEVs) instead of diesel-fuelled trucks

While there is debate around the applicability of BEV drivetrains for heavy-duty vehicles, several major truck manufacturers are backing development and production of BEV trucks over zero emission alternatives such as HFCs. A major anticipated barrier is the time taken to recharge batteries and how disruptive this could be to driver duty cycles and the practicality of heavy transport. However, BEVs are the most efficient use of renewable electricity for transport. Analyses suggest a greater distance can be travelled per kWh of electricity in BEV trucks than HFC trucks due to the inefficiencies of using renewable electricity to make hydrogen by electrolysis versus directly charging vehicle batteries.

BEV trucks are increasingly reporting greater range and ever more rapid recharging times. This is increasing their ability to align with practical driving schedules. For example, rapid recharging of trucks is now reported, where over 80% charge can be delivered during the 45-minute breaks mandated for heavy-duty truck drivers. We expect that the feasibility of BEV trucks for the water sector will be company specific, depending on the level of work required for the transport of sludge by road and driving cultures of different water companies. For example, some companies report 24-hour access to Sludge Treatment Centres (STCs), with sludge delivered by tanker throughout the night, while STCs of other companies report access at business hours only. This could introduce the prospect of overnight charging for some companies, where the number of truck journeys is significantly reduced.

Funded activity synergies:

- CHP or onsite renewables expansion

Decarbonisation conflicts:

- Electricity used for charging should be renewable and additional

Applicability: Could be company or even site specific depending on the practicality of updating or re-evaluating driver duty cycles.

Summary: Water companies will likely need to perform individual assessments to decide whether BEV trucks are suitably practical for their requirements, e.g. to transport sludge. Continued rapid advancements in BEV trucks in terms of range and recharge times could make this decision more in favour of BEVs over time but it remains unclear whether BEVs will be applicable to all companies across all sites. Vehicle charging infrastructure is becoming more familiar and more abundant over time. From this perspective BEV trucks might be more feasible for the water sector than HFC trucks for the coming AMP period.

3.2.8 Carbon capture, storage and utilisation

Carbon capture, storage and utilisation (CHP) **TRL 7**	Water resources Raw water distribution Water treatment Treated water distribution Retail Sewage collection Sewage treatment **Sludge treatment** Sludge disposal	Scope	**1**
		Kind	**Operational**
		Effect	**Compensate**

Capture and storage of carbon dioxide from Combined Heat and Power (CHP engines)

Water companies use CHP engines to generate electricity and heat at their treatment works. Where biogas is used as the fuel this energy is considered renewable. However, water companies are increasingly pushing their biogas end-use away from CHP and towards biomethane grid injection. In this instance, some water companies have reported that CHP engines are fuelled by natural gas, meaning their outputs are not renewable. Similarly, the carbon dioxide (CO_2) in exhaust gases of CHP engines fuelled by biogas is biogenic and virtually guaranteed to be carbon neutral, whereas CO_2 from natural gas-fuelled CHP is not.

In theory, CO_2 from CHP can be captured so that it isn't emitted to the atmosphere. Due to leaks from biogas processing, delivery and imperfect CO_2 capture, carbon capture and storage will not make biogas CHP or natural gas CHP Net Zero technologies (with natural gas impacts being worse due to a slightly higher global warming potential than biomethane). However, it is likely that carbon capture from CHP engines will be required to align with legislative Net Zero requirements. This could be stored in similar fashion to CCS applied to biomethane to grid plants (recognising the potential shortcomings of this technology in terms of Net Zero, as discussed further). However, CHP exhaust gas will be a more challenging CO_2 source because of its high temperature and mixture with other bulk gases, e.g. dinitrogen (N_2).

Application of CHP CCS to Ofwat's innovation fund includes utilisation as well as storage, with applications such as capture of CO_2 within organomineral fertiliser products. However, the stability of captured CO_2 within such products remains uncertain. It is possible this will be quickly released into the atmosphere and not stored for over an environmentally meaningful timeframe. This aspect will need to be demonstrated as part of ongoing and future study.

Funded activity synergies:

- Performed in tandem with biogas CHP

Applicability: Applicable at sites with biogas production.

Summary: Our opinion remains similar to that of CCS as part of biomethane to grid. However, CCS from CHP engines is likely to be an even bigger challenge. There is a risk that this will be used to excuse the increased import of natural gas into CHP before the efficacy, practicality and economics of CCS at Sludge Treatment Centre relevant scales is adequately demonstrated in the UK. There is also not yet sufficient evidence that CO_2 captured and incorporated within products (e.g. organomineral fertiliser products) will remain stable for sufficient timeframes to impact global warming potential. There is a risk CO_2 captured in these products will be rapidly emitted to the atmosphere after use. As a result, we don't yet consider this to be a Net Zero technology.

More work must be done to:

- Develop the CCS market and understand opportunities and barriers for individually small scale and collectively diffuse sources of CO_2, relative to large industrial point sources and hubs.

- Understand the nature of storage and associated permanence of carbon sequestration, for example where CO_2 is incorporated within paint or fertiliser products.

3.2.9 Nature Based Solutions - Treatment wetlands for wastewater treatment

NBS - Treatment wetlands for wastewater treatment **TRL 8**	Water resources Raw water distribution Water treatment Treated water distribution Retail **Sewage collection** **Sewage treatment** Sludge treatment Sludge disposal	Scope	**1 + 2 + 3**
		Kind	**Operational**
		Effect	**Reduce**

Treatment wetlands offer green infrastructure solutions or 'nature based solutions' which may offer alignment with Net Zero principles though trade-offs between operational and capital carbon impacts require scrutiny, along with their importance with wider decarbonisation transition (green spaces, active travel, climate resilience and adaptation).

Funded activity synergies:

- May allow reduced chemical inputs, capital maintenance expenditure

- Synergy with NBS interest/focus at sector level

Decarbonisation conflicts:

- Treatment wetlands produce GHG emissions (primarily methane if flooded; nitrous oxide also if reaerating) and in addition to capital carbon impacts from construction, may not be a decarbonisation solution.

Applicability: Applicable where selected site space requirements exist and where sufficient effluent treatment can be achieved through conventional or augmented (forced bed aeration, superoxygenated[82], geochemical augmentation[83]) exists.

Summary: In terms of reported Scope 1, 2 and 3 emissions, treatment wetland solutions may allow for reduced chemical and electrical inputs (Scopes 1 and 2) but may be a source of process emissions (Scope 1) and come with significant construction impacts (Scope 3) and lower lifetime than traditional grey solutions (Socpe 3). The net zero alignment of treatment wetlands to replace conventional wastewater treatment technologies is not well supported by existing literature and this is a recognised gap for further work - though wider benefits of NBS (potential community amenity, wildlife, biodiversity) are recognised as significant (dependent upon scale) and better reported.

82 https://www.sciencedirect.com/science/article/abs/pii/S0048969718339895

83 https://pubmed.ncbi.nlm.nih.gov/30189526/

3.2.10 Low carbon concrete

Low carbon concrete TRL 9	Water resources Raw water distribution Water treatment Treated water distribution Retail Sewage collection Sewage treatment Sludge treatment Sludge disposal	Scope	1
		Kind	Operational
		Effect	Substitute

Concrete with a reduced embodied carbon through use of alternative or advanced materials

Concrete is used widely throughout the water sector, including for critical structures such as footings, tanks and aeration lanes and non-structural uses, e.g. kerbstones. Traditional concrete has an embodied carbon of 430 kg CO_2 equivalents per cubic metre. About 58% is associated with the cement ingredient of concrete, while reinforcing steel makes up another 19% of the embodied carbon in concrete structures.

Where the elimination or substitution of concrete is impossible or impractical, the embodied carbon of concrete could be reduced by selecting alternative cementitious materials or incorporating materials that actively capture and sequester carbon. For example, blast furnace slag, a waste product of the steel industry, can be used to replace up to 50% of the CEM01 ordinary Portland cement responsible for the high embodied carbon. Another example is the inclusion of advanced graphene materials that have been recovered from sustainable carbon sources. In addition to carbon sequestration, the benefits promised by graphene include increased strength (decreasing the volume of concrete and steel required to form a stable structure) and increased durability (improving the structures serviceable lifetime).

However, major barriers to the implementation of such low carbon concretes for the immediate future in AMP8 include the availability of the substituting materials and the lack of design codes available for non-standard concrete designs. It is also possible that low carbon concrete materials would not be supported by water companies' own asset standards.

In response to this, Jacobs' development of a framework for low carbon concrete along with the Environment Agency (EA)[84] has highlighted the more likely use of low carbon concrete materials for non-structural purposes, such as hole-filling or roadside kerbs. It is much more likely that critical structures will use standard concrete aligning to design codes in order to manage risk, e.g. of structural failure.

Summary: While innovations in low carbon concrete materials offer exciting possibilities, it is likely that any use for the coming AMP period will be restricted to non-structural applications. It remains uncertain what savings in embodied carbon will be possible, but benefit is likely to be muted if low carbon concrete cannot be used for structural purposes.

The applicability of low-carbon concrete for the UK water sector could grow beyond 2030 and ways to accelerate the certifying suitable design code and internal asset standards of WaSCs and WoCs should be explored in the interim. The Institution of Civil Engineers (ICE) have developed a Low Carbon Concrete Routemap that can be referred to as guidance for overcoming technical and regulatory hurdles and barriers in internal governance[85].

More work must be done to:

- Establish End of Waste for recovered materials and their incorporation into cement.
- Development of design codes and asset standards to permit use in structural projects.

84 https://www.jacobs.com/newsroom/news/decarbonizing-construction-uk

85 https://www.ice.org.uk/media/q12jkljj/low-carbon-concrete-routemap.pdf

3.2.11 Sewage sludge (co)combustion

Sewage sludge (co)combustion TRL 8	Water resources Raw water distribution Water treatment Treated water distribution Retail Sewage collection Sewage treatment **Sludge treatment** **Sludge disposal**	Scope	**1 or 3**
		Kind	**Operational**
		Effect	**Substitute**

Combustion or co-combustion of sludge following its transformation into fuel

Sewage sludge contains an intrinsic calorific heating value, derived from its organic carbon content. This is greatest in raw sludge, but even Advanced Anaerobic Digestion (AAD) can only recover around 55-60% of energy from sludge (as biogas). Thermal combustion techniques are able to convert sludge into energy. Much of this can be recovered.

The primary purpose of combustion is the generation of heat for some practical or industrial use. This might be considered subtly different than incineration, where the primary function is the disposal of waste (although some energy recovery is possible). An example would be the use of dried sludge in cement kiln processes, which has some historic precedent in the UK[86]. This has Net Zero potential where sludge substitutes for fossil-based fuels. Typically, sludge must be received as a dried product to be compatible with such combustion processes.

For a process to be considered combustion, the feedstock (e.g. sludge or biosolids) would need to be classified as a fuel, rather than a waste. It has been argued (e.g. in Scotland) that the process of drying and pelletising sludge to be combusted by a 3rd party effectively transforms sludge from a waste material into a fuel. While there are some reports of continued use of dried sludge in cement kilns in the UK[87], there is precedent that refutes this claim (e.g. in SEPA in Scotland), with dried sludge continuing to be considered waste by the environmental regulator, at least in reported historic instances[88]. This has can have regulatory implications for the permitting of combustion processes using dried sludge, that have been insurmountable in the past. It is possible that the mixing of sludge with other materials in a co-combustion process would even further complicate permitting.

Other considerations for (co)combustion of sludge are the method used to dry sludge. If natural gas is used this will undermine the carbon benefit of sludge as a fuel and could lead to a net carbon emission. Combustion or incineration of sludge is also associated with a high emission of nitrous oxide greenhouse gas, which could also lead to a net carbon emission.

Funded activity synergies:

- Combustion of sludge could generate renewable heat onsite that could be used to dry sludge, creating a closed-loop system

Decarbonisation conflicts:

- The use of natural gas to dry sludge and the emission of nitrous oxide from combustion of sludge could undermine the carbon benefit from any fossil-fuel substitution and lead to a net carbon emission.

Applicability: Applicable at sites with a clear purpose for the heat generated. Even in this case it is uncertain that sludge will be classified as a fuel by the environmental regulator.

Summary: The feasibility of (co)combustion relies heavily on the transformation of sludge or biosolids from a waste to a fuel in the eyes of the environmental regulator. If classified as a waste, there is a high risk that requirements under the Waste Incineration Directive (WID) will be too onerous for (co)combustion to be practical or economic or that existing processes will be unable to suitably adjust their permits to accommodate sludge. There are also likely to be additional requirements under the Industrial Emissions Directive (IED). A full carbon and energy balance would also be needed to determine whether the

86 https://www.cemnet.com/News/story/147307/cement-group-to-pioneer-new-fuel.html

87 https://www.drax.com/sustainable-bioenergy/how-scotlands-sewage-becomes-renewable-energy/#:~:text=In%20operation%20since%202002%2C%20Daldowie,%2C%20low%2Dodour%20fuel%20pellets

88 https://www.scotcourts.gov.uk/search-judgments/judgment?id=ed7987a6-8980-69d2-b500-ff0000d74aa7

process results in a net carbon emission, e.g. through the possible use of natural gas for sludge drying and the emission of nitrous oxide upon combustion of sludge.

More work must be done to:

- Establish End of Waste for dried biosolids material and its application as a fuel
- Perform a lifecycle carbon assessment to understand the Net Zero implications versus the baseline of majority biosolids to land.

3.2.12 Hydrothermal processes

Hydrothermal processes **TRL 9**	Water resources Raw water distribution Water treatment Treated water distribution Retail Sewage collection Sewage treatment **Sludge treatment** Sludge disposal	Scope	–
		Kind	–
		Effect	–

This includes a host of sludge treatment technologies, such as Hydrothermal Carbonisation (HTC), Hydrothermal Liquefaction (HTL) and Supercritical Water Oxidation of sludge (SCWO). These processes use a combination of high temperatures and pressures (in combination with chemical additives and catalysts in some iterations) to manipulate or treat sludge. Temperatures and pressures are typically in excess of those used routinely in established anaerobic digestion pre-treatments, e.g. Thermal hydrolysis. Outputs include an energy rich gas, a 'biocrude' liquid that can be digested and a solid hydrochar that can reportedly be dewatered to around 60% dry solids and recycled to land or sent to incineration. Other benefits reported include the destruction or reduction in organic contaminants, such as microplastics and per/poly fluoro alkyl substances (PFAS).

Summary: While promising, these types of processes are not well-demonstrated at scale, with a small number of sites reported outside of the UK for sewage sludge applications. The energy balance remains unclear. It is likely that these processes will be more energy intensive than Thermal Hydrolysis (higher temperatures and pressures) but it isn't clear that they result in greater energy recovery. Claims of organic contaminant removal are encouraging, but we do not see this well-evidenced yet. Practically it could be difficult to integrate these processes into the UK sector over the next AMP because it is already on the way to becoming saturated by anaerobic digestion pre-treatments such as Thermal and Enzymatic hydrolysis, that are already well-demonstrated. As a result, we don't yet consider these processes as Net Zero driven technologies for the UK water sector.

More work must be done to:

Maintain a watching brief of developments in this area to understand how these technologies could be integrated within the UK water sector.
In particular the possible advantages of high-dry solids hydrochar if sewage sludge incineration becomes favoured in the future through restrictions around biosolids to land.

3.2.13 Sewage sludge incineration

Sewage sludge incineration **TRL 9**	Water resources Raw water distribution Water treatment Treated water distribution Retail Sewage collection Sewage treatment Sludge treatment **Sludge disposal**	Scope	–
		Kind	–
		Effect	–

This is the disposal of sewage sludge or biosolids by thermal destruction, generating heat energy and a waste ash. If able to operate auto-thermally, with the sludge itself fuelling the thermal process without a consistent supply of natural gas, a degree of energy recovery as heat and electricity is possible. The UK has a mixed historic experience with incinerators, although it is possible that modern incineration would allow for more auto-thermal operation, improved energy recovery and better emissions controls than previous experiences in England and Wales.

Summary: We do not see enough evidence from routine operation of state-of-the-art incinerators to consider sewage sludge incineration a Net Zero technology. We expect incineration would be driven by regulatory constraints on landbank for biosolids recycling, rather than Net Zero. Historic issues with consistency of sludge feedstocks have reduced the opportunity for auto-thermal operation (requiring natural gas imports) and therefore will compromise net energy recovery. It is likely that a sizeable fraction of heat produced will be used to dry (or partially dry) sludge to create a consistent feedstock rather than generate excess renewable energy. Sewage sludge incineration is also associated with high emission of nitrous oxide (N_2O) in flue gas. N_2O could be further exacerbated through the injection of ammonia or urea into flue gas to reduce nitrogen oxide (NOx) emissions. Such Selective Non-Catalytic Reduction (SNCR) of NOx is a feature of modern incinerators.

More work must be done to:

- Sewage sludge incineration could be implemented through drivers other than Net Zero, such as restrictions of biosolids to land regulations. In this event it will be critical to perform a lifecycle carbon assessment to understand the Net Zero implications versus the baseline of majority biosolids to land.

3.2.14 Green electricity purchase

Green electricity purchase **TRL 9**	**Water resources** **Raw water distribution** **Water treatment** **Treated water distribution** **Retail** **Sewage collection** **Sewage treatment** **Sludge treatment** **Sludge disposal**	Scope	**2**
		Kind	**Operational**
		Effect	**Substitute**

This is the purchase of grid electricity via green energy tariffs. Ostensibly, power purchased through such tariffs is derived from a renewable source (e.g. wind or solar) fed into the National Grid. However, there is a finite average proportion of renewable electricity available via the grid, currently. As a result, renewable electricity 'secured' by one company cannot also be used by another.

For example, The Climate Change Committee's briefing document on corporate procurement of renewable energy[89] reports limited impact on emissions on a company or country level, because:

- "Most forms of procurement do not actually lead to increased renewable electricity generation within the wider UK system (considered as 'additionality'), as the majority of renewable

89 https://www.theccc.org.uk/wp-content/uploads/2020/12/Corporate-Procurement-of-Renewable-Energy-Implications-and-Considerations-Terri-Wills.pdf

electricity being purchased either already exists or is being supported through Government mechanisms including Contracts for Difference."

- "Most forms of procurement do not lead to renewable electricity generating the actual power that is consumed by the corporation; meaning, in most cases the electrons flowing into the company's buildings and operations are comprised of a mix of fossil fuel generated electrons and renewable electricity generated electrons that are representative of the grid to which the company is connected."

Although excess profits from Green tariffs may be invested into new renewables projects in the future, this is not instantaneous and remains out of companies' control. Within a renewables procurement hierarchy (Figure 15) even 'high-quality' green tariffs are expected to find it difficult to prove additionality[90].

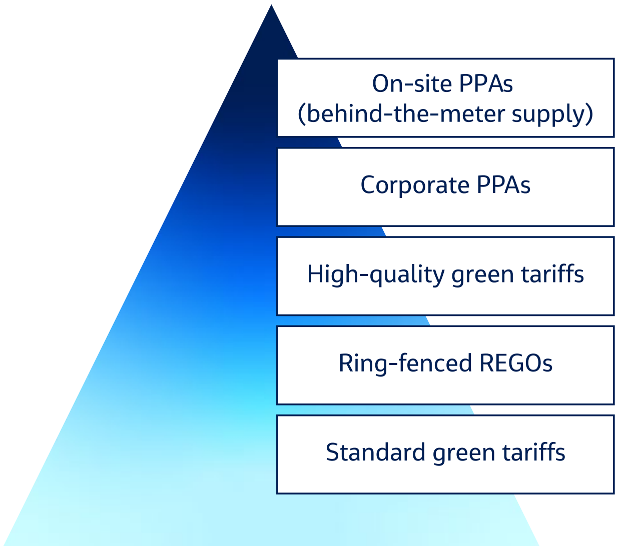


Figure 15 - Renewable electricity procurement hierarchy detailing nuances in types of Green tariff. Figure based on article by Sabrina Andrei, JLL[90].

By contrast, onsite renewables or Power Purchase Agreements (PPAs) for offsite renewables can stimulate dedicated, additional renewable electricity that doesn't compromise other grid users' potential to decarbonise. Ultimately the electricity grid is expected to independently decarbonise, however this journey will not be complete over the next AMP period.

Summary: Water UK's Net Zero 2030 Routemap suggests the largest negative emissions (-0.62 Mt CO_2e) are derived from Green tariff purchases. This is almost six times greater than renewable energy exported by the water sector (e.g. by biogas CHP or onsite renewables). A continuation of this trend risks future reliance on this strategy for the sector that will not deliver real-world carbon emission reduction in the UK. It is possible that future reliance on electricity purchase through Green tariffs will not be considered a viable decarbonisation strategy going forwards for water companies that are certified aligned to Science Based Targets initiative (SBTi), however not all companies have signed up to SBTi. We therefore do not consider Green electricity purchase to be a Net Zero solution, unless additionality of renewables sources can be verified. They should only be used when alternative options for onsite renewables and PPAs have been explored and reasonably discounted, which rationale might be site specific.

90 https://www.jll.co.uk/en/views/is-all-renewable-energy-procurement-equally-as-green

3.2.15 Mainstream (cold) anaerobic digestion

Mainstream (cold) anaerobic digestion **TRL 6**	Water resources Raw water distribution Water treatment Treated water distribution Retail Sewage collection **Sewage treatment** Sludge treatment Sludge disposal	Scope	**1 + 2 + 3**
		Kind	**Operational**
		Effect	**Eliminate**

Alternative low-energy (or even energy positive) wastewater treatment.

The organic matter in wastewater can be treated aerobically or anaerobically. Anaerobic treatment is preferential because it allows methanogenic bacteria to produce methane and release energy for beneficial use. By contrast, aerobic treatment does not allow energy capture and in the case of intensified processes such as activated sludge, it requires high energy inputs.

Anaerobic treatment tends to work best at temperatures of around 30 °C or higher, with high concentrations of organic matter. Mainstream (cold) anaerobic digestion seeks to overcome these limitations and apply anaerobic conditions to the entire wastewater flow at a site, which is at low temperatures and relatively low concentrations. Successful adoption of this technology would reduce or eliminate the energy requirement for aeration in activated sludge and other intensified treatment processes and could result in a net energy gain from the process instead.

The technology is widely used in tropical and subtropical climates and in industrial wastewater treatment in the UK and is being piloted in the UK – including by Welsh Water and in emerging innovation work led by Thames Water.

Mainstream (cold) anaerobic digestion could disrupt existing treatment trains by supplementing or replacing existing aerated treatment. Methane capture would require either additional plant, or installation on sites which have existing biogas infrastructure. The technology might need to be supported with methane degassing and chemical nutrient removal. Depending on the source and quantity of chemicals, this could reduce or reverse the technology's decarbonisation impact.

Funded activity synergies:

- Possible increased energy production on wastewater sites without existing digestion assets.
- Reduced sludge production, reducing dewatering and transport work.
- Reduced need for aeration.
- Reduced recirculation of ammonia from digestors, further reducing aeration energy.
- Reduced need for advanced digestion technologies to access volatile solids, reducing heat energy requirements.
- Synergistic with replacement of existing plant at the end of its life. Tanks may be reusable, but aeration equipment would not be.

Decarbonisation conflicts:

- Likely requirement for continued secondary treatment to remove ammonia and/or nitrogen and for chemical phosphorus removal which may also require additional tertiary filtration stages.
- Likely requirement for methane degassing.
- Not compatible with alternative mainstream treatment decarbonisation technologies.

Applicability: Applicability within existing site arrangements is unclear – e.g. whether downstream of primary treatment or in place of this. However, large sites are most likely to have the infrastructure needed to make use of the methane generated.

Summary: This technology has been shown to reduce BOD loads under UK conditions, but to our knowledge is not yet ready to supplant conventional activated sludge or biofilter processes here. If it can be used to replace activated sludge it would bring very substantial reductions in site energy demands for aeration and digestion pre-treatment.

More work must be done to:

- Develop the business case for its implementation, e.g. at small, isolated rural works or at large Band 6 sites.As a disruptive technology, will assets be stranded or be written off by its implementation?
- Continue developing solutions for corresponding nutrient removal (or recovery) following carbonaceous treatment.
- Develop a holistic lifecycle carbon analysis approach that considers possible increases in fugitive methane emissions and embodied carbon in chemicals used for carbon dosing or within ion exchange solutions.

3.2.16 Organomineral fertiliser production

Organomineral fertiliser production **TRL 5-6**	Water resources Raw water distribution Water treatment Treated water distribution Retail Sewage collection **Sewage treatment** **Sludge treatment** **Sludge disposal**	Scope	**1**
		Kind	**Operational**
		Effect	**Reduce**

Combines drying, ammonia recovery and potential for carbon capture and may offer alignment with Net Zero subject to carbon impact assessment at some wastewater treatment sites.

Sidestream liquors from anaerobic digestion processes are very high in ammonia due to the breakdown of nitrogen containing sludges into ammonia. These liquors may be treated in sidestream processes – with very high nitrous oxide emissions from industry investigation in Denmark and elsewhere in Europe – or through the mainstream treatment plant (resulting in additional nitrogen transformation and formation of nitrous oxide here too).

This ammonia typically needs to be treated or is treated alongside organic matter, which in most large works is achieved through forced aeration. This is an energy intensive process, and also produces nitrous oxide, a powerful greenhouse gas. In addition, on many sites the methane produced by anaerobic digestion is combusted in combined heat and power engines, or may be cleaned, upgrade and injected to the gas grid. Both of these processes produce carbon dioxide.

In emerging product applications, organomineral fertiliser production can recover the ammonia instead of transforming it through biological processes while utilising the carbon dioxide when captured from biogas end uses. These are combined with biosolids to produce a pelletised fertiliser product[91]. An environmental product standard with carbon impact and end of waste status would likely be required, unless utilised on Water Company owned landbank. This makes it suitable only for sites with high concentrations of ammonia available, such as sites with advanced anaerobic digestion and high strength liquor returns; otherwise ammonia would need to be imported from other sources.

The technology's alignment with Net Zero is most likely due to the potential Scope 1 process emissions benefits of removing ammonia and avoiding nitrous oxide production where an existing (on-site) source of ammonia in sludge liquors is utilised. However - the technology is energy intensive and is likely to require heat for both ammonia stripping from digestate and sludge drying and pelletising. Sites with combined heat and power engines might produce heat, but if there are other existing demands such as thermal hydrolysis, an external energy source such as fossil (natural) gas is likely to be required. Sites without CHP engines powered by biogas will need to import energy to power the CHPs.

Technology providers have referenced carbon sequestration benefits due to the process utilising separated CO_2 from biogas upgrading facilities, which is then used in the fertiliser production process and forms part of the product.

91 https://www.severntrent.com/media/news-releases/severn-trent-recycles-waste-into--super-fertiliser--using-world-/

This claim of carbon benefit is considered problematic due to:

- The presence of biogas upgrading possibly meaning fossil (natural) gas imports may be required to sustain the energy balance of the fertiliser production process which would not align the solution with Net Zero principles

- The quality of the quoted carbon sequestration – with a lack of published evidence for the net carbon balance for existing demonstrations or generally and in particular a lack of evidence for whether the carbon dioxide in fertiliser product remains in soil systems or is simply released back to the atmosphere.

- Companies who have signed up to SBTi™ accredited emissions reduction pathways must prioritise emissions reduction and the technology requires significant additional chemical, heat and energy inputs – effectively increasing reported emissions. Any resulting carbon benefit of lower carbon fertiliser products, if supported through appropriate EPS and recognition as a lower carbon alternative, would fall outside of reported company emissions and not be able to be offset against the higher Scope 1 and 2 emissions which would result from employing the technology at a WwTW or bioresources site.

The market and end of waste status for the product created are not publicly known at this time, but if there is a market for the product this technology could be synergistic with farmers' compliance with the Farming Rules for Water and improvement to the resilience of sludge-to-land practices (as stated in most recent Water Industry National Environment Programme drivers) by creating a more transportable and storable product (than biosolids cake). However, it is unlikely that contaminants of emerging concern found in biosolids, e.g. microplastics and Per/poly Fluoro Alkyl Substances (PFAS), will be removed from final Organomineral fertiliser products. Anticipated regulation of such contaminants in biosolids could ultimately dictate whether recycling to land will remain a practical outlet by the end of AMP 8.

Until details of the Environment Agency's proposed Sludge Strategy[92] are known, we cannot suppose whether Organomineral fertilisers production will be practical in the long term. Analysis of literature in public domain (e.g. patents) indicate that manufactured nitrate fertilisers may be imported and incorporated into the final product, although it is unclear how vital these are to the overall process. Recent events around the volatility of natural gas markets and the knock-on impacts upon the cost and supply of nitrogen fertiliser suggests this could be a key vulnerability of some processes creating organomineral fertiliser products from biosolids. The combined uncertainty around contaminants in the product and reliance on volatile supply chains for chemical inputs begs the question whether Organomineral fertiliser production is an adequately future-proofed Net Zero technology, while the possibility that natural gas is used to provide heat for sludge drying questions its intrinsic Net Zero credentials.

Funded activity synergies:

- Upgrades to CHP engines.

- Fate of biosolids to land which could support development of enhanced biosolids fertiliser products and/or reduced mass for land application.

Decarbonisation conflicts:

- Requires a large amount of heat. Heat generated on site might already be committed to other uses. This could lead to the increased import of natural gas.

- The ability of the technology to sequester carbon in the long term is not clear. Mineralised carbon within the matrix of the pellets may be released into the atmosphere when in contact with acidic soils. We have not found any published information on this.

Applicability: Applicable to wastewater sites with highly concentrated liquor returns such as sites with advanced anaerobic digestion. Particularly applicable to sites with combined heat and power engines or biogas upgrading for grid injection.

Summary: This technology combines several technologies (drying, pelletisation, ammonia recovery and fertiliser production) into one package. However, it is likely to rely on heat from CHP engines, many of which are being converted to run on natural gas as companies switch their biogas production to grid injection, and it has a large energy demand. It is also likely to require the external supply of nitrate fertiliser as an input, which introduces implications of carbon, cost and supply chain reliability. The process might not

92 https://www.gov.uk/government/publications/environment-agency-strategy-for-safe-and-sustainable-sludge-use/environment-agency-strategy-for-safe-and-sustainable-sludge-use

offer materially greater resilience against future regulation of contaminants, that are likely to remain in the product. Its capability to sequester carbon in the long term is not clear. We consider that to evaluate its Net Zero credentials, more information needs to be released into the public domain.

More work must be done to:

- Establish End of Waste for recovered material and its application.
- Better understand the risk of exposure to volatile or unreliable supply chains and strategies for mitigation.
- Demonstrate the permanence of sequestration of captured carbon and rationalise how this can or cannot be counted within Net Zero reporting frameworks.
- Maintain a watching brief of environmental regulation impacting biosolids to land and attempt to understand whether organomineral fertilisers are capable of mitigating risks as they emerge, particularly around contaminants of emerging concern.

3.2.17 Water treatment sludge recycling to land

Water treatment sludge recycling to land **TRL 9**	Water resources Raw water distribution **Water treatment** Treated water distribution Retail Sewage collection Sewage treatment Sludge treatment Sludge disposal	Scope	**3**
		Kind	**Operational**
		Effect	**Reduce**

Residual solids or sludges from water treatment can be formed following the coagulation of solids from surface waters, e.g. after addition of ferric or alum coagulants, or precipitation of dissolved solids in groundwater, e.g. by oxidation of dissolved iron compounds. Physical and chemical properties may vary however, they are typified by low nutrient content (at least in bioavailable form), modest organic matter content and can contain elevated levels of heavy metals and other contaminants[93].

Possible disposal routes for water treatment sludge include discharge to sewer, lagoon storage (interim measure), landfilling or land spreading. Water treatment sludges do not have the same agronomic benefits as biosolids derived from wastewater sludge and are expected to be generated in much smaller volumes. Anecdotal and non-public sources indicate that a large proportion of this material is already recycled to land. These factors strongly indicate a marginal Net Zero potential for avoiding emissions, e.g. from substitution of manufactured fertilisers, carbon sequestration in soils or avoiding emissions from landfilling. As a result, we do not consider recycling water treatment sludge to land to be a Net Zero solution.

Water companies outside of the UK have demonstrated improved circularity for ferric-based drinking water sludges that could deliver Net Zero benefit, e.g. by substituting out embodied carbon in virgin materials or for desulphurisation of biogas production in anaerobic digestion of waste[94].

More work must be done to:

- Establish End of Waste for recovered material and its application.
- Calculate the scale of ferric sludge production in the UK and therefore understand the potential benefit for reducing embodied and operational carbon by this approach, recognising the widespread use of chemical phosphorus removal in the existing system.
- Understand applicability within the water sector and in commercial AD sector in order to understand the boundaries of any carbon benefit.

93 http://randd.defra.gov.uk/Document.aspx?Document=SP0578_10137_FRP.pdf

94 https://aquaminerals.com/ferric-hydroxide/

3.2.18 Alum-sludges in cement manufacture

Alum-based water treatment sludges use in cement manufacture **TRL 7**	Water resources Raw water distribution **Water treatment** Treated water distribution Retail Sewage collection Sewage treatment Sludge treatment Sludge disposal	Scope	**3**
		Kind	**Embodied**
		Effect	**Reduce**

Where alum-based coagulants are used in water treatment, the resulting alum-sludge has the potential to be used as a cementitious material, e.g. as a component of concrete. As discussed in section 3.2.10 for low-carbon concrete, conventional cementitious materials possess a large, embodied carbon. Alum sludge could substitute for these carbon-intensive inputs, thereby lowering the embodied carbon of concrete structures. For example, Scottish Water are partners within the Alu Circles pan-European initiative to drive circular solutions for alum sludges[95]. Irish Water already report sustainable outlets for 75% of their drinking water sludge, specifically referring to the use of alum sludge as a substitute for bauxite as a raw material in cement as one such outlet[96].

However, we expect this technology is still not ready for application by WaSCs and WoCs in England and Wales for the next AMP and so hasn't been shortlisted as a Net Zero technology.

More work must be done to:

- Establish End of Waste for recovered material and its incorporation into cement.
- Development of design codes and asset standards to permit use of alum sludge derived cement in structural projects.
- Calculate the scale of alum sludge production in England and Wales and therefore understand the potential benefit for reducing embodied carbon by this approach.

95 https://www.alliedwaters.com/project/alucircles/

96 https://www.crf.ie/wp-content/uploads/2022/03/CRU202228a-Irish-Water-Performance-Assessment-Report-No.-6.pdf

Conclusion and recommendations

4 Conclusion and recommendations

This project was commissioned by Ofwat to identify technologies and interventions likely to be capable of reducing greenhouse gas (GHG) emissions during the investment period (2025 – 2030) covered by PR24. In particular, the project focused on identifying, reviewing the applicability, readiness and scalability of GHG reduction technologies and interventions applicable to water companies in England and Wales.

The assessment undertaken included global literature review to identify established and emerging Net Zero technologies and interventions applicable to the UK water sector and gather key information for analysis - e.g. around costs and carbon emissions. This also included input from Jacobs extensive global network of subject matter experts and from Ofwat. A compiled longlist of identified technologies was refined into an ultimate shortlist through a detailed Multi Criteria Analysis (MCA) assessment exercise. Through this process, combined to our professional opinions and judgements we have developed several recommendations around Net Zero technologies;

- monitoring and mitigation of process emissions of nitrous oxide and methane are likely to offer greatest benefits to reduce emissions. Solutions capable of reducing processes emissions have scored consistently highly in all scenarios within the MCA and should be a priority for decarbonisation. These are also likely to offer some of the lowest cost opportunities from high level cost considerations. We expect these to be primarily WaSC focussed, based on the significantly larger process emissions reported for wastewater treatment versus water treatment (as shown in Water UK's Net Zero 2030 Routemap);

- after mitigation of process emissions, other key technologies which scored highly from the multi-criteria analysis undertaken were renewable electricity procurement through Power Purchase Agreements (PPAs, used here as shorthand to group behind-the-meter and private-wire renewables and corporate PPAs via the grid), pump efficiency and vacuum methane recovery; conversely

- A wider range of viable options exist for WaSCs to reduce GHG emissions, particularly when such emission are viewed from an overall and sector wider perspective;

- the viable options for WoCs to reduce GHG identified through this analysis were fewer by number than for WaSCs due to much lower direct process emissions. However, as most of the GHG emissions for WoCs are from scope 2 and 3 emissions, in particular power consumption (see Figure 7), large reductions are feasible from reducing electricity consumption through reducing overall water demand (e.g. leakage reduction, water efficiency), improving asset energy efficiency, and power purchase agreements;

- energy recovery from wastewater residuals is already undertaken at scale through advanced or conventional anaerobic digestion. However, recommendations from Water UK's Net Zero Routemap along with financial incentives appear to be pushing water companies towards increased grid injection of biomethane and away from biogas CHP. Where heat from CHP is heavily consumed at bioresources sites, export of biomethane may result in the reciprocal import of natural gas to maintain the energy balance. Upgrading of biogas to biomethane for grid injection, where companies require a reciprocal increase in the import of fossil gas does not offer alignment with Net Zero principles as set out by Ofwat and could result in net carbon emission in the wider system. We recommend that energy and carbon balances of new biomethane to grid plants are scrutinised to avoid this, particularly for sites where Thermal Hydrolysis or other heat intensive processes (e.g. sludge drying, thermal stripping of ammonia) are installed or planned;

- grid electricity remains the largest reported source of GHG emissions in the water sector. Water UK's Net Zero 2030 Routemap (Figure 7) shows that 85% of negative emissions reported are from electricity purchase via Green tariffs. While Green tariffs can be relatively straight-forward to implement, they offer the least potential to directly impact reportable carbon emission reductions at a national level. Conversely, behind the meter or private wire renewables or corporate PPAs offer the greatest potential for additional carbon emission reductions, it is recognised they might not be straightforward to implement in all circumstances. Therefore, transition to Net Zero should align with renewable electricity hierarchies for procurement of electricity (Figure 14);

- beyond production and local reuse of biogas, resource recovery technologies (e.g. nitrogen, phosphorus, cellulose) may not actually reduce emissions in alignment with Net Zero Principles as set out by Ofwat and as per science-based frameworks (e.g. where these require additional imports of fossil gas and increase in Scope 1 emissions). Where companies embrace such technologies, they must substantiate this further to show alignment with Net Zero principles and carbon reduction hierarchies through the use of life cycle carbon assessment;

- offsetting to achieve Net Zero is not aligned with Net Zero principles or the Science Based Targets initiative but the carbon benefits of resource recovery (e.g. biomethane, heat recovery from final effluent, nitrogen stripping and recovery) may offer the opportunity to reduce emissions in agriculture or industry (e.g. nitrogen recovery or biosolids to substitute fossil-based fertilisers or heat recovery to substitute fossil gas derived heating). As such, this will require greater steer at government level, e.g. as payments through Environmental Land Management Schemes (ELMS) such as the Sustainable Farming Initiative (SFI)[97]. This is a mechanism for funding farmers to build soil organic carbon, distributing the cost of these offsets and emissions reductions in wider society. Strong cross-sector collaboration will support development of associated technologies and solutions. Key barriers will exist during AMP8 – for example resource recovery technologies lack end of waste status.

- existing technology solutions are likely to offer substantial mitigation opportunities. These are also likely to have multiple additional benefits, such as greater water efficiency helping to reduce home energy usage and costs which in turn leads to reduced GHG emissions . However, to reach their full potential, some technologies will require further innovation development to reach their net zero potential – e.g. low energy ammonia recovery without the need to import additional fossil based gas which would otherwise increase Scope 1 emissions; and

- there is a lack of evidence for the carbon impact of or alignment of technologies in relation to allowing companies to mitigate GHG emissions in line with Net Zero principles. This was subsequently identified as a gap requiring further work such as needing to focus on providing sector specific case studies and apply existing methodologies – e.g. to show life cycle analysis (LCA) with respect to carbon impacts to support whether technology solutions are aligned with Net Zero principles.

- all shortlisted technologies applicable to WoCs and WaSCs respectively, will be applicable to all such companies. However, the extent of their applicability could vary in some cases. For example, the decarbonisation potential of Advanced Anaerobic Digestion (AAD) will be less for WaSCs already treating most or all of their sludge by AAD versus WaSCs. Differences in geography and population distributions across the sector are also likely to impact the applicability or size of opportunities.

97 https://www.gov.uk/government/collections/sustainable-farming-incentive-guidance#sustainable-farming-incentive:-full-scheme-information

In evaluation and substantiation of Net Zero alignment, carbon assessment is required at project and programme level as appropriate. In addition to company-level emissions reduction pathways which are increasingly likely to be developed through third party schemes such as SBTi™ science-based analysis to assess the Net Zero attributes of technologies must be put forward in conjunction with business cases. This should be in accordance with recognised carbon accounting protocols and methodologies in addition to Ofwat guidance to date and supported by sector level guidance and clear assurance frameworks.

This assessment requires to be site specific and associated carbon assessment should align with recognised, science-based Net Zero principles and recognised GHG inventory assessment frameworks – demonstrating transparency, accuracy, completeness, comparability and consistency. In particular, energy balances and site level carbon assessments are vital to support Net Zero alignment at project and aggregated programme level.

Work is required at sector level to improve on the understanding of Net Zero technologies and to undertake required baselining assessment and development of sector level guidelines and protocols to allow progress in mitigation - in particular of process emissions of nitrous oxide and methane for WaSCs which offer greatest potential and may also offer lowest cost mitigation opportunities in some cases. Maximising the adoption of Net Zero technologies requires science-based approaches towards the quantification of emissions and justification of Net Zero alignment. This will likely require accreditation/evaluation frameworks to support the science base, particularly in emerging areas, and in the case of some resource recovery opportunities, policy barriers require to be addressed. There is significant global work in these areas for the sector to learn from. For WoCs, beyond power purchase agreements for green energy, water efficiency - in household, supply, distribution, and treatment - is likely to offer greatest opportunities to reduce emissions.

Appendices

Appendix A. Technology Shortlisting

Table A 1. Shortlist of Net Zero technologies

No.	Description	Applicability within sector
1	Mainstream nutrient recovery from wastewater (chemical, e.g. ion exchange).	Removal and recovery of nitrogen and phosphorus as a mainstream wastewater treatment. Avoids energy of forced aeration for nitrification & associated process N¬2O. Avoids embodied carbon for chemical dosing of P (e.g. ferric) but increased use of other chemicals (e.g. salt for ion exchange regeneration brines).
2	Mainstream dissolved methane recovery from wastewater (e.g. degas membrane).	Follows mainstream anaerobic treatment to recover dissolved methane from the anaerobic effluent. Maximises biogas recovery and reduces methane emission to atmosphere.
3	Site wide methane monitoring and proactive mitigation.	Reduces leaks of methane at wastewater treatment works. Programmes operating in Europe (e.g. Sweden).
4	Membrane Aerated Biofilm Reactor (MABR) for mainstream wastewater treatment.	More efficient delivery of low-pressure air or oxygen than conventional blowers to reduce forced aeration energy. Lower N_2O process emissions than traditional forced aeration processes measured (e.g. Denmark).
5	Mainstream short cut nitrification secondary treatment	SCNR and SND require reduced energy input and carbon demand for nitrification and denitrification. Implemented outside of the UK.
6	Enhanced Biological Phosphorus Removal (EBPR)	Biological P removal allows biological P reduction with limited chemical (e.g. ferric) input (trim) and may offer lower carbon opportunities. Must be balanced against greater energy for recirculation pumping, larger concrete tanks. A few sites already in the UK.
7	Simultaneous nitrification/ denitrification in secondary treatment.	SND offers reduced aeration input and energy requirement whilst achieving TN reduction. May require increased pumping energy and larger concrete tanks. Widespread outside the UK.
8	Conversion of secondary nitrifying treatment to nitrifying/denitrifying	Through shortcut or conventional N removal pathways, this may offer improved opportunity for N_2O reduction.
9	Mainstream deammonification	Can allow reduced aeration energy similar to that in liquor treatment plants but for mainstream wastewater flow.
10	Augmentation processes - to intensify secondary biological treatment through increased SRT or improved settlement.	Avoids construction of additional tankage. E.g. continuous flow granulation. IFAS media
11	Biocatalyst technologies	Augment or improve secondary treatment with potential to reduce N_2O process emissions. Achieved through regular seeding of tanks with biocatalyst.
12	Process set point optimisation for N_2O	Reduced N_2O emissions by optimising existing processes.
13	Real time control for optimisation of N_2O.	Reduced N_2O emissions by optimising existing processes using real time control.

No.	Description	Applicability within sector
14	Vacuum extraction of methane	Recovers dissolved methane from digested sludge streams, e.g. EloVac. Increases biogas yield and reduces methane emission to atmosphere. Balanced against energy use for extraction.
15	UV LED disinfection	Significantly reduced power demand vs conventional UV disinfection
16	Algae photobioreactor phosphorus removal	Avoids embodied carbon from chemical (e.g. ferric) dosing for phosphorus removal. Generates a P-rich biomass that can be digested to generate biogas or replace manufactured fertiliser. Must be balanced against energy demand, likely UV LEDs.
17	P removal by Natural/waste-derived adsorbents (e.g. steel slag)	Avoids embodied carbon from conventional chemical dosing for P removal using natural or waste adsorbents or processes. likely at small and/or rural works as part of wider nature-based treatment solutions.
18	Recycled water treatment sludge (not to land)	Treated water sludges rich in ferric or alum can be reused instead of virgin chemical for phosphorus removal, desulphurisation, or odour control. Evidence for this as yet insufficient in UK but if feasible may provide carbon benefits.
19	Sidestream deammonification	Removes ammonia from sludge liquor using less aeration energy than traditional activated sludge processes. Can be associated with high N_2O emissions that can outweigh benefit.
20	Mains Cleaning	Lower water use/recycling approaches to mains cleaning
21	Optimisation of water losses	Reduced water losses in WTW
22	Leakage reduction and water efficiency	Reduced losses in networks. Reducing customer water use (domestic and commercial) offers reduce emissions form all downstream treatment processes.
23	Rising main non-return valve maintenance	Proactive maintenance to avoid backflow and improve system efficiency.
24	Storm water separation and treatment	Avoid stormwater ingress and reduce associated Scope 2 and 3 (electrical, chemical) treatment impacts. Treatment of surface runoff through SUDS, other nature based solutions and avoid runoff into sewers and associated infrastructure and treatment emissions.
25	Storm water separation and treatment	Nature based solutions (NBS) such as sustainable urban drainage systems (SUDS) and treatment wetlands can be applied to stormwaters separated from combined sewer systems. These reduce the need for in line storage and additional treatment capacity which is likely required to address current combined sewer overflow (CSO) challenges the sector faces in AMP8.
26	Odour control optimisation	Optimisation of odour control systems, e.g. to reduce energy demand.
27	Grit/aggregate recovery and reuse	Can avoid use of virgin construction materials. May avoid emission of methane from associated organic content after landfilling and/or transport.
28	Energy recovery from screenings	May avoid emission of methane from associated organics after landfilling. Can recover energy but critically dependant on proportion of plastic vs organic but plastic pyrolysis may actually increase WaSC emissions from screenings.
29	Cellulose recovery and reuse	May allow capacity augmentation for certain site configurations (e.g. Where no PST). Recovered material can be recycled to replace fossil-based materials or digested to recover additional biogas.

No.	Description	Applicability within sector
30	Advanced AD - thermal hydrolysis	Produces more biogas than conventional AD. Expands treatment capacity with reduced capital assets than building new digesters. Balanced against increased energy (heat) demand for process.
31	Advanced AD - enzymatic hydrolysis (e.g. Monsal, HpH)	Produces more biogas than conventional AD. Expands treatment capacity with reduced capital assets than building new digesters. Balanced against increased energy (heat) demand for process.
32	Intermediate thermal hydrolysis (ITHP)	Can be a smaller THP because primary sludge is already digested, less heat demand than conventional THP.
33	Hydrothermal/supercritical sludge pre-treatments (e.g. carbonization, liquefaction)	Direct energy recovery, produce a c.60% dry solids hydrochar that can be autothermally combusted to recover energy. Produces a bio-crude that can be digested to recover biogas. Balanced against energy demand for process.
34	Codigestion	Can generate additional biogas using new or existing digester capacity to treat imported organic waste (e.g. food waste) simultaneously with sludge. Could generate more high-strength liquors that must be treated.
35	Pyrolysis (sludge or biosolids)	Recovers energy from sludge that is inaccessible via AD or AAD. Minimises residual solids for transport (e.g. to land). Generates a stable carbon biochar or ash that can be sequestered in soil or as a component of concrete.
36	Gasification (sludge or biosolids)	Recovers energy from sludge that is inaccessible via AD or AAD. Minimises residual solids for transport (e.g. to land). Generates a stable carbon biochar or ash that can be sequestered in soil or as a component of concrete.
37	Mainstream (cold) anaerobic treatment	Treats the whole wastewater carbonaceous load anaerobically to maximise biogas production and eliminate aeration energy
38	Carbon sequestration through biosolids to land	Can sequester a portion of biosolids' organic carbon in soils over an indeterminant amount of time. Also capable of substituting carbon-intensive manufactured fertilisers. Balanced against emissions (e.g. N_2O) associated with biosolids spreading on land.
39	Thickening and dewatering efficiency improvement (existing assets)	E.g. polymer optimisation/re-selection, blending of cake.
40	Enhanced mechanical dewatering (e.g. Bucher press, Volute)	Alternative technologies to conventional belts and centrifuges that offer a higher % dry solids in the dewatered sludge. Reduced emissions from sludge/biosolids transport. May be balanced against increased energy/polymer use.
41	Biodrying of biosolids	Uses heat from aerobic microbes to drive off water in biosolids without direct use of exogenous heat, e.g. from natural gas. Higher dry solids for reduced transport emissions and may offer reduced carbon emissions from biosolids storage and spreading (N_2O and CH_4). May be balance against energy for forced aeration.
42	Other low energy biosolids drying methods	Methods that use 'waste' heat or other exogenous/renewable heat source to dry sludge/biosolids and avoid use of natural gas. This could be 3rd party waste heat, heat from biogas Combined Heat and Power (CHP) engines, direct heat from biogas, solar heat energy or a combination of these.

No.	Description	Applicability within sector
43	Organomineral fertiliser products (e.g. CCm process)	Combines biosolids drying (transport, storage/spreading emissions), ammonia recovery (reduced load to WwTW & N_2O), and carbon capture (stabilise captured CO_2 from upgrading plant or CHP into a solid). This may be balanced against emissions once products are applied to land.
44	Sludge liquor ammonia recovery	Avoids return of ammonia load to WwTW & associated aeration energy & N_2O emission. Can generate a product that replaces manufactured fertiliser. Benefits may be balanced against an increased use of chemicals (pH swing) and/or heat (renewable or natural gas) and wider system impacts.
45	Sludge liquor phosphorus recovery	Avoids return of P to WwTW & associated embodied carbon of chemical (e.g. ferric) dosing or energy in EBPR. Can generate a product that replaces manufactured fertiliser. Must balance against chemicals (e.g. pH swing) and type of site.
46	Final Effluent Electrolysis	Can be used to create green hydrogen and a pure oxygen co-product that can be recycled to enhance aerobic treatment, including possibility of lower N_2O emissions. Depends critically on the source of electricity used to power the electrolyser.
47	Hydrogen from biogas/biomethane	Converts biogas/biomethane into biohydrogen that can be used as a zero-emission fuel. Opportunity to capture carbon from methane to make biohydrogen carbon negative. Balanced against some energy losses and wider system impacts from existing biogas applications.
48	Renewable fuel tanker (biomethane)	Lower emission transport of sludge and/or treated biosolids vs diesel.
49	Renewable fuel tanker (hydrogen fuel cell)	Zero emission transport of sludge and/or treated biosolids. Depends critically on the source of hydrogen.
50	Renewable fuel tanker (hydrogen internal combustion)	(Near) Zero emission transport of sludge and/or treated biosolids. Depends critically on the source of hydrogen
51	Renewable fuel tanker (Battery electric)	Zero emission transport of sludge and/or treated biosolids. Depends critically on the source of power used to charge batteries
52	Alternative fuel tanker	Substitutes diesel for a lower emission fossil fuel, e.g. CNG, biodiesel. Could reduce emissions versus equivalent transport using diesel
53	Microbial Fuel Cell	Generates renewable energy while treating COD in wastewater or liquor.
54	Biosolids (co)composting	Composting biosolids can stabilise nutrients to reduce N_2O emission and improve carbon sequestration when spread on land.
55	Advanced UV control	More energy efficient treatment to better manage dose control.
56	Activated sludge process optimisation	Optimisation of ASP through control and asset health
57	Return activated sludge control	Optimisation of RAS return to minimise pumping, maximise aeration efficiency
58	FOG recovery - pump stations/inlet	Recovers FOG at pumping stations and inlet. Reduces emissions associated with its treatment and can be used as feedstock in renewable energy production.
59	Rag-resistant pumping	Deragger pumps installed on network and at WwTW to reduce pump downtime, maintenance and downstream impacts.
60	Improved screening	Improved inlet works screening to safeguard downstream assets, reduce wear and tear and operational effort.

No.	Description	Applicability within sector
61	WTW sludge reuse as soil conditioner	Recycling of water treatment sludge by spreading it on land as soil conditioner. Could improve soil structure and provide organic matter.
62	GAC/filter media recovery from backwash	Recovery and return of Granular Activated Carbon (GAC) filter material that would otherwise be lost during filter backwashing. Reduces replenishment with virgin material
63	Carbon capture storage and utilisation	Capture of CO_2 following the combustion of biogas or natural gas in CHP engines, with the potential to use captured CO_2 within products.
64	Recycled steel	or use alternative materials instead of steel
65	Recycled aggregate for construction	Reuse of aggregate, sand, soil extracted onsite, at other sites or 3rd party sites within capital projects as an alternative to virgin materials
66	Digital twins	A digital representation of complex treatment trains or whole treatment works. Can be used to drive efficiency and associated emissions reduction but depends on the type of digital twin.
67	Nature based solutions - treatment wetlands for stormwater or enhanced nutrient removal (with augmentation only).	TW may offer lower carbon alternatives (though carbon balance/ sequestration not supported by evidence base for UK sector I don't think) than carbon and energy intensive treatment for stormwater, Nitrogen and Phosphorus.
68	Nature based solutions - SUDS as a low C technology to remove stormwater and reduce downstream, Water resources and sewage collection)	Separating stormwater may provide lower carbon solutions than continuing to convey and treat storm water and prevent storm spills.
69	Active network management	Improved analysis tools and data collection/usage to monitor water quality and losses in real-time to improve operational efficiency.
70	Real time optimisation of water source/ distribution selection	Use of existing and additional drinking water network flow and quality data and demand profiles/modelling to optimise water distribution and source utilisation.
71	Low carbon concrete	Concrete has a very high level of embodied carbon by mass. Specification changes to reduce embodied carbon in concrete may have a significant impact on Net Zero targets
72	Anaerobic digestion with combined heat and power	Produces renewable heat and power
73	Sewage sludge incineration	Can recover energy from sludge through combustion. Net Zero credentials will critically rely on whether combustion is autothermal (i.e. no natural gas use) and ability to control/mitigate direct emissions (e.g. N_2O)
74	Sewage sludge (co)combustion	Use of dried sewage sludge as an alternative to fossil fuels in commercial processes (e.g. cement kilns). Will critically depend on method used to dry sludge (fossil gas or renewable heat) and ability to control/mitigate direct emissions (e.g. N_2O)
75	Effluent heat recovery - off site	Products renewable heat
76	Heat recovery - on site	Enhanced renewable heat recovery on site
77	Biomethane to grid	Upgrading biogas into biomethane as a natural gas substitute and injection into the national gas grid. Can reduce emissions versus combustion of equivalent quantity of natural gas.
78	Install CHP engines	Install Combined Heat and Power engines to allow generation of renewable electricity and heat from biogas at sludge treatment centres.

No.	Description	Applicability within sector
79	Reduce flaring	Reduce the quantity of biogas that is flared and therefore not beneficially used.
80	Micro-renewables (e.g. solar /wind or outfall hydro) for treatment and distribution	Small scale renewable electricity production.
81	Energy sub-metering and management	Improved metering to better understand and manage use.
82	Procurement of green electricity	Purchase of grid electricity through a Green tariff
83	Power purchase agreements (e.g. solar/wind)	With on-land renewables, W/WaSC non-reg owned or other renewables.
84	Hydroelectric turbines	In-works or small scale turbines to recover energy across existing hydraulic gradients.
85	Heat and lighting control and replacement	Smart control of heat and lighting in buildings and replacement of energy inefficient components.
86	High efficiency motors	Contentious, may gain 1-2% but require replacing whole motor. Rarely viable on energy savings but could be part of new asset policy.
87	High efficiency transformers	Use of high efficiency transformers to realise energy savings.
88	Asset health and maintenance	Proactive rather than reactive maintenance. Not direct net zero technology.
89	Asset standard challenge for Net Zero solutions	Revision or review of companies' asset standards to allow or preference methods or materials with reduced embodied carbon.
90	Pumping efficiency	80% energy pumping across WaSCs. Should have pump efficiency programme - many have these; testing large pumps - upgrading. Could be greatest materiality. Could recut impellors, optimise pumps. Network pumping efficiency - could remove booster PS.
91	Opportunities to minimise static head pipework in service reservoirs	Alleviate hydraulic constraints/minimise pumping requirements through optimisation of SR levels and control.
92	Innovative network solutions to minimise system heads	System analysis to improve hydraulic profiles through dynamic modelling/network review.
93	Alum sludge use in cement manufacture	Incorporation of sludge comprising alum-based coagulant as a cementitious material as an alternative to virgin materials with comparably high embodied carbon.
94	Clean DO probes	Maintenance of DO probes for efficient monitoring and control of forced aeration systems
95	Grit/cleaning removal from ASPs/ digesters	Periodic removal of built-up grit etc in activated sludge or anaerobic digestion tanks that can impede efficient operation
96	High efficiency diffusers for ASPs	Air blowing represents a significant electrical demand at wastewater treatment works with forced aeration activated sludge processes. Use of efficient diffusers could reduce the specific power demand of secondary treatment versus less efficient diffuser models.
97	Covered forced aeration processes with headspace air abatement	Covering of activated sludge processes or liquor treatment plants using forced aeration and abatement of the headspace gas prior to emission to atmosphere to reduce or eliminated N_2O emissions

Table A 2. Technologies not progressed to the mid-list based on their TRL assessment.

Technology or solution	Common name	TRLv	Rationale
Mainstream nutrient recovery (chemical, e.g. ion exchange)	Mainstream nutrient recovery	6	Ion exchange technologies have been piloted as part of SMART Plant project, where they were classified as TRL 6. They continue to be piloted by Cranfield University and Severn Trent Water. Such technologies will be examined in the lab as part of the Thames Water led, Ofwat innovation project 'Transforming the Energy Balance of Wastewater Treatment'
Dissolved methane recovery - membrane	Mainstream CH_4 recovery	6	Membrane technologies are being piloted by Cranfield University and Severn Trent Water to recover dissolved methane from AnMBR effluent. While degas membranes systems are commercially available off the shelf, these are not specifically designed for this application. Their TRL is judged to be below 7.
Mainstream deammonification	Mainstream deammonification	6	Expected to be below TRL 7
Biocatalyst technologies	Biocatalysts	6	Biocatalysts will be investigated as part of an Ofwat innovation funded project led by Severn Trent Water and supported by Jacobs. These are judged to be below TRL 7 at this time.
Final Effluent Electrolysis	FE electrolysis	5	Electrolysis of final effluent to produce hydrogen comprises part of the Ofwat innovation funded 'Triple Carbon Reduction' project led by Anglian Water and supported by Jacobs.
Hydrogen from biogas/biomethane	Hydrogen from biogas	5	Several technology companies and research groups are studying the production of hydrogen from methane, using biogas or biomethane as a feedstock. In the UK these include the Ofwat innovation funded HyValue project, led by Welsh Water and a bid to BEIS' hydrogen from biomass competition led by United Utilities in partnership with innovative technology company Levidian and Jacobs. However, the technologies in question are judged to be below TRL 7, particularly applied to biogas.
Microbial Fuel Cell	MFC	6	Microbial Fuel Cells have been piloted in niche operations, such treatment and energy production from source separated urine at public events. However, they are judged to be below TRL 7 for applications at wastewater treatment works.
Covered forced aeration processes with headspace air abatement	Covered forced aeration processes with headspace air abatement	6 or below	Some trials planned but not yet technically ready

Table A 3. Technologies not shortlisted and rationale on the basis of the 80/20 rule – that 80% of emissions are likely to come from 20% of processes.

Technology or solution	Common name	Rationale
Biological phosphorus removal through EBPR	EBPR	Unlikely to be applicable during AMP8 due to current asset base in England and Wales. However, may be individual cases where it is applicable.
Simultaneous nitrification and denitrification as alternative secondary treatment	Simultaneous nit/denit	Unlikely to be AMP8 timescale given majority asset base in England and Wales which largely does not support biological denitrification at present and lack of science-base for the efficacy of SND systems to offer sufficient quality and GHG emissions outcomes (whether continuous flow or batch systems). May be an opportunity for research in individual cases supported by detailed monitoring and trials.
Augmentation processes - to intensify secondary biological treatment through increased SRT or improved settlement through granulation.	Bio-augmentation	Net zero benefit unclear and unlikely to apply for majority of assets in England and Wales as most relevant to process conditions afforded by biological nutrient removal configurations within ASPs to allow the necessary process feeding conditions to be met to support granule development in continuous flow systems; evidence for batch systems at full scale very limited with regards to GHG emissions. IFAS and other augmentation processes or other means (e.g. significant capacity increase of tankage) to increase SRT are not likely to be employed by companies for other AMP8 drivers.
Augmentation processes - to intensify secondary biological treatment through increased SRT or improved settlement through granulation.	Bio-augmentation	Net zero benefit unclear and unlikely to apply for majority of assets in England and Wales.
UV LED disinfection	UV LED disinfection	Any Net Zero benefit likely to be marginal given asset base. Only 11% of load treated at WwTW with a UV consent based on PR19 data for the sector[98] and supported by more recent annual performance report data of companies.
Algae photobioreactor phosphorus removal	Algae photobioreactor	Currently applicable only to very small sites. Any Net Zero benefit likely to be marginal. Fate of algal biomass not demonstrated.
P removal by natural/waste-derived adsorbents (e.g. steel slag)	Natural/waste-derived P removal	Likely applicable to smaller/rural sites. Equivalent quantities of ferric chemical and associated embodied carbon likely to be small. Any Net Zero benefit likely to be marginal i.e. not one of the 20% of processes causing 80% of emissions as per the Pareto Principle.
Recycled water treatment sludge (not to land)	Ferric WTW sludge reuse	Not demonstrated in UK. Possible regulatory barriers around End of Waste. Any Net Zero benefit likely to be marginal.
Sidestream deammonification	Sidestream deam-monification	More used to benefit capacity at works. Strong evidence N_2O emissions are greater through intensive sidestream treatment.

98 https://www.ofwat.gov.uk/wp-content/uploads/2019/09/FM_WWW1-APR-2018-19-update.xlsx

Technology or solution	Common name	Rationale
Mains cleaning	Mains cleaning	Net zero benefit unclear/marginal i.e. not one of the 20% of processes causing 80% of emissions as per the Pareto Principle
Rising main non-return valve maintenance	Rising main valve maintenance	Net zero benefit unclear/marginal i.e. not one of the 20% of processes causing 80% of emissions as per the Pareto Principle.
Odour control optimisation	Optimised odour control	Not considered to be a primarily Net Zero technology.
Grit/aggregate recovery and reuse	Grit recovery	Any Net Zero benefit likely to be marginal, emissions from landfilling organic component relatively small. Quantities relatively small on scale of construction.
Energy recovery from screenings	Energy from screenings	Likely not ready for AMP 8. Plastic content may introduce and increase Scope 1 emissions. Fate of bio-oil not established.
Cellulose recovery and reuse	Cellulose recovery	Net Zero benefit not sufficiently proven as a result of direct selective cellulose recovery in primary treatment. Needs to be further evidenced as detailed in Section 3.2.1
Hydrothermal/supercritical sludge pre-treatments (e.g. carbonization, liquefaction)	HTC or HTL	Commercial scale applications to sludge only now emerging outside of the UK[99]. UK already has high density of Thermal Hydrolysis, unclear how HTC or HTL fit to this treatment train or relative energy requirements.
Mainstream (cold) anaerobic treatment	Mainstream anaerobic	Unlikely to be ready for UK sector in AMP 8. In particular the removal of nutrient load in low carbon anaerobic effluent needs to be demonstrated.
Carbon sequestration through biosolids to land	C sequestration biosolids	Almost all biosolids cake already recycled to land in England and Wales. Carbon benefits difficult to measure and are unlikely to be additional.
Thickening and dewatering efficiency improvement (existing assets)	Dewatering efficiency	Any Net Zero benefit likely to be marginal, i.e. not one of the 20% of processes causing 80% of emissions as per the Pareto Principle
Enhanced mechanical dewatering	Advanced mech dewat	Any Net Zero benefit likely to be marginal or very site specific enhanced performance in % dry solids[100]. May increased energy and polymer use.
Organomineral fertiliser products (e.g. CCm process)	Co-composting (sludge)	Unlikely to further benefit transport emissions compared to dried pellets or granules (i.e. without additional of manufactured fertiliser inputs). Permanence of any captured carbon needs further evidence.
Sludge liquor phosphorus recovery	P recovery (liquors)	Not primarily a Net Zero technology. Needs Bio-P treatment in WWN+ to be effective[101]. At best, <10% of P load is expected to be treated by Bio-P (see Section 3.2.2). Therefore has limited applicability. End of Waste status for recovered struvite uncertain. Any carbon benefit from end-use would likely fall outside water company boundary.
Renewable fuel tanker (hydrogen fuel cell)	Tanker (H2 FC)	Unlikely to be ready for AMP8.
Renewable fuel tanker (hydrogen internal combustion)	Tanker (H2 ICE)	Not ready for next AMP

99 https://www.terranova-energy.com/en/technology/

100 https://conferences.aquaenviro.co.uk/wp-content/uploads/sites/7/2017/03/Ester-Rus-Dewatering.pdf

101 https://www.vesiyhdistys.fi/wp-content/uploads/2019/12/GWRCPhosphorusCompendiumFinalReport2019-March-20.pdf

Technology or solution	Common name	Rationale
Renewable fuel tanker (Battery electric)	Renewable fuel tanker (Battery electric) Tanker (BEV)	Might be ready for next AMP but unclear if supporting infrastructure will allow full potential in next AMP. Electricity must be from an additional renewable source.
Transport CNG/LNG fuelled	Tanker (CNG/ LNG)	Carbon benefit relatively marginal versus diesel. Could lock-in use of fossil fuels for longer.
Biosolids (co)composting	Co-composting	Carbon benefits likely to sit outside of companies' carbon reporting boundaries. Increased transport emissions due to greater volumes transported. Regulatory barriers around End of Waste.
Process aeration optimisation	ASP optimisation	Should take place as part of business as usual to maintain operability.
Should take place as part of business as usual to maintain operability.	RAS control	Should take place as part of business as usual to maintain operability.
Should take place as part of business as usual to maintain operability.	FOG recovery	Benefit might be marginal considering pump stations represent a relatively diffuse source. Improved recovery at inlet may require energy intensive Dissolved Air Flotation (DAF) or Chemical Enhanced Primary Treatment (CEPT), that have operational and embodied carbon trade-offs.
Rag-resistant pumping	Rag resistant pumps	Very common throughout the sector already. Possibly one company that could shift a large proportion of its sludge in this direction but benefits already largely realised for the sector
Improved screening	Improved screening	Should take place as part of business as usual to maintain operability.
WTW sludge reuse as soil conditioner	WTW sludge to land	Nutrient and organic matter content and overall volumes low compared to biosolids. Any substitution of manufactured fertiliser or carbon sequestration likely to be marginal.
GAC/filter media recovery from backwash	Filter media recovery	Already widely used, little opportunity for additional benefit.
Carbon capture storage and utilisation	CCUS biogas upgrading	Can be some benefit but Almost all sludge already digested and most biogas already sent to CHP. Flaring needs to be retained as a safety measure.
Recycled steel	Recycled steel	Energy recovery relatively marginal. Large N_2O emissions.
Recycled aggregate for construction	Recycled aggregate	Any Net Zero benefit likely to be marginal i.e. not one of the 20% of processes causing 80% of emissions as per the Pareto Principle.
Digital twins	Digital twins	Can depend on the nature of the Digital Twin but already being done and not a Net Zero technology in itself.

Technology or solution	Common name	Rationale
Active network management	Active network management	Net Zero benefit unclear i.e. not one of the 20% of processes causing 80% of emissions as per the Pareto Principle.
Real time optimisation of water source/ distribution selection	Real time optimised water distribution	Net zero benefit unclear/marginal . i.e. not one of the 20% of processes causing 80% of emissions as per the Pareto Principle.
Anaerobic digestion with combined heat and power	AD and CHP	Already implemented at large scale, little opportunity for additional benefit.
Sewage sludge incineration	Incineration	Not considered a Net Zero technology. Existing circularity and associated carbon benefit will be lost. Net energy recovery might be marginal, especially if partial sludge drying required. Emission of N_2O is likely to be large[102] and may counter-balance any carbon benefit.
Sewage sludge (co) combustion	Co-combustion	Regulatory complexity may restrict its deployment. Net Zero potential critically dependant on how sludge is dried and whether fossil gas is used. Emission of N_2O is likely to be large (as for incineration) and may counter-balance any carbon benefit.
Effluent heat recovery - off site	Heat recovery (offsite)	Low scale of deployment to date and carbon benefits unlikely to fall within water company reporting boundaries.
Install CHP engines	CHP	Already in widespread deployment. Little opportunity for further benefit.
Reduce flaring	Reduced flaring	Relative opportunity expected to be minor i.e. not one of the 20% of processes causing 80% of emissions as per the Pareto Principle
Carbon capture and storage from CHP exhaust gas.	CCUS CHP	Not likely to be ready for AMP8 installation; end use and permanence of carbon storage currently unclear/not supported by required infrastructure.
Micro-renewables (e.g. solar /wind or outfall hydro) for treatment and distribution	Micro-renewables	Ready opportunities likely already exploited. Further benefits likely to be relatively marginal
Energy sub-metering and management	Energy sub-metering management	Likely already done as part of business as usual.
Procurement of green electricity	Green electricity	Green tariffs are at the foot of renewable electricity procurement hierarchies and should only be used once other options above in the hierarchy have been fully explored (see Section 3.2.14). They may present issues of additionality within some Net Zero reporting frameworks.

102 https://www.ipcc.ch/site/assets/uploads/2018/03/5_Waste-1.pdf

Technology or solution	Common name	Rationale
Hydroelectric turbines	Hydroelectricity	Limited application or readily available opportunities already exploited.
Heat and lighting control and replacement	Heat and light control	Likely already implemented at scale, giving limited opportunity for further benefit.
High efficiency motors	High efficiency motors High efficiency motors	Net zero benefit unclear/insufficient information.
High efficiency transformers	High efficiency transformers	Net zero benefit unclear/insufficient information.
Asset health and maintenance	Asset health and maintenance	Linked to other process optimisation solutions but in itself not considered a net zero technology.
Asset standard challenge for NZ solutions	Challenging asset standards	Could support development of Net Zero solutions, e.g. low carbon concrete but not considered a Net Zero technology in itself.
Opportunities to minimise static head pipework in service reservoirs	Minimise static head pipes in service reservoirs	Net zero benefit unclear/insufficient information.
Innovative network solutions to minimise system heads	Innovative minimised system heads	Net zero benefit unclear/insufficient information.
Alum sludge use in cement manufacture	WTW sludge in cement	Limited scale of opportunity and potential issues with obtaining End of Waste status. Design codes and asset standards would also likely need to be developed. This restricts applicability in the next AMP.
Clean DO probes	Clean DO probes	Should take place as part of business as usual to maintain operability.
Grit/cleaning removal from ASPs/digesters	Grit removal from ASPs & digesters	Grit removal from ASPs & digesters

Table A 4. Heatmap of technology/solution scored performance within each weighted scenario. Technologies and solutions are ordered based on their total cumulative relative score across all scenarios. Cells are colour coded based on their relative scored position.

Technology or solution / Scenario score ->	Decarb max	Economy plus	Minimal disruption	Max confidence	Total
CH_4 monitoring & mitigation	1.00	1.00	1.00	0.93	3.93
PPAs	0.94	0.94	0.94	1.00	3.82
Process optimisation for N_2O reduction	0.91	0.91	0.91	0.85	3.58
AAD EH or APD	0.84	0.85	0.94	0.91	3.53
Vacuum CH_4 recovery	0.95	0.87	0.91	0.81	3.54
Pump efficiency	0.87	0.88	0.92	0.86	3.52
Real-time N_2O control	0.90	0.91	0.86	0.84	3.51
Low-energy drying (sludge)	0.87	0.88	0.84	0.90	3.48
AAD THP	0.83	0.84	0.89	0.90	3.46
Tanker (biomethane)	0.86	0.87	0.83	0.89	3.45
ITHP	0.82	0.84	0.92	0.86	3.43
Leakage reduction & Water efficiency	0.91	0.83	0.87	0.81	3.41
Codigestion	0.91	0.87	0.83	0.81	3.41
Biodrying (sludge)	0.86	0.87	0.83	0.81	3.37
Conversion to nit/denit	0.80	0.82	0.82	0.88	3.33
MABR	0.84	0.81	0.86	0.79	3.30
Stormwater separation & treatment	0.86	0.79	0.87	0.77	3.28
Heat recovery (onsite)	0.79	0.81	0.81	0.79	3.19
Gasification/pyrolysis (sludge)	0.83	0.76	0.76	0.78	3.12
Biomethane to grid	0.74	0.72	0.72	0.82	2.99
N stripping (liquors)	0.76	0.78	0.69	0.76	2.98

Appendix B. Literature Review

We note the deliverables from this project must support your benchmarking and evaluation of plans at PR24 – so information integrity and reliability is key. To ensure integrity and reliability of information gathered through literature review, a tiered approach to sourcing data was deployed, prioritising the best sources with highest priority first (Table A 5.

Table A 5. Prioritised list of literature source types considered for cost and carbon assessments.

Priority	Source description
1	Recent disaggregated out-turn cost and benefit data – for example recent cost benefit assessment in the Danish water sector around resource recovery for net zero and circular economy.
2	Academic or other peer reviewed papers for technologies or interventions which have been applied in the UK or elsewhere (e.g. global scientific studies on process emissions and our ongoing work developing a Good Practice Guide on the subject for UKWIR).
3	Publicly available case studies, papers or conference presentation material (e.g. on Nature Based solutions implemented in other parts of the world).
4	Supplier provided data with Jacobs' interpretation based on engineering principles (e.g. for energy efficiency technologies in the market).
5	Calculations from industry information (e.g. life cycle analysis case studies, calculations on embodied emissions from the delivery of concrete assets made from base data on materials quantities).
6	Other sources of evidence.

Where information is not available (most likely for technologies which are immature / have not been implemented at scale and in many cases for the carbon life cycle impacts), we have applied engineering judgement and semi-quantitative assessment.

Table A 6. Prioritised list of literature source types considered for cost and carbon assessments.

Innovation Competition	Technology	Considered to be a Net Zero technology for longlist?
Water Breakthrough Challenge 1	Alternative approaches to phosphorus removal on rural wastewater treatment works	Yes
	CatchmentLIFE	No
	Enabling Whole Life Carbon Design	Yes – enabling method only
	Industrial Symbiosis	No
	Leak Detection using Dark Fibre	Yes
	Organics Ammonia Recovery	Yes
	Reservoir water community monitoring for algal associated risk assessment	No

Innovation Competition	Technology	Considered to be a Net Zero technology for longlist?
Water Breakthrough Challenge 1	Seagrass Seeds of Recovery	No
	Smarter Tanks to build a resilient network	No
	Supporting customers in vulnerable circumstances	No
	UK Water Sector Innovation Centre of Excellence (CoE)	No
Innovation in Water Challenge (IWC)	CaSTCo: Catchment Systems Thinking Cooperative (CaSTCo)	No
	Artificial Intelligence of Things Enabling Autonomous Waste Catchments	No
	Flexible local water supply schemes pilot	No
	Transforming the energy balance of wastewater treatment	Yes
	Triple Carbon Reduction	Yes
	AI & Sewer Defect Analysis	No
	Water neutrality at NAV sites	Yes
	Transforming Customers' Lives: Integrated Pathways to Fair and Sustainable Water (FAIR WATER)	No
	Safe Smart Systems – Embedding resilience for the future through automation and artificial intelligence	Yes
Water Breakthrough Challenge Catalyst Stream	HERU for Screenings	Yes
	Catalysing a NET-ZERO future	Yes
	Defusing the nitrate timebomb	No
	Designer Liner	No
	Pipebots for rising mains	No
	Support For All	No
	SuPR Loofah (Sustainable Phosphorus Recovery)	Yes
	Tap Water Forensics	No
	Sub-Seasonal Forecasting to Improve Operational Decision Making	No
	Incentivising community-centric rainwater management	No
	Unlocking bioresource market growth using a collaborative decision support tool	No
	Unlocking digital twins	No
	Water Quality As-A-Service Treatment-2-Tap	No

Innovation Competition	Technology	Considered to be a Net Zero technology for longlist?
Water Breakthrough Transform Stream	CHP exhaust carbon capture and utilisation (CECCU)	Yes
	NLRTC (National Leakage Research and Test Centre	Yes
	Managing Background Leakage	Yes
	SENECA (Sludge, Energy, Nutrients, Environment, Carbon & Agriculture)	Yes*
	HyValue - Hydrogen from Biogas	Yes

*this project was offered partial funding for its initial phase. The partners are considering this offer.

Appendix C. MCA

Table A 7. Description and score ranges used for metrics within the MCA.

Scoring category	Description	Score range
Decarbonisation hierarchy	Technology categorised based on recognised best practice for GHG management hierarchy, including Ofwat guidance and scored accordingly.	1-5
Feasibility	Feasibility for UK water sector, including applicability to prevalent existing technologies, ways of working and regulation.	0-3
Scalability	Scalability. Includes the cost, resource and personnel requirements, and potential impact on net emissions. We will seek to quantify the potential decarbonisation impact of the technology if deployed at the fullest possible scale.	0-3
Decarbonisation potential	Likely scale of net carbon benefit, taking into account any trade-offs, energy use or carbon emitted through use of the technology.	0-3
Cost and resources	Technology, solution or intervention cost and resource requirements, taking into account the Pareto Principle (80% of consequences come from 20% of causes).	0-3
Scale of use in UK	Readiness of given technology, solution or intervention for full and working operation in the UK.	0-3
Scale of use outside UK	Readiness of given technology, solution or intervention for full and working operation outside the UK.	0-3
Synergies	Potential for the suggested technology, solution, or intervention to work in tandem with another technology, solution, or intervention to achieve further solutions (e.g. increased efficiency, less waste).	0-3
Freedom from conflicts	Avoiding impact on outcomes of other suggested technologies (e.g. use of waste heat already consumed in the wider system).	0-3
Data confidence	Reliability of cost and carbon information available at time of review. Literature judged via an information resource hierarchy.	0-3

Table A 8. Scoring guidance used for metrics in the MCA

Scoring category	Scoring guidance
Decarbonisation hierarchy	1 – Compensate – Offsets 2 – Compensate – Sequestration/ Recovery & reuse 3 – Substitute 4 – Reduce 5 – Eliminate
Feasibility	0 - Not feasible, or unlikely to be feasible due to intractable difficulties 1 - Likely to be feasible only with significant regulatory, cultural, technological or other advancement 2 - Likely to be feasible with limited, realistic advancement in above areas 3 - Likely to be feasible with minimal or no advancement
Scalability	With technology at its most developed: 0 - No or almost no potential to scale 1 - Applicability limited to select few circumstances 2 - Applicable to appreciable fraction of sector 3 - Applicable across entire sector
Decarbonisation potential	0 - No effect or adverse effect 1 - Minimal effect 2 - Some effect 3 - Important, strategic effect
Cost and resources	Compared to current business as usual, and for replacement technologies assuming that a natural asset lifecycle is followed: 0 - Likely to be prohibitively expensive 1 - Likely to be costly and noticeably add to customer bills if implemented at scale 2 - Costs likely to be borne as part of business as usual if implemented at scale 3 - No cost or cost negative
Scale of use in UK	0 - Not used in water sector, no or little use in other sectors 1 - Not used in water sector, but used extensively in other sectors 2 - Some use in water sector 3 - Extensive use in water sector
Scale of use outside UK	0 - Not used in water sector, no or little use in other sectors 1 - Not used in water sector, but used extensively in other sectors 2 - Some use in water sector 3 - Extensive use in water sector
Synergies	0 - None identified 1 - Tenuous link at best to other drivers 2 - Incidental link at best, technology might be installed to achieve another driver in limited cases 3 - Strong link to other drivers, technology likely to be installed to achieve other driver
Freedom from conflicts	0 - Strong conflict/s with other important objectives. 1 - Some conflicts which can be accepted or managed with a proportionate effort. 2 - Very limited foreseeable conflicts 3 - No known conflicts
Data confidence	0 - Limited information available, unreliable sources 1 - Some reliable information available but falls below standard required for high-level benchmarking 2 - Information considered sufficient for high-level benchmarking 3 - Extensive, detailed and reliable information available

Table A 9. Multi Criteria Analysis (MCA) bare scores and accompanying rationale.

Technology or solution	Feasibility	Scalability	Decarbonisation potential	Cost and resources requirements	Scale of current use in the UK	Scale of current use outside the UK	Synergies with other outcomes	Freedom from conflicts with other outcomes	Certainty of available information
CH_4 monitoring & mitigation	3 technologies available	3 Most applicable for STWs with biosolids treatment but these represent most load/ impact	3 reduction of fugitive CH_4 emissions	2 technology available at reasonable cost, tank covering, enclosure to capture methane will require capital	2 use outside of sector plus existing reactive work in UK though quantification lacking	3 Used outside of UK, e.g. in Denmark	3 Can improve energy recovery yield for CHP or biomethane	3 No foreseeable conflicts	2 information from studies but widespread in the water sector
PPA's	2 existing examples of onsite renewables and private wires to adjacent renewables generation. Could be outbid by gov or 3rd parties.	2 applicable where sufficient space onsite. Can invest in renewables generation virtually anywhere	2 electricity one of largest emissions in water and in wastewater. PPA & onsite renewables ensure renewables are additional and not removing availability from other industries or users, e.g. just using green tariffs. Without storage, there will be occasions where grid electricity will be required, e.g. without wind or sun. Carbon benefit will decrease relative to grid electricity assuming UK grid decarbonises independently.	1 requires upfront capital investment. Payback related to the cost of grid electricity.	2 existing examples of onsite renewables and private wires to adjacent renewables generation.	2 Likely similar to the UK. Might not have restrictions around gaining revenues through appointed businesses.	1 could free up some biogas for more biomethane.	2 could occupy space or divert funds away from other projects	3 these are now established. Some uncertainty of rate at which UK grid will decarbonise independently
Process optimisation for N_2O	2 process parameters such as DO can be easily controlled to optimise N_2O	2 applicable at ASPs with functional process control and ability to alter SPs but not trickling filters	3 reduce N_2O emissions, may reduce or increase aeration energy	2 instrumentation available at reasonable cost but short lifetime (frequent replacement of probe)	0 few water companies monitoring only not improving process performance	1 emerging evidence	2 potential for energy efficiencies, process stability	3 not known conflict	3 certainty of technology to provide mitigation solution from published work

Technology or solution	Feasibility	Scalability	Decarbonisation potential	Cost and resources requirements	Scale of current use in the UK	Scale of current use outside the UK	Synergies with other outcomes	Freedom from conflicts with other outcomes	Certainty of available information
Vacuum CH^4 recovery	3 sits in the return line similar to an LTP but for dissolved gas	2 applicable at STCs with AD and AAD	3 energy needed to strip methane, claims energy positive if methane is sent to CHP	1 May be cost neutral in terms of additional methane yield versus cost to run plant but capital outlay greater than other mitigation options for process emissions	1 Pilot trials with Welsh/ Northumbri-an/ Scottish	1 similar to UK	3 maximise CHP & biomethane output, reduce methane emitted to atmosphere	3 few conflicts expected, possibly struvite scaling	1 Limited supplier information only
Process energy efficiency	3 widely implement-ed in various forms by companies	2 applicable at medium – large sites – majority of bands/load	2 offers energy efficiency and direct emissions reduction	2 may require systems integration and site controls interrogation	2 Widescale programmatic implemen-tation across companies	2 often implemented	2 may offer synergies and improved process function	2 unlikely to conflict, could impact on process emissions.	2 multiple case studies exist
Real-time N_2O control	1 being done in case studies but not continuously	2 Applicable across ASPs but not trickling filters. Automation required, workforce trained.	3 reduce N_2O emissions, may reduce or increase aeration (grid) energy	2 instrumentation available at reasonable cost but short lifetime (frequent replacement of probe)	0 few water companies real time monitoring only not controlling/ mitigating N_2O	1 only in case studies	2 potential for energy efficiencies, process stability	3 not known conflict	3 certainty of technology to provide mitigation solution from published work
AAD EH or APD	3 numerous Monsal HpH plants in UK	2 applicable to most AD sites, especially if they struggle for capacity, larger footprint than THP	2 likely lower embodied carbon as increases capacity of existing digesters, increased biogas yield but less than THP, less likely than THP to need NG support	2 costs of new assets but likely lower than for new digester capacity plus increase biogas revenues possible	3 Numerous plants in the UK	3 numerous plants	2 increase CHP or biomethane output, mustn't lead to increased use NG	2 less likely to compete with sludge drying, NH_3 stripping for waste heat than TH	3 Processes are well established in the UK, yielding reliable data

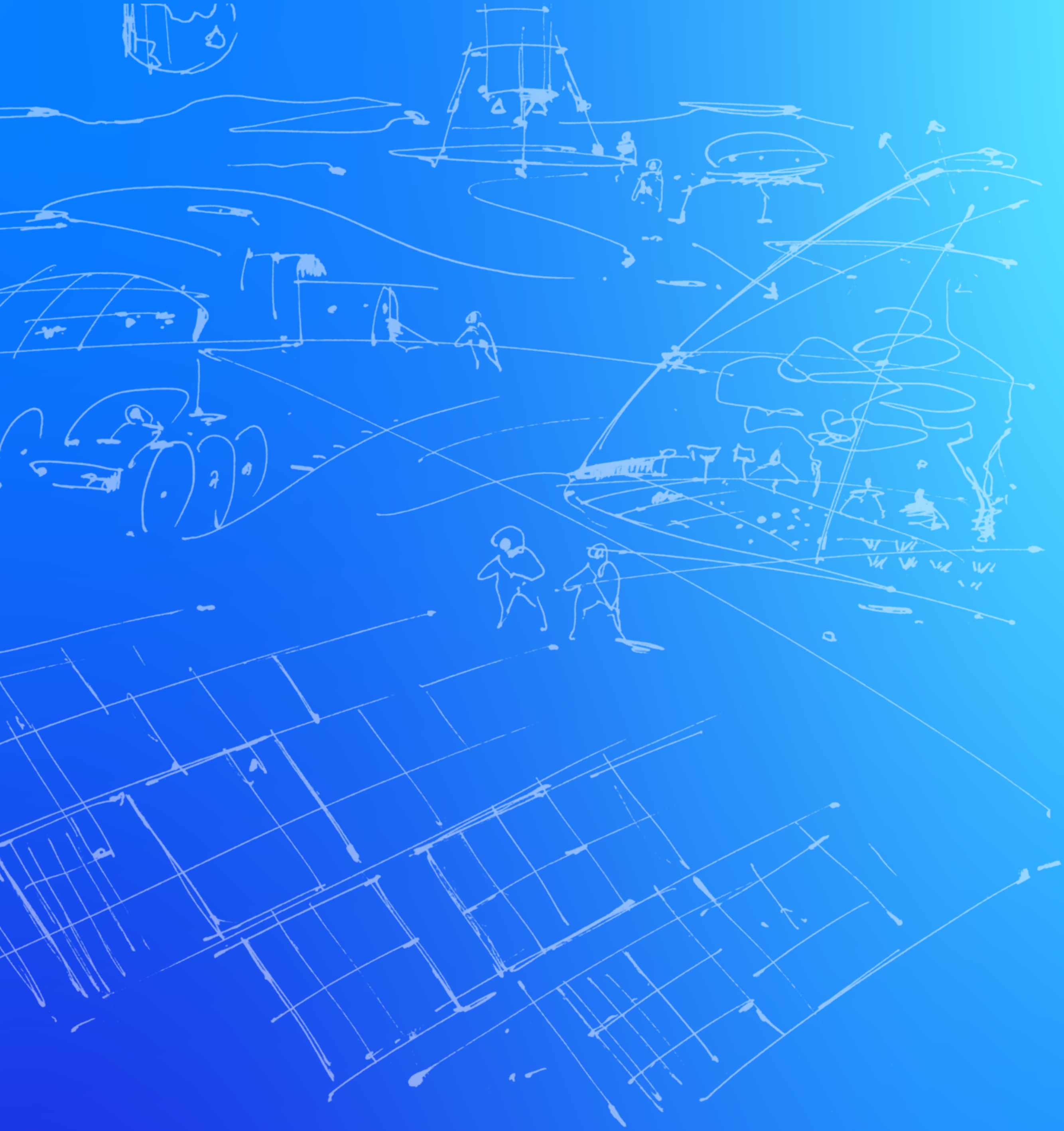
Technology or solution	Feasibility	Scalability	Decarbonisation potential	Cost and resources requirements	Scale of current use in the UK	Scale of current use outside the UK	Synergies with other outcomes	Freedom from conflicts with other outcomes	Certainty of available information
Low-energy drying (sludge)	2 some history of therma drying methods	2 will require surplus waste heat. May already be in use, e.g. THP, NH_3 stripping	2 could reduce transport without using NG for drying. Must use waste heat and avoid wider system impacts	2 higher throughput and lower footprint than biodrying	2 belt dryers in Ireland and Isle of man, trials in Thames (paddle)	3 numerous reference examples	2 can reduce transport by increasing %DS. Could be low energy way to dry sludge prior to pyrolysis/ gasification. Could stabilise carbon for better sequestration in soil	1 Competition for waste heat (THP, NH_3 stripping) or reduction in CHP biomethane from biogas	3 Jacobs currently doing review
ITHP	3 different config of established THP tech	2 applicable to most AD sites, especially if they struggle for capacity	2 less about digester capacity than THP, but more gas and likely less NG support needed	2 costs of new assets but likely lower than for new digester capacity plus increase biogas revenues possible	3 Studied in the UK and possibly implemented at least one site	2 Studied outside the UK	2 increase CHP or biomethane output, mustn't lead to increased use NG	2 if less heat needed then maybe less competition with sludge drying, NH_3 stripping	2 Process has been studied in the UK, yielding data
Tanker (biomethane)	2 trucks need to be based near biomethane plant or biomethane refuelling station	2 trucks need to be based near biomethane plant or biomethane refuelling station	2 large decarb vs diesel but transport relatively small GHG contributor	2 New trucks can be phased in, new biomethane plants might be expensive & access to subsidy tricky	2 some UK examples but biomethane mostly injected into gas grid currently	2 Many examples but not universal	2 biogas upgrading to biomethane	1 biogas used in vehicles cannot be used to generate renewable electricity and heat	3 good UK studies
AAD EH or APD	3 numerous Monsal HpH plants in UK	2 applicable to most AD sites, especially if they struggle for capacity, larger footprint than THP	2 likely lower embodied carbon as increases capacity of existing digesters, increased biogas yield but less than THP, less likely than THP to need NG support	2 costs of new assets but likely lower than for new digester capacity plus increase biogas revenues possible	3 Numerous plants in the UK	3 numerous plants	2 increase CHP or biomethane output, mustn't lead to increased use NG	2 less likely to compete with sludge drying, NH_3 stripping for waste heat than TH	3 Processes are well established in the UK, yielding reliable data

Technology or solution	Feasibility	Scalability	Decarbonisation potential	Cost and resources requirements	Scale of current use in the UK	Scale of current use outside the UK	Synergies with other outcomes	Freedom from conflicts with other outcomes	Certainty of available information
Biodrying (sludge)	1 composting as a treatment or post treatment not common in UK. May need to be done in air extracted buildings with large footprint	3 may be applicable to most digested sludges, not reliant on waste heat source	2 could reduce transport without using NG for drying. There are emissions from composting	1 could be costly if enclosed but chance for co-funding	0 not done in the UK	3 Aerated static pile, aerated in vessel in US, tunnel composting in Netherlands	2 can reduce transport by increasing %DS. Could be low energy way to dry sludge prior to pyrolysis/ gasification. Could stabilise carbon for better sequestration in soil	3 can be done at end of treatment. Some power needed for aeration	3 Jacobs currently doing review
Conversion to nit/denit	2 widespread	2 can be implemented but will require additional tankage and embodied carbon or augmentation options.	2 reduce N_2O emissions, may reduce or increase aeration energy; may require Scope 3 embedded emissions increase	1 May require additional tankage at some sites, not at others. Instrumentation available at reasonable cost	2 used for STWs with TN permits	2 used; emerging evidence for N_2O application	1 Reduced oxygen demand though may require external carbon	2 possibly impacts around sludge production, carbon emissions from replacement of technology (embodied)	3 widespread
MABR	2 used as IFAS to expand capacity in existing lanes	1 use where limited headroom capacity at AS works	2 reduce aeration energy, reduce N_2O production, reduce need to pour more concrete, WLC analysis required for capital plant	2 retro fit into existing aeration lanes	1 limited to individual pilots and 1 or 2 planned at full scale	2 greater use in Denmark at scale	2 synergy with H2 production by electrolysis but developmental	2 possibly impacts around sludge production, energy recovery and C seq from biosolids	2 some good data from Denmark & links with OxyMem on Ofwat innovation projects

Technology or solution	Feasibility	Scalability	Decarbonisation potential	Cost and resources requirements	Scale of current use in the UK	Scale of current use outside the UK	Synergies with other outcomes	Freedom from conflicts with other outcomes	Certainty of available information
Water efficiency	2 feasible across water cycle – from customer usage, water efficient devices through to distribution and on-site efficiencies	2 applicable to most assets though granular data may be lacking to scale/ implement	2 likely lower operational efficiency; significant opportunity in customer homes for water efficiency, reduced hot water heating (circa 4-5% UK GHG emissions)	1 large scale implementation costly.	2 many UK examples though water efficiency in the home lacking relative to other geographices (e.g. Australia).	2 often utilised particularly in response to drought periods.	3 high synergies – reduces energy re-quirements, reduces wastewater flows.	3 No conflicts evident.	1 Very limited information on decarbonisa-tion potential in published literature
AAD THP	3 27 THP plants in the UK	2 applicable to most AD sites, especially if they struggle for capacity	2 likely lower embodied carbon as increases capacity of existing digesters, increased biogas yield, can increase NG demand for support fuel	2 costs of new assets but likely lower than for new digester capacity plus increase biogas revenues possible	3 Numerous UK plants	3 Numerous plants	2 increase CHP or biomethane output, mustn't lead to increased use NG	1 compete with sludge drying, NH_3 stripping for waste heat	3 Processes are well established in the UK, yielding reliable data
Codigestion	1 needs biosolids to land into EPR, change ways of working. Although SEPA appear to have allowed it this time (they have been obstructive in the past)	2 may need increased access to land outlets restricting geography	2 increase energy recovery, need to avoid increased fugitive methane emissions	2 may need more capacity but greater revenue recovery	1 trials in Scotland (Nigg) with distillery waste	3 extensive codigestion globally	3 increase opportunity for CHP, biomethane and hydrogen	2 risk of increased ammonia in liquors	2 many examples globally but limited examples under UK relevant regulatory frameworks

Technology or solution	Feasibility	Scalability	Decarbonisation potential	Cost and resources requirements	Scale of current use in the UK	Scale of current use outside the UK	Synergies with other outcomes	Freedom from conflicts with other outcomes	Certainty of available information
Stormwater separation & treatment	2 - likely feasible with more col-laboration and support for WaSCs to co-manage surface water and through funded op-portunities.	2 considered scalable – at cost. Disruptive but cities (e.g. Copenhagen) have large programmes of work.	1 Limited evidence, Storm Overflow Evidence Project (SOEP) project suggests poor carbon comparison with grey infra solutions	1 High cost – SOEP has recently undertaken sector level costing.	2 Some planned separation and treatment by WASCs	3 widespread implemen-tation for greenfield, increasing application for brownfield	3 high synergy with other outcomes – reduces flow and load variability, enhances stability, reduced piston effect etc.	3 no foreseeable conflicts	1 very limited evidence on the decarbonisa-tion potential in published literature
Heat recover (onsite)	2 relatively new process for sector	2 Need a co-located or very proximate demand for recovered heat	3 reduce demand for fossil-fuelled heat	2 Cost of new assets and renewable electricity purchase. Cost benefits from improved efficiency.	2 two early examples with Anglian Water recovering heat for nearby tomato greenhouses, plans for residential heating by Thames Water	2 A small number of onsite examples referenced by suppliers.	2 can help heat demand of other processes, THP, sludge drying, NH_3 stripping	3 No foreseeable conflicts	2 Information from suppliers and a small number of case studies.
Gasification/ pyrolysis (sludge)	1 needs fur-ther demon-stration in UK con-text, need understand regulation on biochar product	1 remains unclear on footprint, interactions with IED etc	2 energy recovery (unclear if excess after sludge drying), reduced biosolids storage & spreading emissions. C seq can't be used in SBTi but scores well under Oxford principles	1 likely to be expensive & driven by sludge to land regs & net zero	1 one pilot example at Thames water	2 A number of emerging commercial scale plants in water sector	2 reduced emissions from long term sludge/ biosolids storage	2 no conflicts around renewable heat if self-sufficient sludge drying	2 EngD thesis info and Jacobs own data plus global examples

Technology or solution	Feasibility	Scalability	Decarbonisation potential	Cost and resources requirements	Scale of current use in the UK	Scale of current use outside the UK	Synergies with other outcomes	Freedom from conflicts with other outcomes	Certainty of available information
Biomethane to grid	2 due to extensive experience but limited accessibility of GGSS, lower hanging fruit may already exist e.g. access to injection points	1 limited sites available - large site close to injection point	2 but this depends on what the opportunity cost is and scale. Depends on methane leakage/slip. Limited by sludge	2 new subsidies may be difficult to access but wholesale prices are high currently	3 several commercial scale plants in the water sector, many more in commercial AD	3 Numerous commercial plants	2 can be used in biomethane tankers	1 trade-off with CHP, impact renewable electricity, heat for THP, N stripping, sludge drying	3 tech is well-established in industry
N Stripping (liquors)	1 applicable to sites with high ammonia digestate liquors & excess renewable heat. End use of recovered product uncertain	1 applicable at sites with AD and AAD, more likely with THP but needs heat or chemical	2 sludge liquor loads can be up to 20% of mainstream load, unclear emissions from end use e.g. as fertiliser. Must not use natural gas to supply heat	2 reduced energy & capacity demand in WwTW, possible revenues from recovered products	1 some examples in non-sludge digestates	1 Some examples in digestate and landfill leachate. Historical examples at WwTW in the US	1 ammonia could be converted into hydrogen fuel for sludge tankers	0 could compete with other processes (e.g. THP, sludge drying) for renewable high-grade heat	2 enough data for energy and emissions for high level estimates



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