Process N_2O emissions and Water Net Zero

No laughing matter

Water Companies in England and Water UK released the 'Net Zero 2030 Routemap – Unlocking a net zero carbon future', a plan to realise their ambitious Public Interest Commitment (PIC) to reduce greenhouse gas (GHG) emissions and progress towards net zero operational emissions by 2030. This provides a bold plan of operational emissions reduction and offsets, two decades ahead of the UK Government. In Scotland, Scottish Water have set a target for net zero by 2040, 5 years ahead of the Scottish Government, going beyond operational emissions by including embodied carbon with a 75% reduction from the 2007 baseline by 2030. Further, we see increasing aspiration towards Science Based Targets, which require full consideration of all carbon impacts across the value chain, from peatland in upland catchments through to the embodied carbon in building materials.

Historically, the UK water sector has accounted for about 1% of the national GHG emissions. The majority being Scope 2 – indirect emissions from energy use for water abstraction, treatment and conveyance, and for wastewater collection and treatment. Since 2011, the sector has achieved an overall 45% reduction in operational GHG emissions, mainly through reduction of Scope 2, by increasing renewable generation and as result of the decarbonisation of the national electricity grid.

With Water Companies moving towards purchase of 100% renewable energy, increasingly focus will be on Scope 1 process emissions of nitrous oxide (N_2O) and methane (CH_4) released in the management and treatment of sewage and sludge streams, as evident in Figure 1.

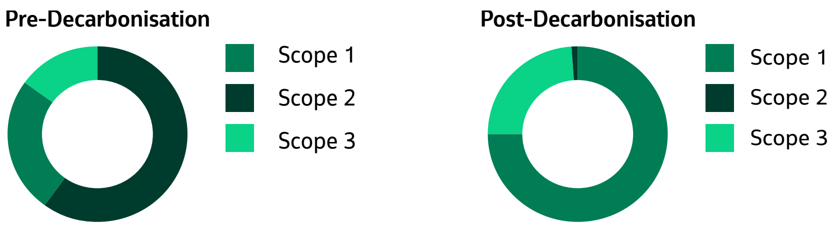


Figure 1. Typical breakdown of Scope emissions for the UK water and sewerage companies (WaSCs) pre- and post-decarbonisation of the energy matrix, both on-site generation and electricity grid.

Understanding N_2O

Notably, the "laughing gas", N_2O is the main GHG emitted during wastewater treatment and the third most abundant GHG in the atmosphere with a global warming potential of 265 times that of carbon dioxide (CO_2) in 100-year life span. With increased academic research on the production and emission of N_2O from wastewater treatment over the past decades, highlighted in the recent IPCC 2019 Refinement to the 2006 Guidelines for National GHG Inventories, the water sector is waking up to this issue and working to improve on accounting of these emissions. There is a real need to better understand and more effectively manage process N_2O emissions from wastewater treatment works (WwTWs). **With a target of up to 60% reduction in process emissions from 2018-2019 baseline by 2030, English Water Companies have much to do in order to make their Public Interest Committent a reality.**

There is clear industry ambition to reduce process emissions, as evidenced by the recent UKWIR publication 'Quantifying and Reducing Direct GHG Emissions from Waste and Water Treatment Processes' which we had the pleasure of authoring. As this recent review shows, the emission factors (EFs) used by the UK water sector through the Carbon Accounting Workbook (CAW), whilst progressive in their origins, are no longer fit for purpose and there is a substantial lack of research to date specific to the UK Water sector. This is required to design an effective industry-wide mitigation programme. To avoid missing their net zero target or the need to resort to low quality abatement, such as the purchase of carbon offsets, we welcome the aspiration for a programme of monitoring, informed by extensive existing global research.

Most site monitoring of process N_2O emissions to date has been conducted for academic research rather than to develop operational strategies to monitor and mitigate emissions (Denmark provides an inspiring exception to this – see Case Study overleaf). Whilst academic research remains key to improved understanding of the microbial mechanisms and operational conditions responsible for N_2O production, triggers and conditions leading to N_2O production in wastewater treatment are now much better understood and mean we can take action today. The only way to start reducing these emissions is to start monitoring them and assessing operational data to characterise and develop mitigation strategies. **Water Companies have an opportunity to take the lead on monitoring and implementing effective mitigation strategies, site by site.** Beyond the carbon reductions that will be achieved, the outcomes of monitoring and resulting mitigations will likely offer wider benefits in terms of better process understanding, stability and performance - and could benefit asset health, health and safety and cost to customers (with potentially lower energy consumption in cases).

1. The Challenge

Complexity of N_2O production and emissions

The production pathways of N_2O in wastewater treatment are highly complex. It occurs as a by-product of nitrification through two distinct pathways, or as an obligatory intermediate of denitrification (Figure 2), in addition to abiotic production to a lesser extent. In general, the importance of one pathway over another will depend on the environmental and operational conditions of the treatment process.

Since the 1990s comprehensive research has been conducted around the world both at lab- and full-scale to understand the mechanisms and factors leading to N_2O production and emission from different configurations of WwTWs. Due to the high complexity and dependence on environmental and operational conditions, global research has demonstrated wide variation in N_2O emissions from different types of treatment, within types of treatment plants, within lanes, and significantly, depending on how monitoring has been undertaken. N_2O emissions can be significantly different. Figure 3 shows a simple graphical summary of this reported variation, built on published work from our partners at Brunel University.

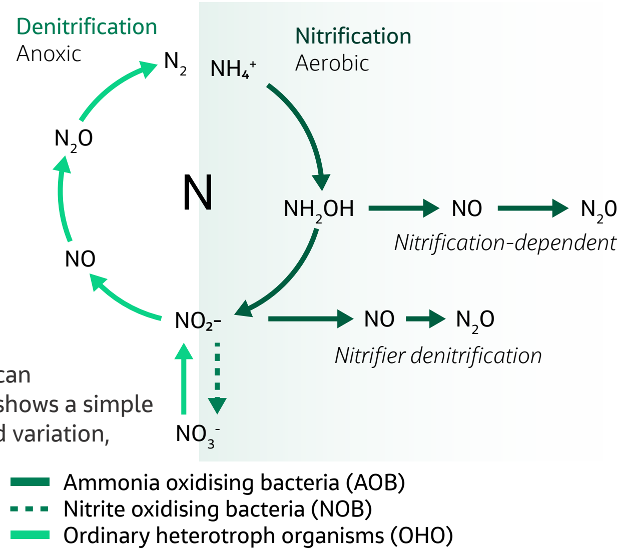


Figure 2. Pathways of N_2O production in the nitrogen cycle.

A key consideration is that the **only biological sink of N_2O is via denitrification**. Whilst this might seem good news for Southern Water or for Severn Trent and others who have historically required to reduce total nitrogen (TN) or have undertaken biological phosphorus (P) removal with denitrification, N_2O production is complex. Full-scale monitoring shows us that biological nutrient removal (BNR) facilities typically have higher measured N_2O emissions. While the **potential for mitigation** for existing treatment processes is there, how this is able to be realised requires the industry to embrace on-site monitoring and assessment of N_2O emissions and to develop operational and PR24 planning strategies which are based on best available methods, considering real time control, operational set points, carbon sufficiency and new treatment solutions.

Critically, the prevalence of nitrification only WwTWs in the UK (for now) means that the action required to mitigate emissions and to *minimise* N_2O production will require better understanding and control within our nitrifying activated sludge treatment plants (ASPs). Because most of the research to date has focused on full-scale BNR WwTWs, there is a real lack of full-scale data mitigation studies of nitrification only WwTWs. Similarly, for fixed-film processes and for surface aerated ASPs, a further complexity is in monitoring and the lack of standard methods.

Current industry carbon accounting methods - Implications of a top-down methodology to estimate N_2O emissions

The UK Water sector report operational carbon emissions through a sector workbook (CAW) – which provides global best practice in water industry reporting methodology in terms of a consistent, auditable process. This uses industry-wide, so called 'top-down' EFs which Water Companies can use to estimate carbon equivalent emissions (CO_2e). As global research shows, using top-down EFs to estimate process N_2O emissions in the water sector offers only a low degree of certainty about actual emissions and provides little opportunity for the understanding required to actually reduce emissions which needs to be our key focus!

In recognition of the high variability of N_2O production, the 2019 IPCC Refinement of the 2006 IPCC Guidelines now provides a three-tier methodology and a decision tree to help identify which EF should be used to estimate process N_2O emissions (Figure 4). A progression from Tier 1 to facility level Tier 3 monitoring and reporting represents an increase in confidence in the estimates, and will require more extensive resources for site measurement and data collection.

The 2019 IPCC Refinement also revised the default EF for Tier 1 method application resulting in a new EF of 1.6% (0.00016 – 0.045 kg N_2O-N/kg N load), which is eight times the current EF applied by the UK Water industry. Whilst analysis of the existing global dataset continues (e.g. de Haas & Ye, 2020 and Hua et al., 2022), and work in Denmark and elsewhere reporting EFs of 0.082-1.2%, still around five times the current UK EF, what is recognised is that when countries complete first global stocktake of carbon emissions in 2023, they *should* be applying the science based IPCC methodology *or a suitable in-country methodology.*

Jacobs

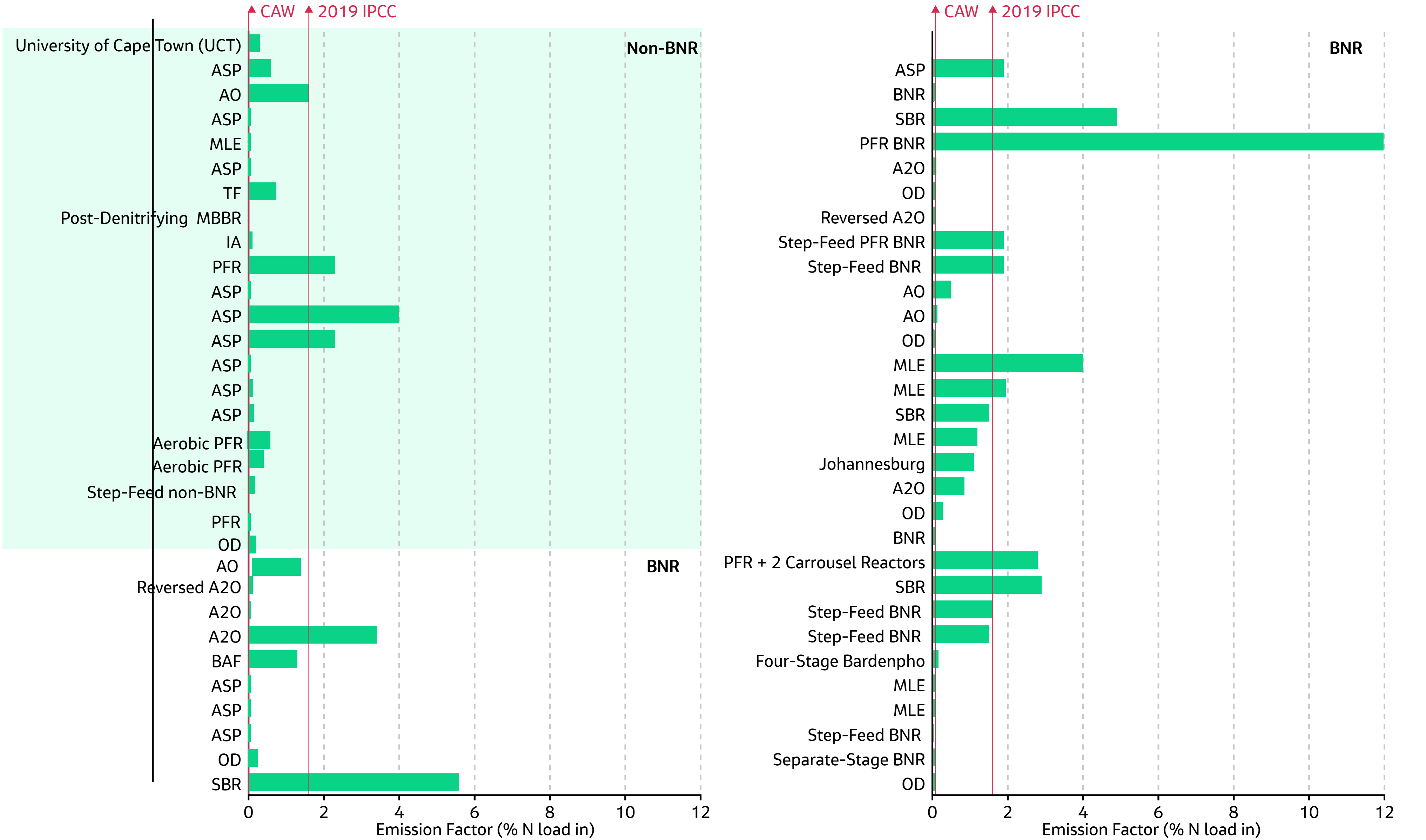


Figure 3. Emission factors (EFs) of N_2O emissions in % N load (kg N_2O-N/kg N load) from literature review (Vasilaki et al., 2019) and edited by Jacobs to include additional published research (n = 61). Although the global dataset contains a total of 81 distinct EFs, here we only display those reported in kg N_2O-N/kg N load in. Shaded green area indicate EFs from assessed non-BNR. ASP: activated sludge plant, AO: anaerobic-oxic activated sludge process, A2O: anaerobic-anoxic-oxic activated sludge process, BAF: biological aerated filter, CAS: conventional activated sludge process, EA: extended aeration process, IA: intermittent aeration process, MBBR: membrane bioreactor, MLE: modified Ludzack-Ettinger, OD: oxidation ditch, PFR: plug-flow reactor, SBR: sequencing batch reactor. Further analysis required to classify treatment types - as recently considered in interesting work by Hua et al. (2022); the point is the EFs and campaigns behind them vary substantially.

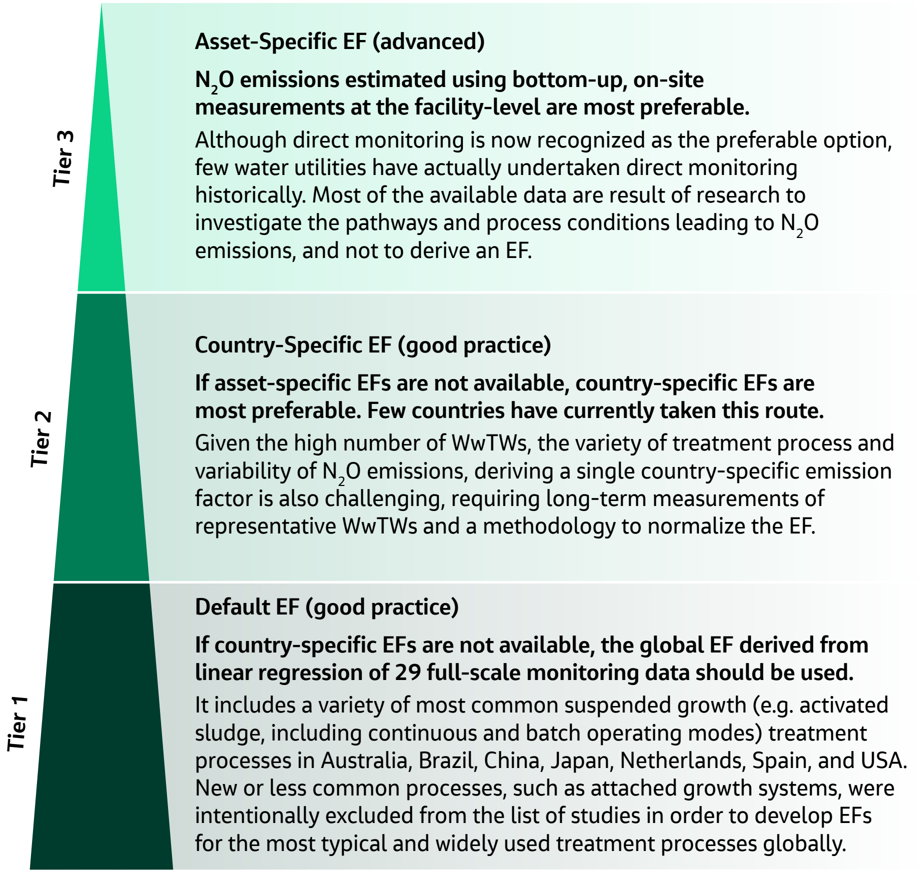


Figure 4. Tier-three approach for selection of EF for top-down N_2O emissions estimation.

The UK Water Sector needs to develop a suitable in-country N_2O methodology

Whilst the CAW offers an admirable reporting tool, the chances of a single top-down EF adequately describing N_2O emissions across the breadth of the UK water sector asset base is slim and the use of a top-down EF offers no opportunity for mitigation.

As the recent UKWIR report notes, the existing EF requires revision and we are pleased to be delivering Phase 2 of this collaborative research to better understand N_2O emissions - though we must measure to mitigate and the focus must be on full-scale monitoring at our assets with greatest mitigation potential and to develop a science based in country methodology for quantifying, reporting and mitigating. Robust Tier 3 EFs for different process types are unlikely; mitigation progress for net zero is highly likely if we start monitoring at scale.

Case Study – Danish Water Sector

In Denmark, the Environmental Protection Agency (EPA) has undertaken a voluntary national programme involving full-scale monitoring at 10 WwTWs for over 2 years, covering about 30% of Danish domestic wastewater load and a variety of treatment types. The intent is to use the outputs from this long-term monitoring to derive a new country-specific EF (Tier 2), which will likely be lower than the new IPCC default Tier 1 method. The final conclusions are expected to be published by the end of 2020.

In addition, monitoring of N_2O emissions from WwTWs will become compulsory in Denmark, with environmental penalties for emissions above specified targets, as proposed on a draft bill aiming to limit releases of N_2O into the atmosphere. WwTWs serving over 30,000 population equivalents (PE) will be required to comply by 2025 as part of a broader effort to make Denmar's water sector climate-neutral by 2030. Water utilities that have undertaken proactive monitoring and mitigation strategies individually or as part of the national monitoring programme, with reductions of up to 85% achieved, will likely have an advantage in maintaining lower levels of process emissions.

Considerations of shadow price for energy efficiency and energy producing technologies in wastewater treatment have been put in place by the Danish EPA and Utilities expect the day may come where, like effluent emissions of nitrogen and phosphorus discharged in Denmark, customers start paying for WwTW factoring in a tax associated with emissions of N_2O. Denmark is a great case study to draw upon for the UK – many positive lessons to learn from a pan-industry, regulator supported monitoring programme is implemented, as Dr. Mikkel Andersen from Unisense Environment shared in a recent webinar we presented.

Real-time monitoring over the full seasonality of incoming flows and loads is important. The world's only online liquid-phase N_2O measurement has provided useful long term datasets and a basis for mitigation as demonstrated by the Danish Water Sector Case Study. Key is the duration of monitoring -for instance, while although long-term weekly grab sampling has been theoretically shown to provide reliable EFs for a WwTW[1], it does not offer insight into the production pathways or diurnal variability of emissions. Long-term on-line monitoring and process data analysis helps us to understand triggers and conditions which lead to N_2O production and emissions. Innovative operational data analysis can also provide insights and data driven techniques to predict, investigate and mitigate - with exciting and globally leading work being undertaken by our colleagues at Brunel University London on this subject. .

1 Daelman et al. (2013). Influence of sampling strategies on the estimated nitrous oxide emission from wastewater treatment plants. Water Research 47 (9), 3120-3130

2. The Opportunity: Developing a Framework for Net Zero Through Long-Term Mitigation of N_2O emissions

So how do we develop a suitable in-country methodology? Through a consistent framework approach which will provide the industry the toolbox it requires for both monitoring and mitigation. Figure 5 summarises our recommended framework to lead the UK water sector towards net zero through long-term mitigation of N_2O emissions. From site selection and development of site-specific monitoring strategies to continuous real-time data collection integrated with process control systems for sustained long-term mitigation.

Monitor & Baseline

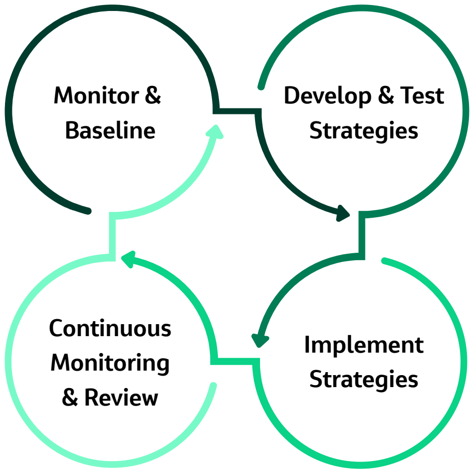
- Develop a monitoring strategy that targets the highest impact WwTWs with greatest mitigation potential.
- Long-term (e.g. 12 months) online monitoring to understand spatial, diurnal and seasonal variability across selected assets.
- Asset-specific EF in alignment with Tier 3 method for Band 6 or largest works.

Develop & Test Strategies

- Identify key process triggers, time of day/year with peak emissions and develop strategies to mitigate.
- Consider process data mining and modelling to provide insights and support evaluation of reduction potential and impact on process performance.

Implement Strategies

- Apply strategies through process interventions and optimisation.
- Combine strategies with control systems (e.g. SCADA) to ensure reduction of N_2O emissions along with continued process performance.
- Best practice knowledge sharing for greater potential of N_2O emissions reduction across the water sector and internationally.



Continuous Monitoring & Review

- Implement mitigation through real time or off line control, enabling long-term reduction of N_2O emissions.
- Use of emerging process models, soft sensors and data-driven tools to predict emissions in the long-term, and potential reduction in smaller WwTWs.
- Inform future infrastructure planning for process design and operations with reduced emissions impact.

Figure 5. Framework for Net Zero Though Long-Term Mitigation of N_2O emissions.

Our suggested considerations in alignment with the framework include the following steps:

1. **Start with ASPs**. We can think about our largest WwTWs with connected PE of 100,000 or more, treating the sewage of 40 million customers in England and Wales. There are around 130 of these – some will offer a great place to start (particularly facilities with high strength liquors or liquor treatment where co-located with on-site bioresources assets). These sites are also likely to be the subject of ongoing work in terms of industrial emissions directive. We can also take science-based approaches to assess sites for N_2O potential and start with high-risk plants. Conduct process assessment to select and prioritise sites considering N2O and process risk, existing operation and site specifics.
2. **Install on-line monitoring and baseline facility emissions**. We do need long term data at multiple sites - we have no UK& I evidence base. The Danish industry took 10 sites this exhibits variation across years; a recent Swiss campaign 12+ months across 7 sites. We should recognise it is possible to take action with less data - consider some quick mitigation wins. With more experience and advanced methods we will likely develop more efficient monitoring strategies, leverage knowledge and digital solutions but to start with we need quality, long term data at multiple sites. Review the UKWIR Good Practice Guide for process emissions once published - we're proudly authoring this with University of Brunel London, Cobalt Water Global with review by colleagues at the University of Queensland.
3. **Analyse emissions and operational data**, taking the opportunity that comes with data to start developing the toolbox likely to be required for future wide-scale mitigation. Data quality and quantity matters, we can use data science but expert knowledge is important.
4. **Start mitigating!** Show the world what is possible. The solutions are likely to range from lower cost process optimisation to new treatment processes/concepts, AI and digital twins.
5. **Monitor – mitigate – repeat:** develop cost effective mitigation strategies, inform current and future asset planning. We need a toolbox approach to address fixed-film processes, surface aerated plants and small treatment works, weighing up the carbon and cost benefit compared with other net zero strategies. And perhaps the cost of carbon.
6. We might also consider the **cost of not mitigating** - a growing question for Ofwat given their role to play in regulation for net zero. If we take the largest WwTWs in England and Wales, some possible carbon prices[2] and the recently published Danish industry National EF which is possibly on the low side for the UK, the cost of current N_2O emissions could be between £30-150m. Conversely, the cost of mitigating N_2O emissions has been shown to be most cost effective - requiring a shadow carbon price of less than £12/ton CO2e in a recent Danish case study[3]. Existing evidence suggests mitigation of N_2O will be best value for customers but we urgently need in-country assessment with life cycle analysis.

So what mitigation is possible?

Mitigation strategies (Figure 6)are emerging but feasible to trial and implement today.

2 For example, a range from £50/t CO_2e to the UK Government's £245/t CO_2e required for UK policy evaluation which could be more worthy of our children.

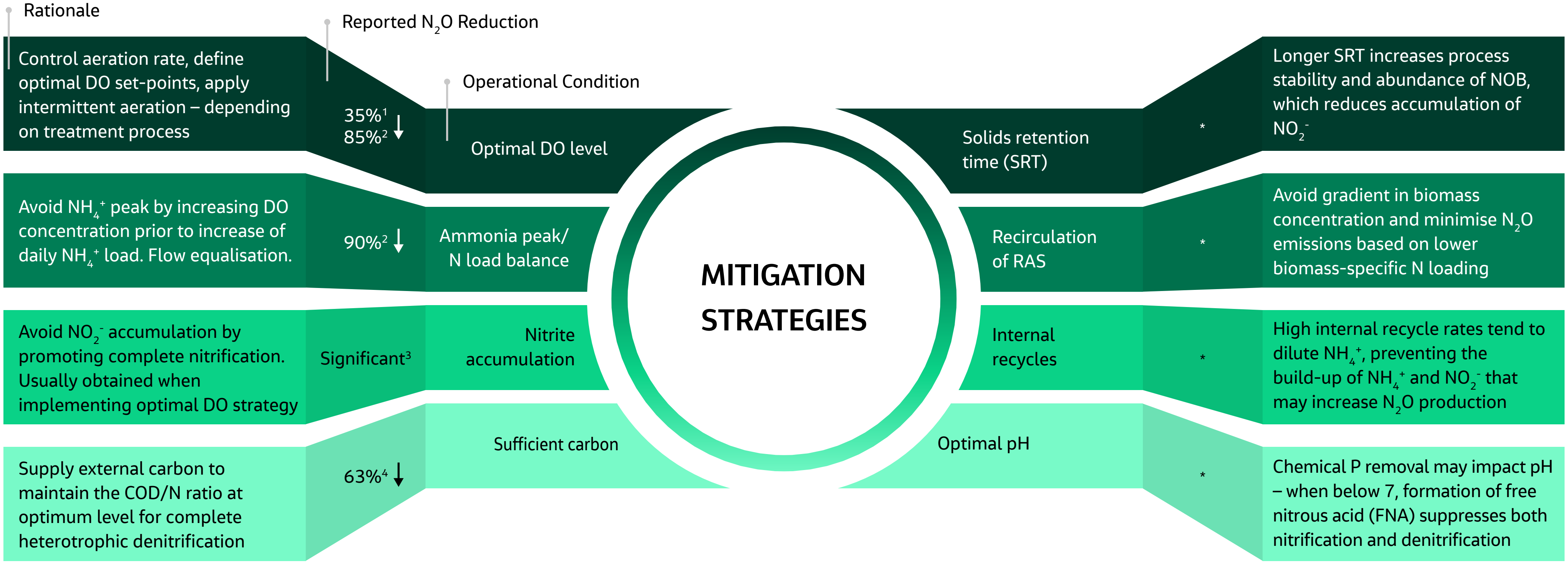
3 Styrelsen for Vand- og Naturforvaltning. (2016). Energipotentialer og CO2-skyggepriser for energibesparende og energiproducerende teknologier i spildevandsrensning.. Miljø- og Fødevareministeriet. See also Farago, M. et al. (2021) which considers resource recovery and N_2O.

Limited work to date mitigating at scale does not consider UK water industry asset types, such as nitrifying and fixed-film processes.

The experience of full-scale mitigation strategies to date is that they *can be* relatively easy interventions in control and optimisation that can be implemented with low to medium cost – and that these ultimately improve process performance, energy consumption and effluent quality. Chances are we will also need MaBR, mainstream anaerobic and lots of other acronyms like perhaps SND, perhaps variants on the AGS theme... We will likely be challenged in the UK by our asset base which generally lacks denitrification and the potential for a N_2O reduction pathway. Further, our weaker sewage and diverse asset base and thousands of small WwTWs which will not lend themselves to monitoring or mitigation. But we must focus on what is possible.

For example, a recent Water Research paper published by Duan et al. (2020)[4] - the team at UQ and partners, have demonstrated a **reduction of 35% in N_2O emissions from a full scale sequencing batch reactor (SBR) along with reduced operational costs due to 20% savings in aeration energy consumption and with no effect on the nutrient performance of the WwTW.**

Whilst evidence from other peer-reviewed full-scale, continuous flow and batch, conventional and (multiple) aerobic granular sludge systems is eagerly awaited, the UK sector has a golden opportunity to contribute substantially to this research of full-scale monitoring and mitigation – with joined up collaborative practice and their commitment to collaborative innovation underpinned in the recent 2050 Innovation Strategy.



1. Duan et al., 2020. Water Research 185 116169.
2. Porro, 2020. Cobalt Water Global N_2O Risk Model.
3. Rodriguez-Caballero et al., 2015. Water Research 71 1-10.
4. Unisense, 2015. N_2O Wastewater System. Aarhus.

* Observed in lab- or pilot-scale, but not applied in full-scale.

Figure 6. Published observed and applied mitigation strategies.

4 Duan et al. (2020). Mitigating nitrous oxide emissions at a full-scale wastewater treatment plant. Water Research 185, 116196.

Whilst optimising the cost of the requisite monitoring campaigns is key, short-term investment in N_2O monitoring and evidence based mitigation strategies could have substantial impact on the reduction of the Water Company's carbon footprint, whilst maintaining compliance and perhaps improving control and Opex. We see great potential for ticking innovation and total value boxes - and with the right collaborative, inclusive approach we will help inform global research and provide the evidence we will so greatly need for future investment. This includes the need to rethink current processes, to enhance and upgrade to lower emission technologies[5], and indeed perhaps to go beyond our current biological nitrogen transformation focus.

While we remain stewards of nitrogen transformation processes in the (circular) economy, our toolbox for addressing N_2O will also likely include new visions for process control, enabled by advanced data-driven approaches such as those led by our colleagues at Brunel University London, innovative knowledge based and machine learning approaches being implemented by Cobalt Water Global, and advanced process modelling and digital twins.

We also need to share results, evaluations and outcomes transparently and show customers the role water companies can play in the route to net zero.

To achieve their ambitious net zero commitment, and to meet the expectations of current and future generations of customers, the water sector must embrace the scale and magnitude of the N_2O challenge and, most importantly, work together to reduce N_2O emissions. It is exciting to see this starting and we welcome action at the pace required. Working together, not in competition is going to get us there faster.

CCC Progress Reports highlight the need for ambitious and direct action by industry regulators such as Ofwat to allow national carbon budgets to be met to achieve 2050 Net Zero in the UK. Water Companies and their supply chains must work with industry regulators to develop the requisite policy and funding frameworks required now to facilitate industry-wide monitoring and mitigation which can be implemented at scale and to inform PR24. Implementing carbon valuation - such as that required for UK Government policy making would seem relevant to consider in our future econometric models and business planning - for best value, for reduced process emissions, for transition to circular economy, for more nature based solutions, in the best interest of customers. There's much we can do on methane too. That's another paper.

Process N_2O emissions mitigation will likely prove our toughest challenge as an industry for net zero. But, as we look back in 8 years' time, we hope we will reflect on the fact that it also provided us with one of our greatest opportunities for inclusive, collaborative innovation and ambitious action - something we worked together at to enable the future we need.

5 Such as membrane aerated biofilm reactors (MaBRs) given recent experience of progressive utilities such as VanCenter Syd (VCS) Denmark.

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