ARUP

Climate Change Committee

Updating wastewater treatment pathways for the Seventh Carbon Budget

Technical report

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1. Introduction

This technical report provides an overview of the methodology and results of a modelling exercise to update the assumptions on UK wastewater emissions modelling to 2050, to inform the CCC's advice to government on the seventh Carbon Budget. The central aim of this project was to develop three emissions pathways with associated costs and energy demands for municipal and industrial wastewater treatment emissions, broken down by devolved nation. Arup developed a do-nothing 'Baseline Projections' pathway, a 'Balanced Pathway' and an 'Additional Action Pathway', in line with the CCC's core seventh Carbon Budget scenarios.[1] The pathways were informed by a detailed review of wastewater decarbonisation technologies, wastewater treatment company plans and stakeholder engagement with industry experts covering both municipal and industrial wastewater.

1.1 Literature review

We carried out a review of literature to provide an understanding of the current landscape of net zero technologies in the UK wastewater industry, and identify key data inputs in terms of technology selection for pathway development, their costs, technology maturity and feasibility of roll out. A summary of the key literature that informed the modelling is presented in Table 1; note that this list is not exhaustive.

Table 1 - Literature review summary of key documents

Title	Summary	Data used
Ofwat, Jacobs (2022) Net Zero Technology Review	Independent review of potential net zero technologies for the wastewater industry in the UK.	Intervention technologies and their applicability to UK wastewater, technology readiness levels
Water UK (2023) Net Zero 2030 Routemap	Routemap for getting the UK water companies to net zero operational emissions by 2030.	N_2O emissions factors, challenges and uncertainties faced in the net zero transition. See section 2.1.2. for more detail on use of emissions factors.
2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories Chapter 6: Wastewater Treatment and Discharge	Guidelines for generating greenhouse gas emissions inventories for the wastewater industry, including emissions factors	N_2O emissions factors (0.016 kg N_2O-N/kg N). See section 2.1.2. for more detail on use of emissions factors.
Ricardo Energy (2019) 2019 Greenhouse Gas Inventory Improvement Programme: Wastewater modelling refinement	Report focussing on improving wastewater emission estimates and modelling methodologies.	Projected change in industrial baseline emissions, based on GVA
Severn Trent Water (2020) Severn Trent Net Zero Investment Report	Net zero investment strategy detailing technological interventions for Severn Trent water.	Technology costs, abatement values, technology readiness levels, site coverage potential
Seven Water and Sewerage Companies (WASC) PR24 business plan submissions (as at March 2024)	Seven WASCs in England and Wales published business plans that included relevant technologies. We reviewed the reports and data tables, and data table commentaries. The reports present investments for the AMP8 investment period, including strategies for achieving net zero.	Technological interventions, costs, abatement values, technology readiness levels, site coverage potential, uncertainties, and limitations of specific technologies.
DEFRA, Jacobs (2022) A review of the measures to reduce Greenhouse Gas (GHG) Emissions from the	Rapid evidence assessment on the measures, benefits and costs associated with decarbonisation technologies for the wastewater sector	Corroborates recommendations that the IPCC's 2019 guidance on

[1] Climate Change Committee (2023). Proposed methodology for the Seventh Carbon Budget advice. Available: https://www.theccc.org.uk/publication/proposed-methodology-for-the-seventh-carbon-budget-advice/

Title	Summary	Data used
wastewater treatment sector, including the benefits and costs - WT15130		emissions factors appears to be the most accurate.

1.2 Stakeholder engagement

Preliminary modelling results were presented and discussed at the monthly 'Carbon Network' meeting on Tuesday 26th March 2024, which was attended by a number of Water and Sewerage Companies (WASCs) who commented on the modelling and provided the following feedback:

- Confirmation of the appropriateness of selected decarbonisation technologies for emissions reduction pathways
- Guidance on the selection of comparative emissions factors
- Guidance on the maximum site coverage potential of certain decarbonisation technologies
- Guidance on the emissions abatement potential of selected decarbonisation technologies

As a follow up to this meeting, WASCs were invited to share further written feedback or schedule a one-to-one call. As such one follow-up conversation was held with Anglian Water on Friday 5th April 2024, during which assumptions were discussed in more detailed and in certain cases revised (see Appendix **1** for the assumptions log).

2. Methodology

2.1 General modelling assumptions

2.1.1 Model boundary

The scope of this study includes direct emissions resulting from municipal and industrial wastewater treatment process (i.e. N_2O and CH_4 emissions), excluding sludge disposal, and any on-site emissions that occur outside the direct treatment process. Scope 2 and 3 emissions are not included, though energy demand associated with the treatment process is captured. We assume the additional roll out of selected decarbonisation technologies does not begin until the next asset management period in England and Wales, 2025.

2.1.2 Emissions Factors

The accuracy of nitrous oxide emissions factors relating to wastewater treatment processes is the subject of much debate within the water industry, with figures ranging widely for comparable technologies. The current value used within Carbon Accounting Workbooks (CAWs) (and reported in the National Atmospheric Emissions Inventory) is currently 0.004 kg N_2O-N/kg N, drawn from UKWIR[2]. In 2019 the IPCC published updated guidelines containing an emissions factor of 0.016 kg N_2O-N/kg N[3] (with a range between 0.00016 - 0.045 kg N_2O-N/kg N, representing significant uncertainty). In 2020 UKWIR updated their original value to 0.008 kg N_2O-N/kg N[2]. Both of these values represent significant divergence from the current value used, and therefore raise concerns of underreporting of UK wastewater emissions.

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[2] UK Water Industry Research, 'Quantifying and Reducing Direct Greenhouse Gas Emissions from Waste and Water Treatment Processes.', 2020, https://UKWIR.org/water-industry-technical-report?object=d8ad3c7a-0f76-40c9-bb00-cc3ecc618666.

[3] IPCC, '2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories Chapter 6: Wastewater Treatment and Discharge', accessed 8 April 2024, https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/5_Volume5/19R_V5_6_Ch06_Wastewater.pdf.

Our central analysis utilised the emissions factor integrated within the CAWs (implicit within the NAEI database), though to test the implication of a higher and potentially more accurate emissions factor, we indicate an upper bound of emissions utilising an emissions factor of 0.016 kg N_2O-N/kg in line with the IPCC guidelines, i.e. a factor of four greater than the central assumption. During the stakeholder engagement outlined in Section 1.2, WASCs indicated that their internal data collection activities derive results that most closely align with the central value within the IPCC 2019 guidelines (0.016 kg N_2O-N/kg), a finding corroborated by a Defra commissioned Jacobs review.[4] Therefore this value was selected as an appropriate comparative emissions factor within our analysis.

For CH_4, WASCs report that they find no current evidence for the need for improved quantification beyond the current UK GHGI method.

2.2 Baseline Projections:

2.2.1 Emissions

Base year CH_4 and N_2O emissions were taken from the National Atmospheric Emissions Inventory[5]. This baseline is split by devolved nation and by industrial and municipal emissions, and uses the AR5 global warming potential values without climate feedback. Extracted emissions data is presented in Table 2.

Base year emissions data from NAEI were projected forward to 2050 reflecting a do-nothing scenario whereby current technologies remain unchanged, based on the below methodologies for municipal and industrial wastewater emissions respectively:

- Municipal wastewater emissions were projected to change based on annual population change by devolved nation (based on central CCC assumptions)
- Industrial wastewater emissions were projected based on analysis by Ricardo's 2019 wastewater modelling refinement exercise[6] using projected Gross Value Added changes by industrial sector.

Table 2 - 2021 greenhouse gas emissions for municipal and industrial wastewater in the UK and each devolved nation

Emission source	NATION	MUNICIPAL ($KTCO_2E$)	INDUSTRIAL ($KTCO_2E$)
N_2O	United Kingdom	779.7	116.8
	England	657.3	98.4
	Northern Ireland	22	3.3
	Scotland	63.5	9.5
	Wales	36.8	5.5
CH_4	United Kingdom	761.7	1164
	England	574.3	1927
	Northern Ireland	70.7	30.3

[4] DEFRA (2022) A review of the measures to reduce Greenhouse Gas (GHG) Emissions from the wastewater treatment sector, including the benefits and costs - WT15130 Available at: defra.gov.uk

[5] (Defra) Department for Environment, Food and Rural Affairs, 'UK Emissions Data Selector - Defra, UK', 2021, https://naei.beis.gov.uk/data/data-selector?view=greenhouse-gases.

[6] Sabino Del Vento and Ricardo Energy, '2019 Greenhouse Gas Inventory Improvement Programme: Wastewater Modelling Refinement', no. 1 (2019).

Emission source	NATION	MUNICIPAL (KTCO$_2$E)	INDUSTRIAL (KTCO$_2$E)
	Scotland	51.7	60.7
	Wales	65.1	45.4

2.2.2 Energy demand

Baseline electricity and fuel (natural gas, biogas, diesel, and gas oil) demand relating to the wastewater treatment process directly was calculated from energy consumption data provided by WASCs' Carbon Accounting Workbooks. We used data for the following WASCs and for the case of England extrapolated this demand based on population served: Scottish Water, Dwr Cymru Welsh Water, Northern Ireland Water, and Thames Water. It was assumed that electricity usage disclosed refers to electricity consumed from the National Grid, excluding any self-generation (e.g., photovoltaic panels). It has also been assumed that combined heat and power (CHP) in waste operations is 100% used for direct wastewater operations rather than, for example, keeping lights on. Note that data received within CAWs related to 2022-23 reporting year; we assume these values are reflective of 2021 values as per our model start year.

Due to a lack of data on industrial energy consumption for wastewater operations, it has been assumed that the industrial electricity and fuel consumption mirrors municipal consumption. The same values were used, scaled up/down by the ratio of industrial to municipal emissions. For devolved nations, energy consumption was extracted from relevant water company's CAW and then scaled up/down based on ratio of population served by wastewater services (figure from CAW) and the population of nation. This was done for NI and Wales, but not Scotland because Scottish Water did not have a figure for population served, and as such reported energy demand by Scottish Water was taken as representative of the national total. England's figures were scaled up from the figures from all England's WASCs. This was done to include all wastewater treatment pathways that may not be done directly by wastewater companies, e.g., septic tanks for remote/rural properties.

Energy demand was projected to 2050 using the same methodologies outlined in Section 2.2.1. Municipal and industrial energy consumption is presented in Table 3

Table 3 – Summary of base year energy consumption data

Nation	Municipal energy demand (TWh)	Industrial energy demand (TWh)
United Kingdom	3.478	5.250
England	2.981	4.055
Northern Ireland	0.015	0.072
Scotland	0.298	1.101
Wales	0.184	0.186

2.2.3 Costs

The technologies selected for the emissions reduction pathways could all be retrofitted into existing plants without requirement for technology replacement, therefore precluding any displaced costs of counterfactual technologies. As such baseline technology costs (for existing treatment works) have not been calculated.

2.3 Emissions Reductions Pathways

2.3.1 Technology selection

To identify a longlist of potential N_2O and CH_4 abatement technologies, a review of the Ofwat study[7] and WASC technology reports and business plans was conducted. Seven WASCs included Net Zero Enhancement Schemes in their draft business plans to be considered for funding through the Ofwat Innovation Fund[8]. A longlist of 15 technologies was identified, listed, and described in Appendix 2 - Technology interventions .

As per the CCC's Seventh Carbon Budget methodology guidance[1], technologies were selected for inclusion within one or both of the emissions reduction pathways based on the following considerations:

- **Technology abatement cost**: technologies were considered for inclusion in the Balanced Pathway and Additional Action Pathway from the first year their estimated technology abatement costs fall below the CCC's central and high carbon price projections respectively. It should be noted that there is high uncertainty and data paucity relating to technology abatement costs for wastewater decarbonisation technologies, with derived results from different sources often ranging by orders of magnitude. See Section 4.2.1 and the assumptions log in Appendix **1** for more detail.
- **Feasibility of roll-out**: Technology maturity was assessed for longlisted technologies, based on available information on 'technology readiness levels' and existing scale of roll-out across the UK. This informed technology deployment start dates as well as the pathway(s) they were included in.
- **Data availability**: The availability of data (e.g. emissions abatement potential and costs) contributed to the selection of modelled technologies. The stakeholder engagement activities were also instrumental in sense-checking shortlisted technologies.

Based on the above selection process, the following technology narratives and corresponding pathways were constructed, with key technology assumptions presented in Appendix 2.

Balanced Pathway narrative:

> *The balanced pathway addressed* N_2O *emissions through the use of covering and containment, enhanced monitoring, real time control (RTC) and digital twins, and MABR, and* CH_4 *emissions through the deployment of AAD. Whilst technology abatement costs for all these technologies fall below the start year central carbon price, they vary in technological maturity, and therefore their roll out is staggered. We assume enhanced monitoring, digital twinning, and covering and containment are rolled out from 2025, whereas MABR is rolled out from 2030. AAD is already deployed across about half of total plants and we assume it is deployed across all plants by 2030. For all technologies (except AAD which is already in widespread diffusion phase) we approximate S-curve dynamics by dividing deployment into three stages representing leaders, majority and laggards.*

Additional Action Pathway narrative:

> *The additional action pathway assumes all the same technologies as the balanced pathway, though these are rolled out at a greater pace. The AAP also includes two additional technologies: high strength liquor treatment which has strong potential to address* N_2O *emissions but is at relatively early stages of development (assume deployment begins 2035) and vacuum extraction of methane, which also has considerable decarbonisation potential but has an abatement cost between the central and high carbon price (falls below the high carbon price from 2035). Both of these technologies are assumed to begin roll out in 2035.*

The following assumptions have been made regarding the site coverage potential of select technology interventions. See Appendix **1** for more detail on assumptions.

[7] Ofwat, 'Ofwat Net Zero Technology Review', 2022, https://www.ofwat.gov.uk/wp-content/uploads/2022/08/Net_Zero_Technology_Review.pdf.

[8] WASCS disclosing Net Zer Enhancement Schemes are: Anglian Water, Hafren Dyfrdwy, Severn Trent, United Utilities, Welsh Water, Wessex Water, and Yorkshire Water.

- Covering and containment is suitable for most activated sludge plants based on population served as opposed to the number of activated sludge sites. This technology is mutually exclusive to Membrane Aerated Biofilm Reactor technology (MABR).
- MABR technology can be retrofitted into existing activated sludge process sites (ASP), however coverage of this may be limited based on existing site footprint and limitations.
- ASP have been assumed to account for 20% of total plant types, covering 80% of the population equivalent (PE) being served, based on June Return numbers from Ofwat[9] and corroborated by internal industry experience.

2.3.2 Deployment profiles

S-curve deployment dynamics were approximated through the roll out of selected technologies in three ‘tranches’. Roll out of technologies across the municipal wastewater sector begins at the start of the regulatory investment period following their earliest deployment year (identified based on cost and maturity as above), and mapping onto the subsequent two investment periods thereafter. For the industrial sector, the deployment start year was assumed to lag 5 years behind the earliest deployment in the municipal sector, to account for reduced incentives and regulatory pressure.

By way of example, if a technology reaches maturity and its abatement cost falls below the selected threshold in 2026, then Tranche 1 in Scotland and Northern Ireland will begin to deploy this technology in 2027 (start of the next deployment period), whilst Tranche 1 in England and Wales will begin to deploy this technology in 2030.

Table 4 - Example earliest deployment tranche start years for each devolved nation.

Nation	Regulatory period length	Tranche 1	Tranche 2	Tranche 3
England and Wales	5 years	2025	2030	2035
Northern Ireland and Scotland	6 years	2027	2033	2039

For both emission reduction pathways, an s-curve deployment profile has been approximated across three tranches intending to reflect technology adoption ‘leaders’, ‘majority’ and ‘laggards’. We assume a linear deployment profile within each tranche, reaching the percentages of full deployment (i.e. ‘maximum site coverage potential’ within the model) outlined in Table 5. For the Balanced Pathway, the approximated s-curve is symmetrical (i.e. both the leaders and the laggards represent 20% of full deployment), whereas for the Additional Action Pathway we assume deployment is slightly front-loaded, (leaders in a given technology represent 30% deployment, laggards represent 10%). This is a high-level qualitatively-derived estimate, however is intended to reflect more ambitious and rapid roll out due to increased policy efforts to develop immature technologies and incentivise their deployment. These assumptions are presented in Table 5, with example deployment profiles for the Balanced pathway shown in Figure 2-1.

Table 5 - Balanced and Additional Action Pathway roll-out tranches

Nation	Balanced Pathway	Additional Action Pathway
Tranche 1 roll out %	20%	30%
Tranche 2 roll out %	60%	60%
Tranche 3 roll out %	20%	10%

[9] Ofwat, ‘WASC Historic Performance: June Returns’, accessed 9 April 2024, https://www.ofwat.gov.uk/regulated-companies/company-obligations/performance/.

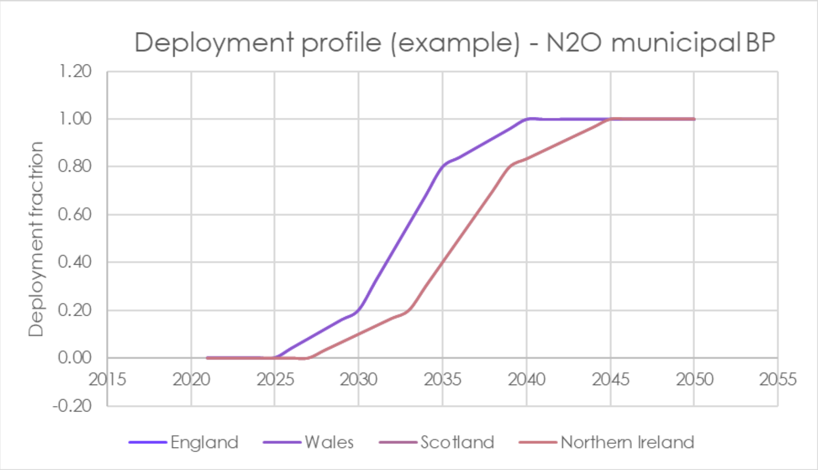


Figure 2-1 - Example Balanced Pathway deployment profiles

2.3.3 Additional energy demand

Additional energy demand associated with decarbonisation technologies was not included within the analysis due to a lack of available data. This section contains a qualitative overview of the likely magnitude of additional energy demand associated with decarbonisation technologies, noting that AAD is the only technology likely to carry a non-marginal additional demand.

For the Balanced Pathway, digital twins and enhanced monitoring and RTC may entail some additional energy demand to control N_2O emissions, however this is assumed to be marginal. MABR may have an energy demand associated with oxygen generation and supply. AAD thermal hydrolysis and intermediate thermal hydrolysis will entail a significant energy demand, these technologies are energy intensive processes which elevate temperature and pressure of sludge to yield greater biogas production; however CHP engines are typically used to recover the energy used for the thermal hydrolysis process. Where biogas is exported or converted to biomethane for injection into the grid, additional gas is typically imported to provide the necessary heat requirement for the thermal hydrolysis process.

For the Additional Action Pathway, additional energy requirements may be required for the high strength liquor treatment process, although this will be dependent on the type and configuration of the technology. Vacuum extraction of methane will have a relatively small energy requirement with operation of a vacuum pump.

2.4 Costs

2.4.1 Technology abatement costs

Technology abatement costs (net present costs per unit abatement over the asset lifetime) were gathered directly from WASC business plan reports or derived for each technology, based on reported Capex, Opex and abatement within business plan spreadsheets and projected over estimated asset lifetimes. Technology abatement costs were used to inform technology selection (alongside maturity assessment and stakeholder engagement) within each Pathway. It should be noted that there is significant uncertainty associated with technology abatement costs, which in some cases range by an order of magnitude for a given technology. See Appendix 2 for a summary of abatement costs, and the accompanying model for further detail and the range of estimates.

2.4.2 Capex and Opex

Capex and Opex data used to construct coskt projections associated with each pathway was extracted directly from the WASC business plan spreadsheets, using median values per unit of abatement (£/MtCO_2e). As different WASCs provided different asset costs, the median value across all WASCs was chosen. Median sampling was chosen as there were some significant outliers. Similarly, the operating expenditure (Opex) was estimated using WASC business plans and scaled up by the total carbon abated by that technology for each devolved nation, expressing Opex as £/MtCO_2e. As different WASCs provided different operational costs, the median value across all WASCs was chosen. Median sampling was chosen as there were some significant outliers, however there is significant uncertainty within values, and Capex and Opex costs often significantly diverge from equivalent 'technology abatement costs' for a given technology. No Capex or Opex data was available of AAD, and so these technology costs are omitted from the analysis. For certain abatement technologies, WASCs have reported negative operational expenditure (e.g. covering and containment). Table 6 summarises unit Capex and Opex data for included decarbonisation technologies.

Table 6 - Capex and Opex per unit abatement for selected technologies

Technology	Median abatement Capex (£/tCO_2e)	Median abatement Opex (£/tCO_2e/yr)
Covering and Containment	109	-29
Enhanced monitoring, Real Time Control (RTC) and digital twin	170	0
MABR	2963	415
AAD	Data unavailable	Data unavailable
High strength liquor treatment	2501	997
Vacuum extraction of methane	266	54

2.4.3 Technological change

Given that a number of selected technologies are not fully mature, we incorporated learning effects into our analysis, reflecting the observation that immature technologies typically experience cost reductions due to learning-by-doing and technological improvements. Maturity was assessed based on Technology Readiness Level (TRL) values from the Ofwat Net Zero report, and from WASC business plans. We assume a 10% learning rate for technologies with a TRL < 8 (the historical learning rate for solar panels is 20% and for the aerospace industry is 15%)[10], which was applied to Capex and Opex forecasts using the following function:

$$c(t) = c(0) * P(t)^{-a}$$

where c(t) is the cost at time t, c(0) is the initial cost, P(t) is the production or level of deployment at time t, and a is the learning rate (10%).

The inclusion of technological change within the model did not warrant the inclusion of any additional technologies within the analysis, however did influence the cost of those included.

[10] Grant Faber et al., 'Adapting Technology Learning Curves for Prospective Techno-Economic and Life Cycle Assessments of Emerging Carbon Capture and Utilization Pathways', *Frontiers in Climate* 4 (14 April 2022): 820261, https://doi.org/10.3389/fclim.2022.820261.

3. Model results:

3.1 Summary results

Figure 3-1 shows a summary of aggregate UK emissions across all three pathways. Total emissions in the baseline grow from 2.8 $MtCO_2e$ in 2021 to 3.0 $MtCO_2e$ in 2050. This represents a 7% increase in emissions. The Balanced pathway reduces emissions to 2.09 $MtCO_2e$ in 2050, representing a 26% decrease in annual emissions from 2021. The Balanced pathway results in a cumulative abatement of 17.9 $MtCO_2e$ in the period 2021 to 2050. The Additional Action pathway reduces emissions to 1.31 $MtCO_2e$ in 2050, representing a 62% decrease in annual emissions from 2021. The Additional Action pathway results in a cumulative abatement of 26.3 $MtCO_2e$ in the period 2021 to 2050.

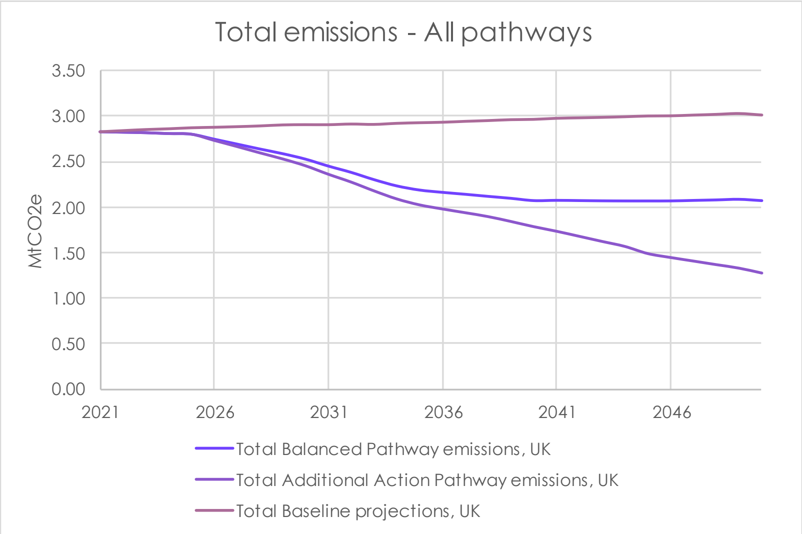


Figure 3-1 – Aggregated UK emissions pathways for baseline projections, BP, and AAP

Table 7 - Summary statistics for emissions reductions

Sector	Pathway	GHG	% reduction in 2050 vs 2021
Municipal	BP	N_2O	47%
		CH_4	14%
	AAP	N_2O	78%
		CH_4	45%
Industrial	BP	N_2O	48%
		CH_4	17%
	AAP	N_2O	79%
		CH_4	41%

As discussed in section 2.1.2, an alternative emissions factor for N_2O can significantly alter the outputs of this model. Figure 3-2 shows the impact of selecting the alternative N_2O emissions factor (0.016 kg N_2O-N/kg N) on total emissions profiles for the three pathways, and Table 8 summarises 2050 emissions under the two emission factor scenarios.

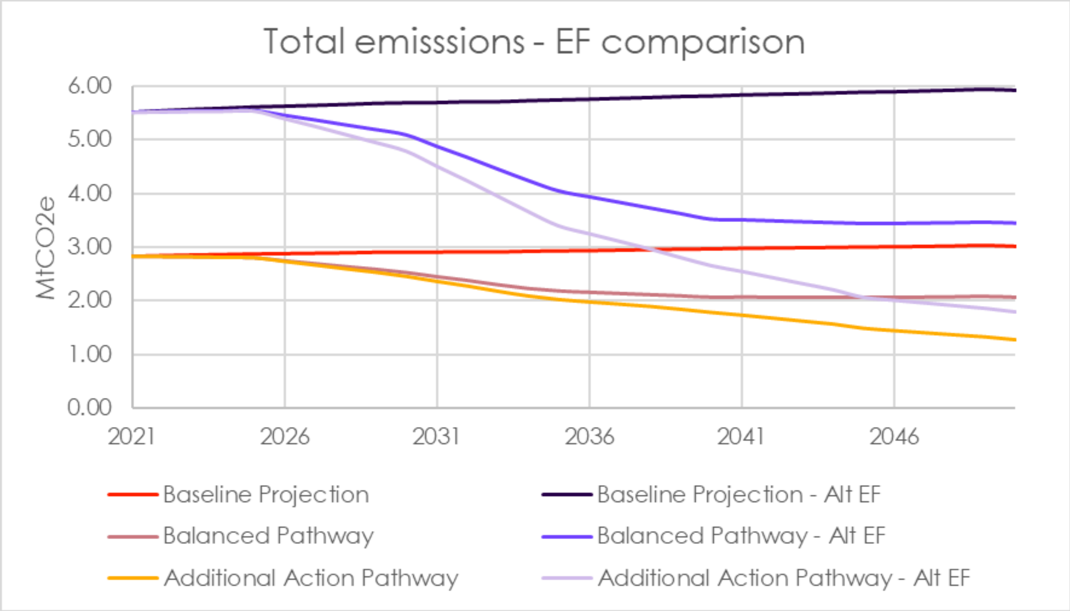


Figure 3-2 comparison between CAW and IPCC 2019, on total emissions across pathways

Table 8 - UK 2050 emissions under central and alternative emissions factors

Pathway	Central emissions factor (CAW) 2050 emissions ($MtCO_2e$)	Alternative emissions factor (IPCC) 2050 emissions ($MtCO_2e$)
Baseline Projection	3.0	5.9
Balanced Pathway	2.1	3.5
Additional Action Pathway	1.3	1.8

3.2 Baseline projections

Under the baseline scenario, total wastewater emissions in the UK increase by 7.1% by 2050, from 2.82 $MtCO_2e$ in 2021, to 3.02 $MtCO_2e$ in 2050 (Figure 3-3). For both CH_4 and N_2O, industrial and municipal emissions increase by the same rate in the baseline scenario. As energy consumption and total wastewater emissions are directly aligned with population growth, all energy sources and emissions see the same 7.1% energy increase through this period, as shown in Figure 3-4 and Appendix 3.

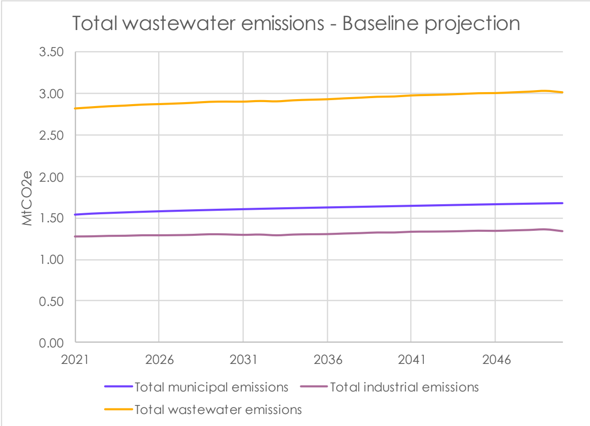


Figure 3-3 - Baseline projection emissions

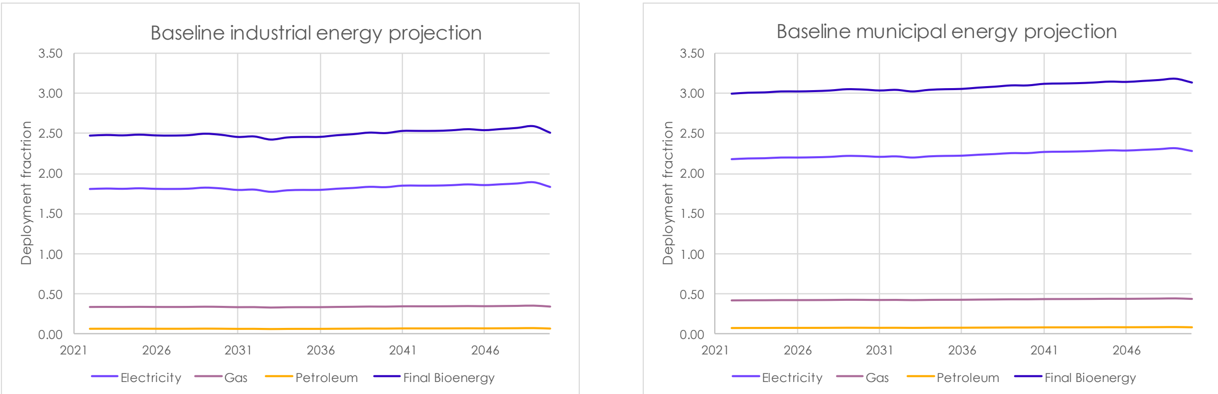
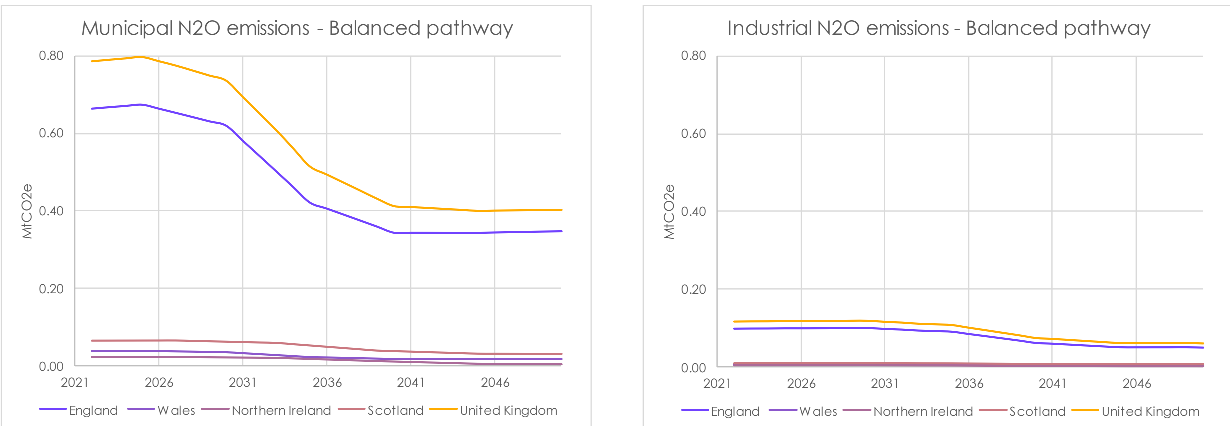


Figure 3-4 – Baseline projection energy demand, by sector

3.3 Balanced Pathway

UK municipal N_2O emissions fall by 47% between 2021 and 2050 in the Balanced Pathway; from 0.79 $MtCO_2e$ to 0.41 $MtCO_2e$. In comparison, UK industrial N_2O emissions fall by 48% between 2021 and 2050; from 0.12 $MtCO_2e$ to 0.06 $MtCO_2e$. UK municipal CH_4 emissions fall by 14% between 2021 and 2050; from 0.76 $MtCO_2e$ to 0.65 $MtCO_2e$. In comparison, UK industrial CH_4 emissions fall by 17% between 2021 and 2050; from 1.17 $MtCO_2e$ to 0.96 $MtCO_2e$. Figure 3-5 presents an overview of Balanced Pathway emissions for the municipal and industrial sector respectively.



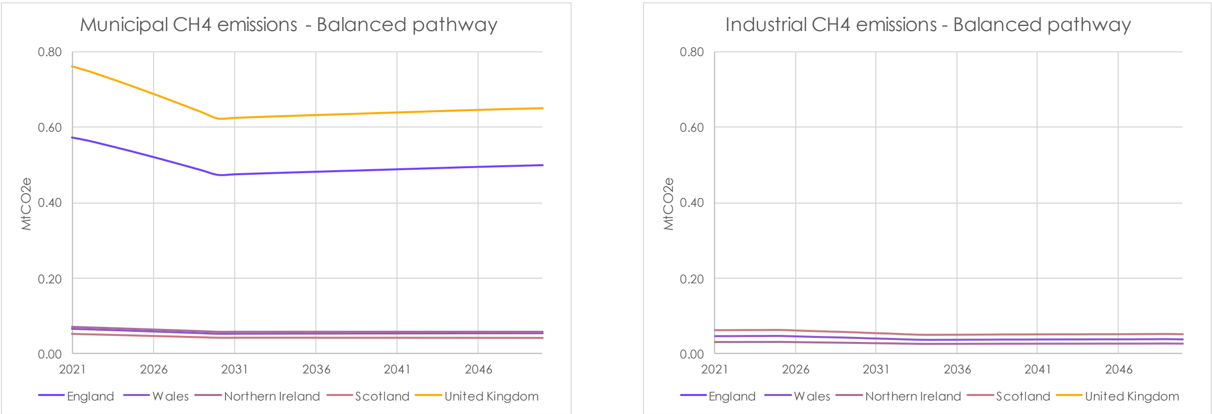


Figure 3-5 - Balanced Pathway emissions by sector, by greenhouse gas

3.4 Additional Action Pathway

UK municipal N_2O emissions fall by 78% between 2021 and 2050; from 0.79 $MtCO_2e$ to 0.17 $MtCO_2e$. In comparison, UK industrial N_2O emissions fall by 79% between 2021 and 2050; from 0.12 $MtCO_2e$ to 0.02 $MtCO_2e$. UK municipal CH_4 emissions fall by 45% between 2021 and 2050; from 0.76 $MtCO_2e$ to 0.42 $MtCO_2e$. In comparison, UK industrial CH_4 emissions fall by 41% between 2021 and 2050; from 1.17 $MtCO_2e$ to 0.69 $MtCO_2e$.

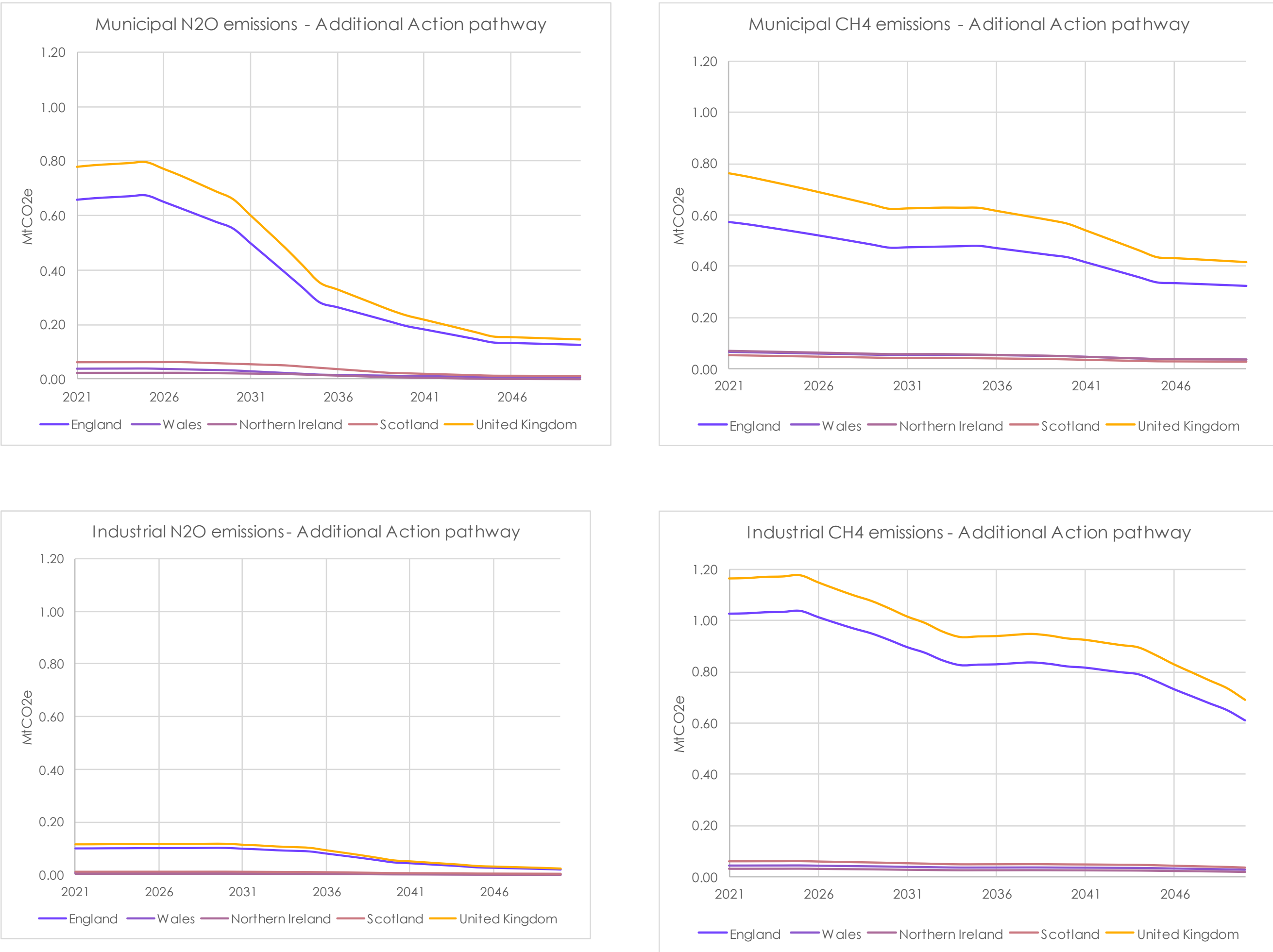


Figure 3-6 – Additional Action pathway emissions by sector, by greenhouse gas

Whilst the Balanced and Additional Action pathways decarbonise at a similar rate initially, as more expensive and effective technologies such as High Strength Liquor Treatment develop, the Additional Action pathway begins to provide significant further reductions compared to the Baseline pathway from 2030 onwards, resulting in a large difference between each pathway by 2050, as can be seen in Figure 3-1.

3.5 Costs

Capex and Opex per unit abatement were determined using data disclosed in the WASC business plans as discussed in section 2.4.2. Figure 3-7 shows aggregated UK Capex and Opex for both emissions reductions pathways, indicating that total Capex reaches approximately £100m by 2050 for the Balanced Pathway, and £200m for the Additional Action Pathway, though noting the high uncertainty within these figures. Total Opex reaches £25m/yr by 2050 for the Additional Action Pathway and <£5m per year for the Balanced Pathway, though noting that the Balanced Pathway Opex only includes MABR and Covering and containment (as below).

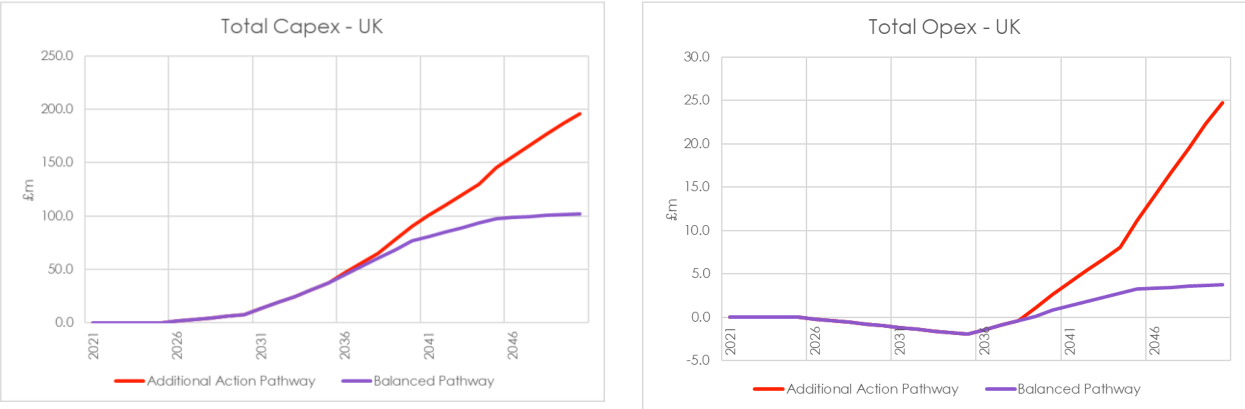


Figure 3-7 – Total UK Capex and Opex profiles for Balanced Pathway and Additional Action Pathway

As discussed, data limitations prevented the inclusion of AAD costs within the cost pathways. WASC business plans also reported zero Opex cost for Monitoring, Real Time Control and Digital Twin technologies. As such, Opex profiles for the Balanced Pathway represent only Covering and containment (with a negative Opex reported by WASCs) and MABR. Due to deployment timings, this results in initially declining Opex costs until MABR is first implemented, which eventually outweighs the impact of Covering and containment, leading to positive Opex costs. See Appendices 4 and 5 for more cost results.

4. Key uncertainties and limitations

This modelling exercise drew on best available data to evaluate wastewater treatment decarbonisation technologies and develop baseline and emissions reduction pathways to 2050. However significant uncertainty remains across wastewater decarbonisation data, with the below having a particularly significant influence on pathway results:

- **Emissions factors**: As highlighted in Section 2.1.2, nitrous oxide emissions factors remain a significant uncertainty amongst the wastewater treatment sector, however consensus amongst WASCs appears to be that the IPCC 2019 guideline figure is more accurate than the current Carbon Accounting Workbook value, indicating the possibility of underreporting emissions by a factor of four. The sensitivity analysis conducted using the IPCC 2019 emissions factor suggests that if this alternative emissions factor is used, 2050 residual emissions are twice as high at 6 $MtCO_2e$.

- **Cost data**: Technology abatement costs, Capex and Opex values derived from WASC business plans were based on small site-specific sample sizes, extrapolated from maximum 5 (and often fewer) years of data. The resulting cost estimates ranged considerably, at times by order of magnitude. As such cost profiles should be treated with caution. The application of technologies to individual sites relies on site specific criteria that cannot be considered at the scale of this study. Thus, maximum site coverage and therefore total emission impact upon deployment of specific technologies contains significant uncertainty. The same site-specific criteria also have significant Capex, Opex, and energy intensity implications, meaning that cost and energy use data also carries uncertainty. The pilot or first installations of intervention technologies are unlikely to take place in challenging sites, and therefore the disclosed costs are likely to be more representative of a best-case installation scenario.

- **Decarbonisation impact**: The decarbonisation impact of each technology was reported as broad ranges within source material (largely Severn Trent's Net Zero Investment Plan), reflecting a limitation in available ex-post data on the demonstrated decarbonisation impact of many decarbonisation technologies, owing to their relative nascency. We took a conservative approach when drawing on this data, utilising lower bounds of reported ranges, and treating abatement across certain technologies (e.g. MABR and Covering and containment) as mutually exclusive. However the cumulative impact of decarbonisation technologies on wastewater emissions is not well known.

- **Energy demand**: Baseline energy demand was estimated through extrapolation of WASC reported demand, using population served. For England, this was done only using Thames Water data, therefore introducing significant uncertainty. As noted in Section 2.2.2, additional demand associated with decarbonisation technologies was not included within the analysis due to data constraints, however AAD in particular would incur increased energy demand.

5. Appendix

Appendix 1 - Assumptions log (see accompanying model for full version)

Type of assumption	Scenario	Plain English description with key details	Assumption value(s)
Base year CH_4 and N_2O emissions	Baseline projection	The base year emissions for municipal and industrial emissions for each devolved nation were extracted from the NAEI database.	$MtCO_2e$ N_2O, municipal + industrial England: 0.8 Wales: 0.04 Scotland: 0.07 Northern Ireland: 0.03 $MtCO_2e$ CH_4, municipal + industrial England: 1.6 Wales: 0.1 Scotland: 0.1 Northern Ireland: 0.1
Technology annual abatement potential	BP + AAP	Where abatement derived from draft BP spreadsheets from WASCs, assume the final year abatement as annual abatement, to gauge abatement potential once installed (as opposed to taking an average that includes ramping up period)	GHG impact on deployment Covering and containment, enhanced monitoring and RTC, digital twin: 65% MABR: 35% AAD: 21% High strength liquor treatment: 20% Vacuum extraction of methane: 40%
Decarb technology asset lifetimes	BP + AAP	For the purpose of calculating abatement costs, assets have been assumed to have a 30 year lifetime to split CAPEX across the lifetime of the asset.	30
Discount rate	BP + AAP	Used to calculate technology abatement costs	3.5%

Type of assumption	Scenario	Plain English description with key details	Assumption value(s)
Municipal electricity consumption	Baseline projection	Data from CAWs - electricity purchased. This does not include electricity that may have been self-generated and used in operations. Used values with activities of Treatment, Pumping, and Sludge.	In TWh: England: 1.45 Scotland: 0.33 Wales: 0.2 Northern Ireland: 0.19
Municipal fuel consumption	Baseline projection	Data from CAWs - natural gas, biogas, diesel, and gas oil. Used values with activities of Pumping, Treatment, Sludge, and CHP.	In TWh: England: 2.99 Scotland: 0.3 Wales: 0.18 Northern Ireland: 0.015
Industrial energy consumption	Baseline projection	For each devolved nation, the industrial electricity and fuel consumption mirrored the municipal consumption. It was scaled up/down by the ratio of industrial to municipal emissions.	
Tech deployment start year - municipal	BP + AAP	The soonest-possible deployment start year was based on technology maturity and abatement cost compared to carbon pricing. For the municipal sector, the actual deployment start year aligned with the next price regulatory period. The technology deployment start year for the industrial sector was set at 5 years following the earliest deployment year in the municipal sector.	Covering and containment, enhanced monitoring and RTC, digital twin England and Wales: 2025 Scotland and Northern Ireland: 2027 MABR England and Wales: 2030 Scotland and Northern Ireland: 2033 AAD England and Wales: 2021 Scotland and Northern Ireland: 2021 High strength liquor treatment: England and Wales: 2035 Scotland and Northern Ireland: 2033 Vacuum extraction of methane England and Wales: 2035 Scotland and Northern Ireland: 2033
Tech deployment rate	BP + AAP	For both the municipal and industrial sectors, technologies were deployed in three tranches. 20% of technology roll-out occurred in tranche 1 by 'leaders', 60% of technology roll-out occurred in tranche 2 by the majority, and the remaining 20% was rolled out in tranche 3 by 'laggards'. In the municipal sector, these tranches aligned with the price regulation periods of each devolved nation. In the industrial sector, these tranches aligned with the price	Deployment Tranche 1: 20% Tranche 2: 60% Tranche 3: 20%

Type of assumption	Scenario	Plain English description with key details	Assumption value(s)
		regulation periods of whichever devolved nation was first to deploy to technology - but occurred five years later.	
Municipal energy consumption	Baseline projection	For devolved nations, energy consumption was extracted from relevant water company's CAW and then scaled up/down based on ratio of population served by wastewater services (figure from CAW) and the population of nation. This was done for NI and Wales, but not Scotland because Scottish Water did not have a figure for population served. For the preliminary results, England's figures were scaled up from the figures for Thames Water. For the final results these figures will be from all of England's WASCs.	England: 3.76 Scotland: 1 Northern Ireland: 1.2 Wales: 1.02
Capex/£MtCO$_2$e	BP + AAP	The capex for a technology was estimated using WASC business plans and scaled up by the total carbon abated by that technology in a devolved nation.	Abatement capex: £m/MtCO$_2$e Covering and containment: 109 Enhanced monitoring and RTC: 170 Digital twin: TBC MABR: 2963 AAD: TBC High strength liquor treatment: 2501 Vacuum extraction of methane: 266

Type of assumption	Scenario	Plain English description with key details	Assumption value(s)
Opex/MtCO$_2$e	BP + AAP	The Opex for a technology was estimated using WASC business plans and scaled up by the total carbon abated by that technology in a devolved nation.	Abatement Opex: £m/MtCO$_2$e Covering and containment: -29 Enhanced monitoring and RTC: 0 Digital twin: TBC MABR: 415 AAD: TBC High strength liquor treatment: 997 Vacuum extraction of methane: 54
Immature technology cost reduction	BP + AAP	Technologies judged to be immature were subject to a learning curve function which reduced their capex/MtCO$_2$e and Opex/MtCO$_2$e factors over time. The greatest cost reduction rate occurs early in the deployment, with the learning curve effect having less impact over time.	10% learning rate
Maximum site coverage potential	BP + AAP	Covering and containment was deemed to be suitable for most activated sludge plants based on population served as opposed to the number of activated sludge sites. This technology is also mutually exclusive to MABR. MABR technology can be retrofitted into existing ASP sites, however coverage of this may be limited based on existing site footprint and limitations and technology is mutually exclusive to covering and containment. Advanced anaerobic digestion in form of THP is already well established in the UK and variations of this technologies have been reported in Jacob's Net Zero Report.	70% for covering and containment, enhanced monitoring and RTC, digital twin 10% for MABR 100% for advanced anaerobic digestion 70% for high strength liquor treatment 70% for vacuum extraction of methane
Industrial emissions projections	Baseline projection	The emissions projections for industrial wastewater followed the projection used in the 2019 Greenhouse Gas	

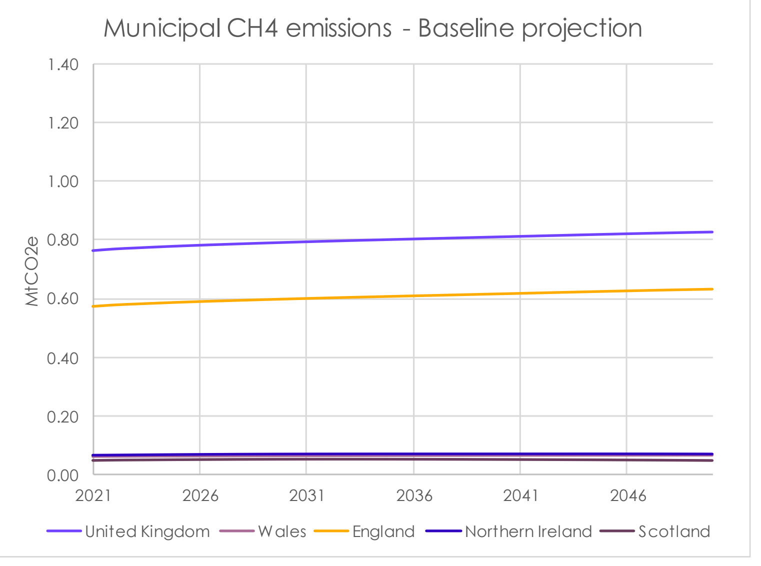
Type of assumption	Scenario	Plain English description with key details	Assumption value(s)
		Inventory Improvement Programme: Wastewater modelling refinement report by Ricardo (page 29.)	
Municipal emissions projections	Baseline projection	The emissions projections for municipal wastewater followed population projections for each devolved nation.	
Population served by the type of wastewater treatment plants suitable for emissions reductions	BP + AAP	Activated sludge plants have been assumed to account for 20% of the total plant types, however accounted for 80% of the PE being served based on historic June Return numbers from OFWAT (2011) and more recent 2019 numbers from DCWW.	80%
Balanced pathway technologies	BP	N_2O abatement technologies: - Covering and containment, enhanced monitoring and RTC, digital twin - MABR CH_4 abatement technologies: - AAD	
Additional action pathway technologies	AAP	N_2O abatement technologies: - Covering and containment, enhanced monitoring and RTC, digital twin - MABR - High strength liquor treatment CH_4 abatement technologies: - AAD - Vacuum extraction of methane	

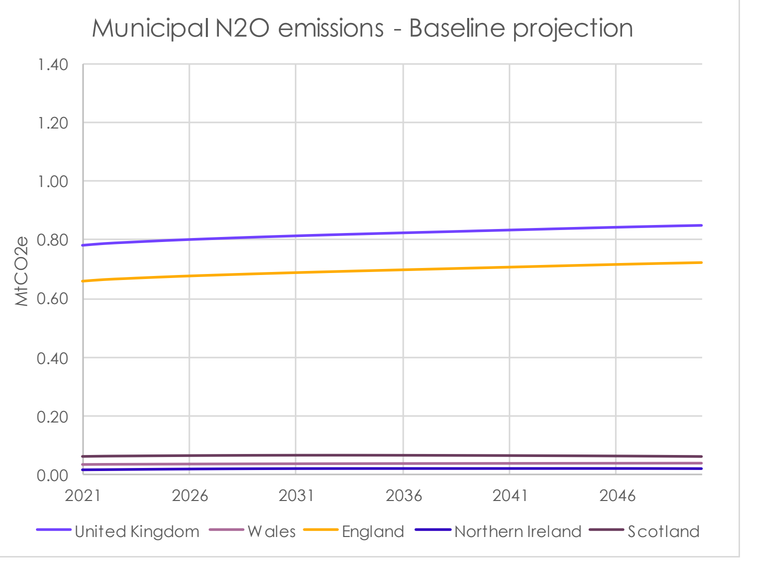
Appendix 2 - Technology interventions summary table

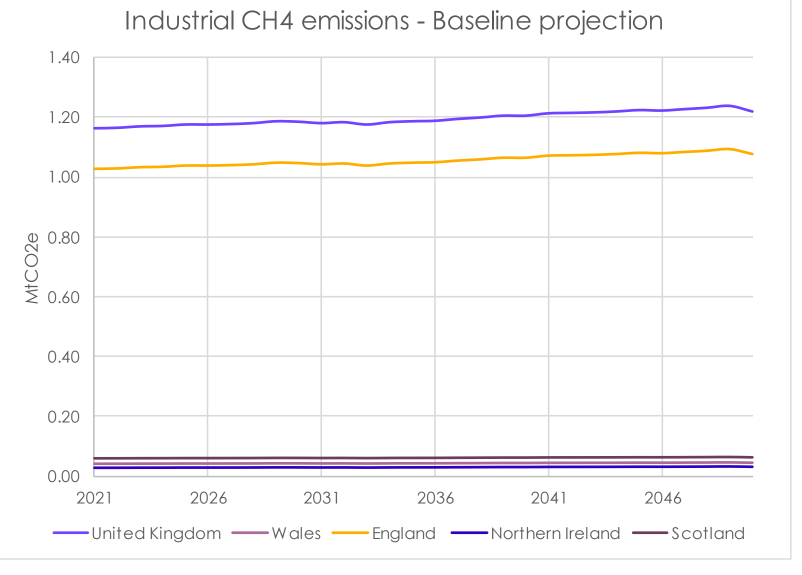
Technology	Description	Technology maturity (Technology Readiness Level)	Emission source targeted	Selected abatement cost value (£/tCO_2e)	Source for lifetime abatement
Covering and Containment	Covering ASP process or liquor treatment plants using forced aeration to contain, reduce and/or eliminate N_2O emissions	TRL = 7 Severn Trent have one site and one trial installation	N_2O	109	Severn Trent Net Zero Investments
Enhanced monitoring and Real Time Control (RTC)	Monitoring emissions and treating root cause (either by extending aeration or allowing for complete denitrification) via feedback from live N_2O monitors	TRL = 8 Demonstrated at scale in Denmark, but more development is required to refine and optimise set-points	N_2O	170	
ASP Denitrification	Offers reduced aeration input and allows for TN removal. Risks process emissions from denitrification if not operated adequately. This may require new/larger anoxic tanks to allow for complete denitrification.	TRL = 9 Technology is mature, but most ASPs in England and Wales are not enabled for denitrification through sufficiently sized anoxic treatment zones, limiting rollout or requiring additional capital infrastructure to implement.	N_2O	317	Severn Trent Net Zero Investments
High strength liquor treatment	N_2O treatment for liquors and side streams to reduce N_2O emissions. Main treatment works (ASP) to be upgraded to prevent N_2O formation pathway	TRL = 5 Currently under investigation in Denmark and elsewhere in Europe	N_2O	145	Severn Trent Net Zero Investments
MABR	Oxygen is provided to the attached biomass on the membrane. MABR (counter diffusion) can reduce emissions when compared to conventional biofilm process.	TRL = 7 Only demonstrated in 1-2 sites	N_2O	321.5	Anglian Water for derived abatement cost Severn Trent Net Zero Investments
Nutrient recovery from wastewater (chemical, ion exchange)	Reduced requirement for forced aeration and potential N_2O emissions, but increases chemical costs.	TRL = 6 Piloted as part of SMART Plant project, and continue to be trialled by Cranfield University and Severn Trent Water and by Ofwat in their "Transforming the Energy Balance of Wastewater Treatment" innovation project	N_2O		n/a
Digital twin	Optimising ASP process parameters to reduce process emissions	TRL = 8 Already in place at different levels, ranging from simplistic processes to treatment trains or whole treatment works	N_2O	130	Severn Trent Net Zero Investments
Anaerobic MBR (AnMBR) to achieve Biological Nitrogen Removal (BNR)	Membrane based technologies used for BNR - containment of N_2O will still be required	TRL not stated. Severn Trent demonstrated the potential in their business plan, but are still in the academic research stage with plans to move through to pilot studies and on to full-scale demonstrations.	N_2O	321.5	Assumed same as MABR

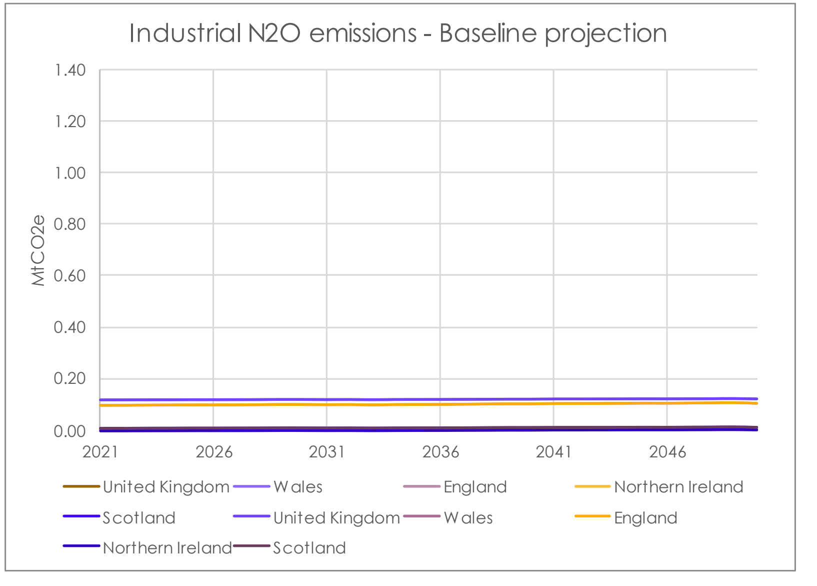
Enhanced methane monitoring and proactive mitigation, containment processes	Identify leak sources of methane at various stages of the WwTP, mitigation of these leak sources and containment	TRL = 7 Has been used outside of sector plus existing reactive work in UK though quantification lacking. Used outside of the UK, e.g. in Denmark	CH_4		Severn Trent Net Zero Investments
Biomethane upgrade to grid	Upgrade biogas to biomethane as a natural gas substitute and inject into grid. Has potential to reduce emissions	TRL = 9 Full scale implementation at multiple sites in the UK	CH_4	172	
Vacuum extraction of methane	Sludge exiting AD 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 with 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.	TRL = 7 Trials in the UK, successful implementation in Denmark. Further developments are also being made in Denmark to apply vacuum extraction on sludge storage tanks rather than immediately downstream of digestion	CH_4	271	Severn Trent Net Zero Investments
Advanced anaerobic digestion: thermal hydrolysis	Thermal hydrolysis elevates 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. Used for increasing yield of biogas recovery from sewage sludge - does not necessarily reduce CH_4 emissions	TRL = 9 Thermal hydrolysis is demonstrated at several sites outside the UK, but not at scale, and the energy balance remains unclear.	CH_4	234	Identified in Severn Trent Net Zero Investment report
Intermediate thermal hydrolysis	Intermediate Thermal Hydrolysis (iTHP), applies the process to Secondary Activated Sludge (SAS) instead of a SAS and Primary Sludge (PS) mix, potentially reducing natural gas need and improving biogas production efficiency. It doesn’t necessarily reduce methane emissions.	TRL = 8 Thames Water have reported that this is more efficient than normal thermal hydrolysis, however it has not been demonstrated at scale and large material footprint requires site-by-site suitability assessment.	CH_4	234	Assumed from cellulose recovery technology identified in Severn Trent Net Zero Investment report
Sewage sludge pyrolysis and/or gasification	Gasification heats to >500C sludge in the absence of oxygen. This releases volatile solids as a combustible syngas, producing an ash. 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.	TRL = 7 Has been demonstrated in the UK, but not progressed to widespread and large scale use. Current technology requires consistent feedstock, and the abrasive nature of sludge can result in high maintenance costs.	CH_4	234	Assumed from cellulose recovery technology identified in Severn Trent Net Zero Investment report
Dissolved methane recovery using membranes	Being piloted to recover dissolved membrane from anaerobic MBR effluent	TRL = 6 Membrane technologies are being piloted by Cranfield University and Severn Trent Water	CH_4		Assumed the same as MABR - but no basis for assumption other than novel tech and membrane based

Appendix 3 - Baseline emissions projections

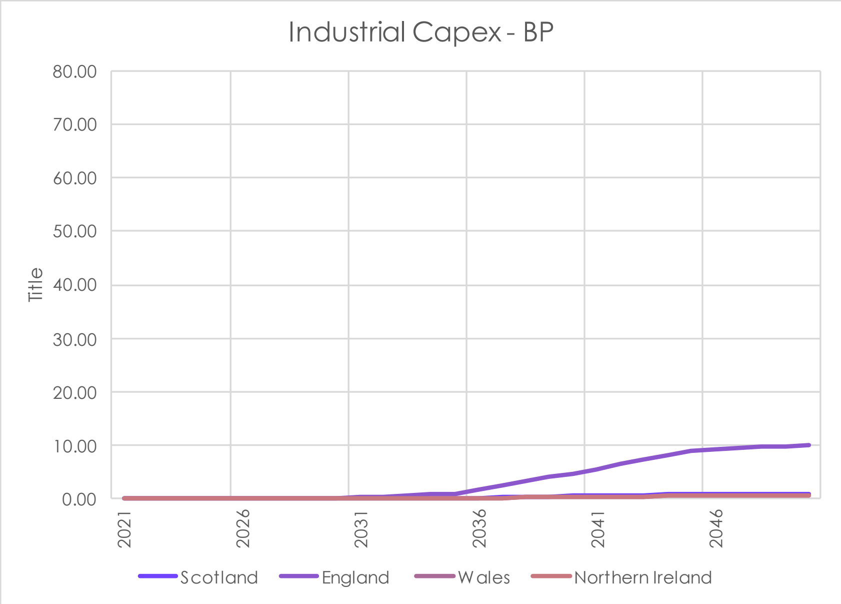


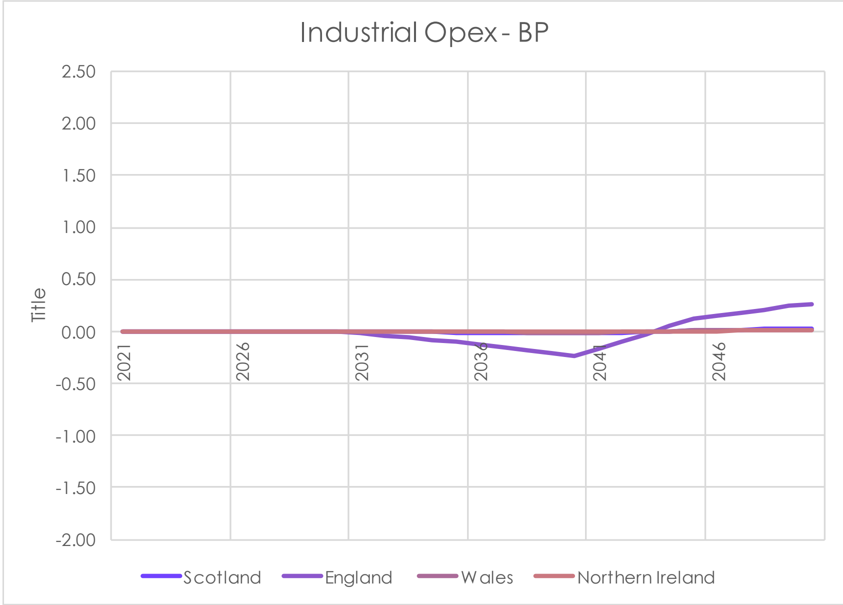


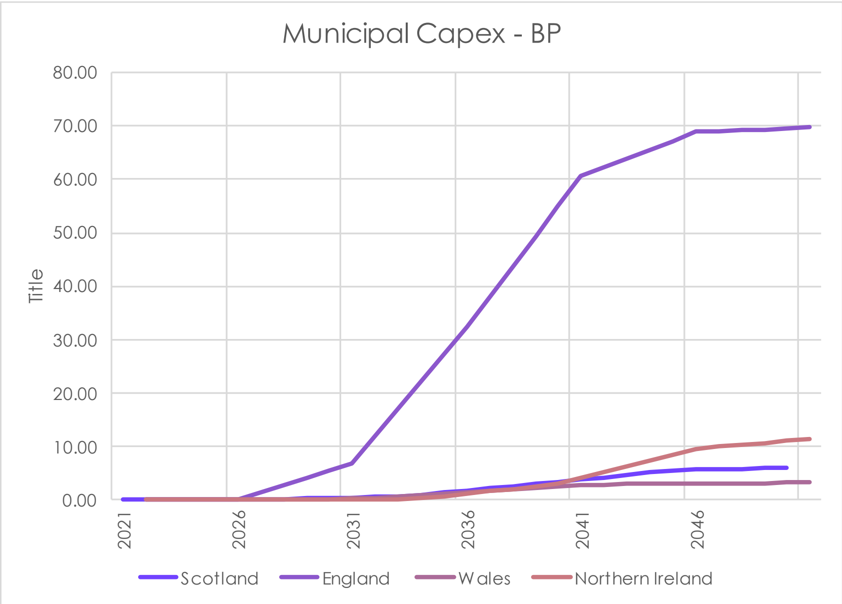


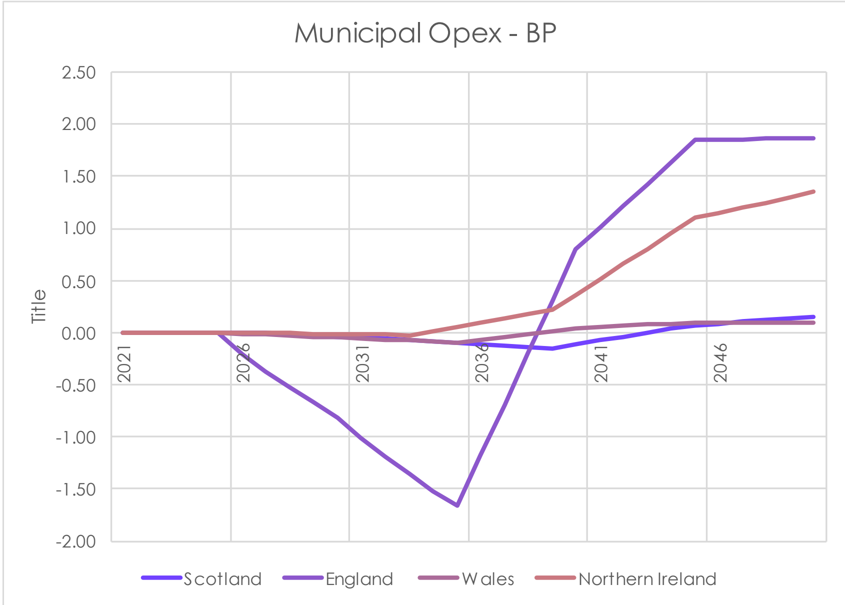


Appendix 4 – Capex and Opex graphs for the Balanced pathway









Appendix 5 -Capex and Opex graphs for the Additional Action pathway