doi: 10.2166/9781789060461_63

Chapter 4

Reporting guidelines

Ariane Coelho Brotto[1] *and Amanda Lake*[2]

[1]*Jacobs, Cottons Lane, London SE1 2QG, UK. E-mail: ariane.brotto@jacobs.com*
[2]*Jacobs, 160 Dundee Street, Edinburgh EH11 1DQ, Scotland. E-mail: amanda.lake@jacobs.com*

SUMMARY

The *Reporting Guidelines* chapter focuses on the accounting methodologies and protocols supporting top-down greenhouse gas (GHG) emissions assessment and reporting of relevance to the urban water system in wastewater treatment of domestic and industrial wastewaters. It summarizes the basis for existing methane (CH_4) and nitrous oxide (N_2O) emission factors, the three-tier approach set out in the internationally accepted Intergovernmental Panel on Climate Change (IPCC) methodology and areas where further work is required. This chapter also summarizes the implications of the 2019 IPCC Refinement on the magnitude of N_2O emissions from secondary treatment, as well as country-specific emission factors developed through national bottom-up monitoring. Finally, this chapter highlights the importance of bottom-up approaches in understanding the opportunities to optimize treatment processes and conditions that minimize direct GHG emissions and help move the water industry towards net zero GHG emissions.

Keywords: Bottom-up, emission factor, emission inventory, IPCC, methodology, top-down

TERMINOLOGY

Term	Definition
Bottom-up	Estimation of emissions based on direct on-site measurement of concentration and emission fluxes, typically at the facility level.
Fugitive emissions	Intentional or unintentional emissions of greenhouse gas that are not produced intentionally by a stack or vent, which may include leaks from process units and pipelines.
Greenhouse gas	Gas that absorbs and emits radiant energy within the thermal infrared range.
Greenhouse gas inventory	Accounting of all greenhouse gas emissions and removals from given sources and sinks from a defined region in a specific period of time.
Methodology	A specific accounting guideline with a foundational set of equations and emission factors based on scientific and applied research to estimate emissions, typically at organizational or regional level.

Protocol	A standardized framework for measuring and reporting GHG emissions. These are usually based on the guiding principles of relevance, completeness, consistency, accuracy and transparency.
Tier 1 method	The IPCC Tier 1 method applies default values for an emission factor and activity parameters. It is considered good practice for countries with limited data.
Tier 2 method	The IPCC Tier 2 method follows the same method as Tier 1 but allows for incorporation of a country-specific emission factor and country-specific activity data, which could include country-specific factors and/or field measurement data from the reporting country.
Tier 3 method	The IPCC Tier 3 method is applied for a country with good data and advanced methodologies. It applies country-specific factors and field measurement data at a country and/or facility level.
Top-down	Estimation of GHG emissions based on generalized equations and emissions factors applied to activity data.

4.1 INTRODUCTION

The influence of human activities on the world's climate system is unequivocal – the unparalleled levels of greenhouse gas (GHG) emissions since pre-industrial times have already caused an estimated 1.09°C (range 0.95–1.2°C) of global warming above pre-industrial levels (IPCC, 2021). Human-induced climate change is already affecting many weather and climate extremes in every region across the globe, resulting in significant and increasingly catastrophic impacts on communities, as well as on ecosystems and natural resources. Under all emissions scenarios, global warming is likely (ranging from *very likely* to *more likely than not*) to exceed 1.5°C between 2021 and 2040 (IPCC, 2021). Limiting global warming to 1.5°C to meet the Paris Agreement will require sharp GHG reduction to net zero emissions by 2050 (Rogelj *et al*., 2018).

The management of domestic and industrial wastewaters causes anthropogenic GHG emissions throughout the urban water cycle. These GHG emissions are related to fossil derived energy (electricity and heat) use for water abstraction, treatment and conveyance, and for wastewater collection and treatment, as well for direct GHG emissions from the treatment processes. Emissions also occur when wastewaters are discharged, treated or untreated, to the environment from centralized and decentralized systems. This includes the discharge of sewage effluent to the environment and, where applicable, the application of sludge residuals, or biosolids, to land. This chapter considers emissions from sewage conveyance and at wastewater treatment plants (WWTPs) but not emissions from natural treatment systems (e.g., wetlands), and from the release of final effluent or sludge residuals to the environment.

Methane (CH_4) and nitrous oxide (N_2O) are the main GHGs emitted during the collection and treatment of wastewater and in the on-site treatment and management of sludge residuals. These direct process emissions are required to be reported under international agreements and are gaining increased attention with the continued reduction of indirect energy-related GHG due to decarbonization of electricity grids with renewable energy. Of particular importance to the water sector, and as discussed in Section 4.2, the relative warming impact (global warming potential, GWP) of CH_4 and N_2O are substantially greater than that of carbon dioxide (CO_2). As a result, these process emissions may form a very substantial part of a facility's operational carbon emissions.

The United Nationals Framework Convention on Climate Change (UNFCCC), an international treaty which came into force in 1994 and seeks to reduce emissions of GHGs, requires Parties to develop, update and publish national emissions inventories. National GHG inventories are essential tools for transparent reporting of anthropogenic emissions and removal of GHGs. The Intergovernmental Panel on Climate Change (IPCC) provides global guidelines and methodologies for quantifying GHG emissions for these national GHG inventories, including for CH_4 and N_2O from wastewater treatment. Guidelines provide a basis for the mutual trust and confidence that are needed for effective implementation of international agreements to address climate change and provide an essential tool for developing policies and monitoring impact (Bartram *et al*., 2019).

In 2015, an historic agreement was reached in Paris between 196 Parties of the UNFCCC. The Paris Agreement seeks to limit global temperature increase to well below 2°C and requires efforts to limit global temperature increase to 1.5°C above pre-industrial levels. It requires each Party to prepare, communicate and maintain successive nationally determined contributions (NDCs) for GHG emissions that it intends to achieve. NDCs must be reported every five years, using international guidance provided by the IPCC. The Paris Agreement allows for a first 'global stocktake' of emissions in 2023 and a review every five years after, with the aim that Parties increase their mitigation efforts and ambition through successive reviews (IPCC, 2020b).

In alignment with the Paris Agreement, countries, local governments, and economic sectors around the world are pledging to achieve net zero within the decades leading up to the recognized requirement for net zero by 2050 to minimize global heating. Reliable accounting of GHG inventories, aligned with international guidelines, are essential within all these spheres of influence to evaluate the magnitude of emissions as accurately as possible and to assess the efforts required to achieve target GHG reductions.

This chapter focuses on the accounting methodologies and protocols supporting top-down GHG emissions assessment and reporting of relevance to wastewater collection and treatment and to water utilities and water industry sectors. It summarizes the basis for existing N_2O and CH_4 emission factors from wastewater collection and treatment, the three-tier approach set out in the internationally accepted IPCC methodology and considerations of how this is being applied, including ongoing work and challenges in the development of country-specific emission factors (EFs) through national monitoring. It explains the implications of the 2019 IPCC Refinement on the magnitude of N_2O emissions from secondary treatment and the development of a revised EF for N_2O. It also considers uncertainty in accounting methodologies and protocols as defined by the IPCC. The following chapters of this book address issues of uncertainty in emissions and emission factors across sites and process types and uncertainty around measurement and analysis methods.

Finally, this chapter highlights the importance of bottom-up approaches in understanding the opportunities to optimize treatment processes and conditions that minimize direct GHG emissions and help move the water industry towards net zero GHG emissions.

4.2 ACCOUNTING CONSIDERATIONS

This section provides an overview of accounting considerations in applying GHG protocols and international best practice. It first considers how wastewater treatment emissions are defined in carbon accounting practice and then the basis for accounting methodologies – defining the concepts of top-down and bottom-up accounting.

4.2.1 Reporting scope considerations for the water industry

GHG emissions can be quantified and reported, whether by country, company or other organization/individual, by Scope. The commonly accepted definitions of emissions Scope 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, that is direct (Scope 1) and indirect (Scope 2 and 3) emissions (Greenhouse Gas Protocol, 2020a, 2020b). These are shown below in Figure 4.1.

The GHG Protocol establishes comprehensive global standardized frameworks to measure and manage greenhouse gas (GHG) emissions from private and public sector operations, value chains and mitigation actions – including for the water sector. Within the water sector, ownership and reporting of emissions as Scope 1 or 3 may be differentiated depending on the type of organization and defined reporting boundaries.

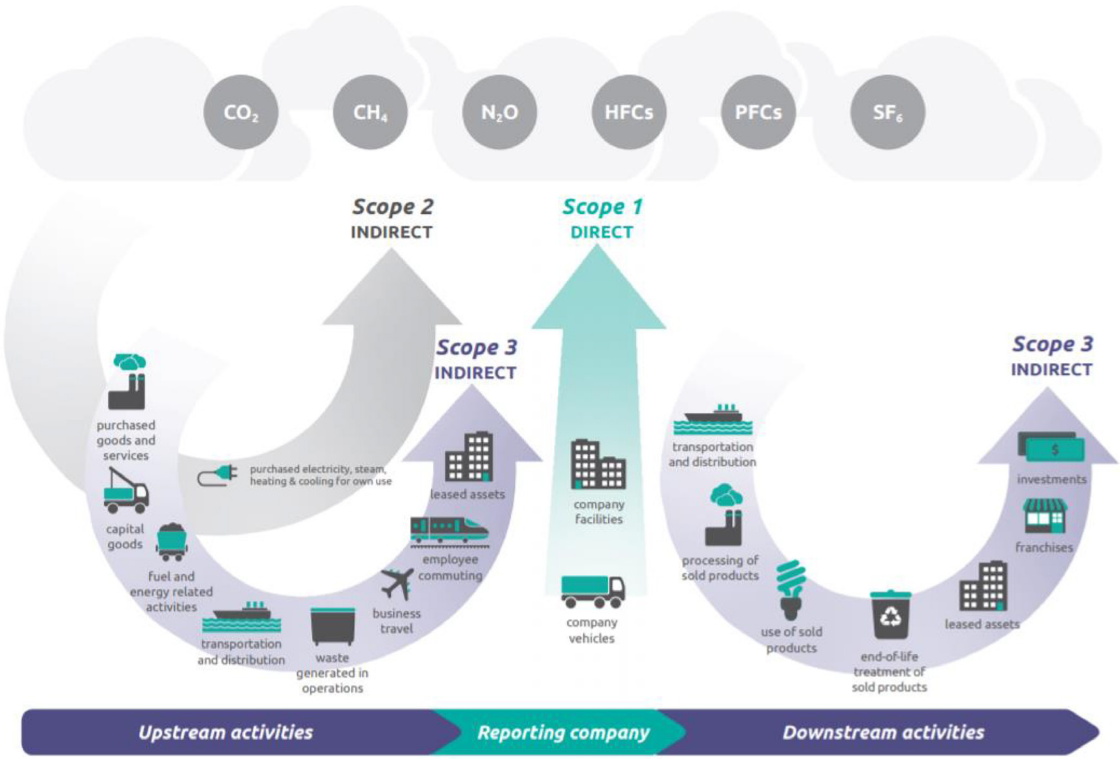

Figure 4.1 Sources and categories of GHG emissions for corporate reporting (Greenhouse Gas Protocol, 2020a, 2020b). HFCs, hydrofluorocarbons; PFCs, perfluorocarbons. With thanks to the World Resources Institute - licensed under a creative commons licence (http://creativecommons.org/licenses/by-nc-nd/3.0)

Reference is also made to the International Standards Organization ISO 14064-1:2018 Greenhouse Gases: Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals. This provides definitions for six categories of GHG emissions and removals for an organization to consider in reporting.

Regional water companies, which may be public or privately owned and provide water services over a regional geography such as city, state, country or other geographic area, usually adopt what is called the control approach (relating to either financial or operational control). Under this approach, these companies account for 100% of all the emissions from operations over which they have control. The relevant international best practice for reporting their emissions is the GHG Protocol Corporate Standard (Greenhouse Gas Protocol, 2015, 2020a, 2020b).

This defines scopes and examples for the waste sector (with respect to 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 (e.g., N_2O emissions from the oxidation of ammoniacal nitrogen in sewage 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 (e.g., 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 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, and 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.

It is noted that CO_2 produced during biological wastewater treatment through biological processes is considered biogenic and not included in reporting. However, CO_2 emissions which occur as a result of fossil carbon in feedstocks used to manufacture a wide range of personal care and/or cleaning products which find their way into sewer systems and onto treatment facilities should be considered for inclusion.

Municipal water companies which are publicly owned and affiliated with a city may adopt a geographic boundary approach, differentiating emissions occurring physically within and outside the city boundary. Global best practice in this case would follow the GHG Global Protocol for Cities – for example as applied by municipal water companies for cities under the C40 Cities initiative (Greenhouse Gas Protocol, 2014) (C40, 2020). This would consider the defined city boundary for emissions reporting and key sources of emissions as per Figure 4.2 below. In the case of wastewater management and treatment the GHG protocol provides scope definitions as (Greenhouse Gas Protocol, 2014):

- Scope 1: GHG emissions from treatment and disposal of waste within the city boundary regardless of whether the waste is generated within or outside the city boundary.
- Scope 2: not applicable to wastewater treatment – all emissions from the use of grid-supplied electricity in waste treatment facilities within the city boundary are typically reported separately and not by the water sector.
- Scope 3: GHG emissions from treatment of waste generated by the city and activities associated with waste treatment (chemical supply, consumables, employee travel) which are treated outside the city boundary or imported from outside the city boundary.

Within the GHG Protocol and, generally, for GHG inventory guidance for organizations reporting and disclosing GHG emissions, quantification of Scope 1 and 2 emissions is mandatory, while Scope 3 emissions quantification can be voluntary in some cases. It is important to consider that there could be significant variation on the overall GHG estimate depending on the boundary definition and reporting requirements.

Table 4.1 provides further examples of GHG emissions relevant to the urban water cycle based on these definitions. For any given case, establishing the basis for defining boundaries and reporting emissions is important, with reference to guiding global best practice set out in the GHG Protocol and/or other relevant guidelines or policy. Reference is again made to ISO 14064-1:2018 which provides useful categories for understanding and reporting of GHG emissions and removals and which may be of benefit to companies or utilities in the water sector.

This chapter covers GHG emissions from sewerage and on-site centralized wastewater treatment processes, with a focus on emissions of CH_4 and N_2O from WWTPs. It does not include discussion of emissions from natural treatment systems (e.g. wetlands) and it does not include emissions from the discharge of treated effluent to aquatic environments – for example rivers and oceans or disposal of used water to land (e.g. for irrigation). However, wetlands for wastewater treatment are included in Chapter 6 of the 2014 Supplement to the 2006 IPCC Guidelines (IPCC, 2014b).

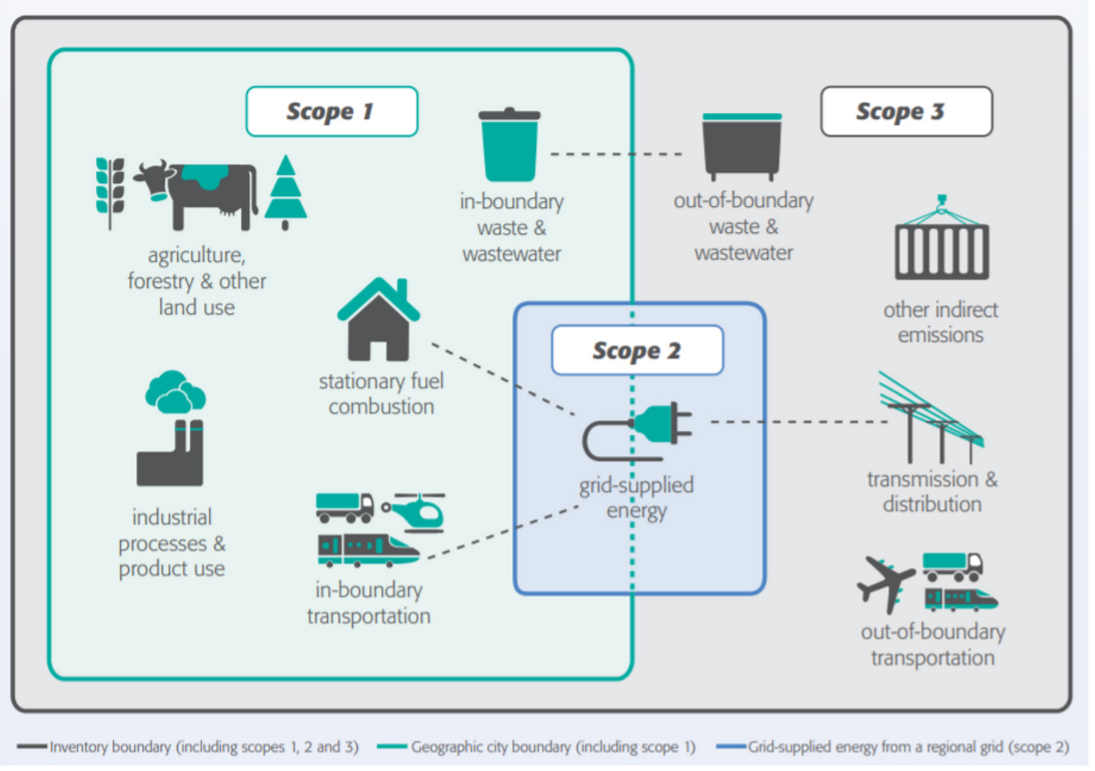

Figure 4.2 Sources of city GHG emissions (Greenhouse Gas Protocol, 2020a, 2020b). With thanks to the World Resources Institute - licensed under a creative commons licence (http://creativecommons.org/licenses/by-nc-nd/3.0)

Also, it does not cover emissions of GHG from the use or management of wastes or emissions from off-site use of resources recovered from wastewater. Nevertheless, it is important to understand that the CH_4 and N_2O emissions associated with these off-site activities to manage (whether use or disposal of) products can be significant relative to on-site activities, particularly the recycling of sewage sludges to land or their disposal to landfill. Depending on the approach as exemplified above, these emissions can be considered either Scope 1 or Scope 3.

It is important to recognize that off-site emissions may be accounted for differently, leading to discrepancies in accounting and reporting of Scope 1 or Scope 3 emissions. Clarity of boundaries for water sector emissions relative to nationally reported emissions inventories is important to provide reporting consistency and relevant baselining for the ambitious GHG emissions required under the Paris Agreement.

As water utilities and companies move towards net zero and Paris-aligned GHG emissions, a more holistic carbon management approach is being adopted to account for all direct and indirect emissions, regardless of the control they have over downstream emissions – adopting methods for life cycle analysis of carbon and other non-economic impacts to enable decision making.

A relevant example where water companies are reporting aligned with corporate Scope 1, 2 and 3 emissions is with respect to end use of treated effluent – for example return to the natural environment – and the disposal of biosolids to land. Whilst they may not be required to report these emissions under existing corporate reporting standards or to support National Inventories, water companies have the potential to substantially influence downstream emissions; for example, the residual N_2O emissions

Table 4.1 Examples of emissions scopes relevant to the urban water cycle.

Scope	Private and/or regional water company serving a defined geographic area (city, town, state, country level)	Municipal water company serving a defined city geographic area[a]
Scope 1	Direct GHG emissions occurring from sources that are owned or controlled by the company	GHG emissions from sources located within the city boundaries
Example:	*Stationary and mobile fuel combustion (on-site use of natural gas and other fuels), process emissions from water and wastewater treatment (N_2O emissions from biological wastewater treatment), fugitive CH_4 emissions during anaerobic treatment and sludge management, and from owned or controlled sewerage networks emissions*	*Stationary and mobile fuel combustion (on-site use of natural gas and other fuels), in-boundary process emissions from water and wastewater treatment (N_2O emissions from biological wastewater treatment), fugitive CH_4 emissions during anaerobic treatment and sludge management, and from owned or controlled sewerage networks, emissions from discharge of treated effluent into aquatic environments if these are within the city boundary (N_2O emissions from receiving water body)*
Scope 2	Indirect GHG emissions from the generation of purchased electricity, heat or steam consumed by the company in its owned or controlled equipment or operations	GHG emissions occurring as a consequence of the use of grid-supplied electricity, heat, steam within the city boundary would be reported in City accounting and not by the water company
Example:	*Purchased electricity, heat and steam*	*None reported by water company/authority*
Scope 3	Indirect emissions as a consequence of the activities of the company, but occurring from sources not owned or controlled by the company	All other GHG emissions that occur outside the city boundary as a result of activities taking place within the city boundary
Example:	*Employee business travel, emissions from waste disposal of effluent and residual streams including N_2O from discharge of treated effluent and N_2O and CH_4 from the storage and recycling of effluent or biosolids to land. Transmission & distribution of electricity, production and distribution of chemicals or other materials*	*Out-of-boundary process emissions from water and wastewater treatment, out-of-boundary transportation, out-of-boundary waste disposal, transmission and distribution of electricity, production and distribution of chemicals*

[a]For municipal water companies, example of emissions may change depending on what is included and excluded from the city boundary.

from treated effluent or biosolids recycled to land. Further, water companies with targets aligned to the Science Based Targets initiative (SBTi) will be required to report on these emissions, where they are significant Scope 3 emissions.

4.2.2 Top-down and bottom-up approach considerations for the water sector

Top-down and bottom-up are the two main GHG accounting inventory methodologies, distinguished based on how the data is obtained and the level of confidence. A top-down approach refers to GHG emissions estimated based on equations with factors and constants which are defined at global level. These are developed from data collected from research or accepted industry practice or based on general assumptions. They provide a methodology for estimation of GHG emissions, significantly relying on default factors.

A bottom-up approach consists of measurements of the actual GHG emissions at the facility level, based on a defined methodology. This could include averaged EFs from facilities to provide a national dataset or specific WWTP data from the measurement of emissions for each facility. A bottom-up approach is preferable and results in an improved methodology for a more accurate GHG inventory. A bottom-up assessment of GHG is possible where high quality data and advanced methodologies exist at a country level.

The following sections provide a description of how top-down and bottom-up emissions are calculated based on best global practice.

4.2.2.1 Top-down methodologies

The top-down estimation of GHG emissions for inventory of emissions can be exemplified in the generalized Equation (4.1):

$$\text{Emission Rate (ER)} = \text{Emission Factor (EF)} \times \text{Activity Data (AD)} \tag{4.1}$$

where the emission rate, usually in mass per a period of time (e.g. kg N_2O/year) is a factor of the human activity by the emitting activity based on site measurements or lookup factors for specific countries, and on appropriate EFs for different emitting sources. For a top-down approach, the EF and activity data will be derived from higher level (e.g. international literature) data compared with a bottom-up estimate, which will use in-country or facility-level datasets.

GHG emissions from chemical and biological processes in the water sector are not as straightforward to estimate as GHG emissions from the power sector, such as quantifying emissions from the burning of fuels. In the case of burning of fuels, the amount of GHG produced is a function of the carbon content of the fuel, thus a direct stoichiometric correlation. Biological processes, conversely, are highly complex and emissions are dependent on the environmental and operational conditions in which the treatment is carried out. As has been discussed, in Chapter 2, N_2O is produced as a by-product or intermediate during biological wastewater treatment of nitrogen-containing resource streams under aerobic and anoxic conditions, and CH_4 is produced during anaerobic treatment of resource streams.

Research to develop the fundamental understanding of GHG production and emissions from biological wastewater treatment processes, in particular N_2O, has been an area of continued progress for almost three decades. Since the first publication on N_2O emission from a small activated sludge treatment works in New Hampshire, USA (Czepiel *et al.*, 1995), significant research has been conducted around the world both at lab- and full-scale to determine the microbial pathways, mechanisms and factors leading to N_2O production and emission from different configurations of WWTPs. Although a general consensus exists, there are still gaps and it remains an area of multi-layered research.

CH_4 emissions generally are due to leakages of CH_4 produced during anaerobic processes used for wastewater and sludge treatment and, whilst often captured for beneficial use as biogas at large centralized facilities, may be emitted unintentionally from tanks, pipework and fittings. CH_4 may also be produced and emitted in sewerage systems. The extent of CH_4 emissions for a site are likely to be highly dependent on on-site operations and gas management controls as well as the nature of processes employed (e.g. enclosed anaerobic digestion versus open secondary digesters or sludge lagoons).

By applying an averaged global EF from a top-down approach to these N_2O and CH_4 emissions from WWTPs, a higher degree of uncertainty is inferred, leading to a lower level of confidence in the GHG estimations for the water sector. However, it is noted that bottom-up emissions of N_2O and CH_4 from different treatment processes when measured at site level (e.g. bottom-up) have been shown to vary significantly, even for the same type of treatment process but with different operational conditions. Bottom-up methodologies based on current reporting protocols are discussed subsequently in Section 4.2.2.2; Chapter 5 discusses full scale quantification of emissions and site level approaches.

4.2.2.2 Bottom-up methodologies

A bottom-up approach follows the same general approach as above in Equation (4.1) but data sources differ – for example, this may consider EFs derived from a national dataset developed from a sub-set of in-country facilities or from data specifically at individual facility (WWTP) level. Increasingly, country level work seeks to develop methodologies which include a country-specific EF for N_2O or CH_4, based on the measurement of emissions across a number of in-country facilities or based on the adoption of a published dataset applicable to the in-country facilities.

A bottom-up approach with a nationally-derived dataset offers an improvement on a top-down approach but does not offer facility-level understanding. Development of advanced methodologies to measure emissions accurately and effectively is important, particularly given the variations exhibited in GHG emissions due to temporal and operational conditions. Hence, a bottom-up approach may also consider a methodology which measures actual GHG emissions from a treatment facility and uses these to develop the GHG inventory for each facility. In this case, compiling the GHG emissions inventory may not require the development and application of an EF and application of Equation (4.1), but instead, may be able to directly report measured emissions. Alternatively, long-term facility monitoring may be used to develop a facility-level EF which, when used in Equation (4.1) with appropriate facility or geographical activity data, can provide GHG inventory emissions estimation. Chapter 5 discusses site-level full-scale quantification of GHG emissions further.

When comparing top-down and bottom-up approaches and considering nationally-derived datasets versus a facility-level emissions quantification, it is important to recognize that an approach which considers globally- or nationally-derived factors does not give insights into the conditions leading to these GHG emissions from a specific treatment process. Given the potential for significant variability in emissions of N_2O and CH_4 between facilities, this limits the ability of a treatment process to be investigated and understood such that mitigations can be applied resulting in low reduction potential value. Conversely, on-site monitoring and development of mitigation and control strategies have a high potential to lead to sustained reduction in process emissions. Moreover, the outcomes of monitoring and resulting mitigations are likely to offer wider benefits to the sector in terms of process safety, stability, performance, operational cost and proactive maintenance.

A top-down approach is considered *good practice*, as explained in the following sections, for situations where data, methodologies and resources are not available at country-level to develop a bottom-up approach to full-scale quantification of GHG emissions. Where resources do exist to develop and apply advanced methodologies, the aim should be to apply advanced methodologies for quantification of GHG emissions at country-level and ideally based on full-scale quantification of GHG emissions. These should be facility-level bottom up approaches, as covered in Chapter 5.

4.3 INTERNATIONAL METHODOLOGIES

This section sets out global practice in GHG accounting methodology, as defined by the IPCC in the IPCC Guidelines (Bartram *et al.*, 2019; IPCC, 2006). The IPCC methodology provides a globally consistent approach for high-level government GHG emissions accounting and reporting. It is also the foundation of most protocols for GHG accounting, such as the most widely used protocol for GHG accounting for businesses and government leaders, the World Resource Institute (WRI) GHG Protocol (Greenhouse Gas Protocol, 2020a, 2020b). Therefore, this chapter focuses mainly on the IPCC methodology while also bringing the perspective of other national and sector-specific methodologies.

4.3.1 The intergovernmental panel on climate change

The IPCC is the international body for assessing the science related to climate change. It was created by the World Meteorological Organization (WMO) and United Nations Environment Programme (UNEP) in 1988 to provide policymakers with regular assessments of the scientific basis of climate change, its impacts and future risks, and options for adaptation and mitigation (IPCC, 2018a).

Through the Task Force on National Greenhouse Gas Inventories, the IPCC provides internationally agreed methodologies for measuring national GHG emissions from the different sectors of the economy based on published research conducted around the world. The methodology is used by

Parties reporting through the National Inventory Reports (NIRs) under the UNFCCC, in compliance with the Kyoto Protocol. The signatory Parties of the 1992 UNFCCC are required to monitor and report annually, at a national scale, their emissions of the six key GHGs, namely: carbon dioxide (CO_2), CH_4, N_2O, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) (United Nations, 2020).

As each GHG has its unique radiative effects over a given period, the GHG emission calculations convert each GHG into one ton of CO_2, known as CO_2 equivalent (CO_2e) based on their global warming potential (GWP) (Equation (4.2)).

$$CO_2e(\text{tonnes/yr}) = GHG(\text{tonnes/yr}) \times GWP_{100} \quad (4.2)$$

The 100-year GWP (GWP_{100}) was adopted by the UNFCCC and its Kyoto Protocol and is now used widely as the default metric (IPCC, 2014a, 2014b). The IPCC is responsible for updating the GWP values as scientific understanding develops. The most recent values are presented in Table 5.1 of the fifth assessment report (AR5) published in 2014, reproduced in Table 4.2 below. The IPCC is currently in its sixth assessment cycle (AR6), which will be finalized in 2022 (IPCC, 2020a, 2020b).

The most recent guidelines for National GHG Inventories are provided in the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (the 2019 Refinement). The 2019 Refinement was adopted by the IPCC at its 49th Session in May 2019 in Kyoto, Japan (Bartram *et al.*, 2019; Federici, 2019). It includes 5 volumes, comprising: Volume 1 – General Guidance and Reporting, Volume 2 – Energy, Volume 3 – Industrial Processes and Product Use, Volume 4 – Agriculture, Forestry and Other Land Use, and Volume 5 – Waste.

4.3.2 IPCC methodologies for the water sector

Within the water sector, for water companies or water utilities treating wastewater the relevant IPCC methodology is found in the 2019 Refinement Volume 5: Waste, Chapter 6: Wastewater Treatment and Discharge. Volume 1: General Guidance for Reporting provides an overview of GHG inventories and includes chapters on uncertainties, consistency, quality assurance and quality control and verification in the protocol.

The IPCC Guidelines follow the top-down approach described in Equation (4.1), comprising EFs and activity constants for estimation of CH_4 and N_2O from wastewater treatment and discharge. The IPCC provides a three-tier methodology to select the EFs and activity data, as discussed in more detail in subsequent sections.

- Tier 1 (*good practice*) method: uses default values for the EF and activity parameters. It is considered good practice for countries with limited data.
- Tier 2 (*good practice*) method: uses a country-specific EF based on field measurements and country-specific activity data.
- Tier 3 (*advanced*) method: uses a country-specific method – for example, based on plant-specific emissions from large WWTPs. It is for countries with good data and advanced methodologies, where direct measurement methods provide a more accurate measurement from each facility.

Table 4.2 Global warming potential (IPCC, 2014a, 2014b).

GHG	GWP_{100}
CO_2	1
CH_4	28
N_2O	265

The three-tier method represents the level of methodological complexity and data requirements. A progression from Tier 1 to Tier 3 represents an increase in confidence in the GHG estimates, and generally requires more extensive resources for site measurement and data collection. Thus, it may not be feasible to use the higher tier methods (Tier 2 and 3), which are generally considered to be more accurate, for every category of the emissions inventory. The IPCC guidance provides considerations on quantitative and qualitative approaches to identify categories that are key sources of emissions to help manage overall inventory uncertainty (IPCC, 2006).

The following sections set out the 2019 Refinement methodology for estimation of CH_4 and N_2O emissions from wastewater treatment. It is noted that the 2019 Refinement did not revise Chapter 5 of the guidelines, which covers solid waste and also covers emissions calculation for the anaerobic treatment of wastewater treatment sludges. Whilst these are reported under the Wastewater Treatment and Discharge category described in Chapter 6 of the guidelines, in the 2019 Refinement Chapter 6 refers to the previous 2006 Guidelines for the relevant methodology for estimation of emissions for the anaerobic treatment of sewage sludges.

4.3.2.1 Methane

The methodology to estimate CH_4 emissions from wastewater treatment and discharge was first introduced by the IPCC in the 1995 IPCC Guidelines for National Greenhouse Gas Inventories, later replaced by the 1996 Revised Guidelines and further revised in the 2006 Guidelines and 2019 Refinement (Volume 5: Waste, Chapter 6: Wastewater Treatment and Discharge) (Bartram *et al.*, 2019).

Chapter 6 (including Table 6.1) in the 2019 Refinement provides methane emissions potential from wastewater and sludge treatment systems and discharge systems. Sewers, and aerobic, anaerobic and sludge treatment systems are considered; composting and incineration are considered elsewhere in the IPCC Guidelines.

CH_4 emissions from decentralized and industrial wastewater treatment and the anaerobic digestion of non-domestic sludges are considered and reported separately from wastewater treatment emissions under the IPCC Guidelines. For this chapter of the Refinement, only CH_4 emissions from centralized treatment plants are considered. As according to Figure 6.1 in Chapter 6 of the 2019 Refinement, on-site sludge treatment, emissions should be reported under the Wastewater Treatment and Discharge category. Conversely, emissions from the off-site treatment of sludges, from composting, incineration, and landfilling of sludges, and for sludge application to land are described in other IPCC chapters and should not be reported within the Wastewater Treatment and Discharge category in National GHG Inventory assessments (Bartram *et al.*, 2019).

The 2019 Refinement acknowledges that in addition to sludge treatment and management, CH_4 emissions may also occur from settling basins and other anaerobic pockets, and especially resulting from sewer networks and being stripped out in turbulent aerobic zones of secondary treatment (Bartram *et al.*, 2019). The potential EF for CH_4 emissions from upstream sewer networks is currently not included in IPCC Guidelines, although there has been significant discourse on the subject. Chapter 3 and Chapter 8 of this book provide further discussion on CH_4 emissions and modeling approaches. The lack of methods to estimate CH_4 emissions from sewers that can easily be implemented by a water company is the key challenge in the assessment of their potential contribution to their CH_4 emissions.

4.3.2.1.1 Methane emissions from wastewater treatment

For CH_4 from wastewater treatment, the IPCC methodology provides a three-tiered approach. For each of these tiered approaches, methane emissions are calculated as the sum of the emissions from each treatment unit and the CH_4 recovered or flared, as detailed in Equation (4.3) (see Section 6.2.2 and Equations 6.1 and 6.1A in IPCC 2019 Refinement), in kg CH_4/year, and Equation (4.4) for calculation of the EF:

$$CH_{4\,\text{emissions}} = ([\text{TOW}_j - S_j] \times \text{EF}_j - R_j) \times [10^{-6}] \qquad (4.3)$$

$$EF_j = B_o \times MCF_j \tag{4.4}$$

where TOW_j is the organics in wastewater treatment/discharge pathway or system, j, in inventory year (kg BOD/year), S_j is the organic component removed from wastewater in the form of sludge (kg BOD/year), j is each type of treatment, EF_j is the EF for treatment/discharge pathway or system, j (kg CH_4/kg BOD), R_j is the amount of CH_4 recovered, for example through anaerobic digestion (AD), or flared from treatment/discharge pathway or system, j, in inventory year (kg CH_4/year), and 10^{-6} is the conversion of kg to Gg. The EF for CH_4 from wastewater treatment is a function of the maximum CH_4 producing potential (B_o) and the CH_4 correction factor (MCF) for the wastewater treatment and discharge system.

The B_o indicates the maximum amount of CH_4 that can be produced for a given amount of biochemical oxygen demand (BOD), while the MCF is the extent to which the CH_4 producing capacity (B_o) is realized. It is *good practice* as set out in the IPCC Guidelines to use country-specific data (Tier 2 or 3) for EFs, which are made up of B_o and MCF values (Bartram *et al.*, 2019).

The default B_o derived based on expert judgment by the lead authors and based on Doorn *et al.* (1997) is 0.6 kg CH_4/kg BOD with the BOD to be estimated based on incoming population per capita figures. MCFs are provided in Table 6.3 of the 2019 Refinement (Bartram *et al.*, 2019).

The MCF recommended for a centralized aerobic treatment plant is 0.03 (0.003–0.09) or 3% CH_4 emission from total influent BOD and was calculated based on on-site measurements from 14 full-scale USA WWTPs (Bellucci *et al.*, 2010; Czepiel *et al.*, 1995; Daelman *et al.*, 2013; Delre *et al.*, 2017; Kozak *et al.*, 2009; Kyung *et al.*, 2015; Wang *et al.*, 2015). These studies include both activated sludge (assumed nitrifying), biological nutrient removal, a sequencing batch reactor (SBR) and an anaerobic/anoxic/oxic (A^2O) process. The highest and 2nd lowest MCFs are reportedly from activated sludge. The data shows significant variability and the IPCC recommend more extensive monitoring and collection of site data to allow better understanding between treatment process types.

Based on the above, and on the default B_o and MCF values (0.6 kg CH_4/kg BOD and 0.03 kg CH_4/kgCH_4), the default EF for CH_4 from wastewater treatment is effectively 0.018 kg CH_4/kg BOD influent. If a country chooses to introduce country-specific data for B_o based on measured composition of wastewater, the MCF must also be updated as MCFs are developed using the default B_o values.

4.3.2.1.2 Methane emissions from sludge treatment

The methodology for CH_4 emissions from on-site sludge treatment was not updated in the IPCC 2019 Refinement and is covered by the 2006 IPCC Guidelines under Volume 5: Waste, Chapter 4: Biological Treatment of Solid Waste for emissions from AD of organic waste (Doorn *et al.*, 2006). This follows a *similar* tiered approach to that described in Section 4.3.2. Note the units and notation used for equation components which are taken directly from the 2006 IPCC Guidelines differ slightly to those used in Section 4.3.2.1.1 above, as provided in the IPCC 2019 Refinement.

For CH_4 from sludge treatment, the default methodology approach to calculate CH_4 emissions from sludge treatment for any tier is the difference between the methane emissions produced from the mass of organic waste (sewage sludge) treated by biological treatment type i (either composting or anaerobic digestion) and the emission factor for each treatment type as g CH_4/kg waste treated and the CH_4 recovered or flared, as detailed in Equation (4.5), in kg CH_4/year, and Equation (4.6) for calculation of the EF:

$$CH_{4\,\text{emissions}} = M_i \times EF_i \times [10^{-3}] - R \tag{4.5}$$

$$EF_i = B_o \times MCI \tag{4.6}$$

where M_i is the mass of organic waste treated by biological treatment (Gg) in each type of treatment, EF_{ji} is the EF for treatment (g CH_4/kg waste treated), R is the amount of CH_4 recovered and utilized (e.g. combusted to biogenic carbon dioxide on site or valorized to biomethane for use off site) or flared in inventory year (Gg), and 10^{-3} is the conversion of g to kg. The EF for CH_4 from biological treatment of sludge, *i*, is provided by Tier 1, 2 or 3 measurement, with Tier 1 values provided in Table 4.1 of Chapter 5 of the 2006 IPCC Guidelines.

As the IPCC Guidelines note, consistency between CH_4 (and N_2O) emissions from composting or anaerobic treatment of sludge and emissions from treatment of sludge reported in the Wastewater Treatment and Discharge category should be checked. Further, if emissions from anaerobic digestion are reported under Biological Treatment of Solid Waste, practitioners should check that these emissions are not also included under the Energy Sector.

Estimation of CH_4 emissions from sludge that is managed off-site from the WWTP using landfill (Volume 5, Chapter 3: Solid Waste Disposal), incineration (Volume 5, Chapter 5: Incineration and Open Burning of Waste), composting (Volume 5, Chapter 4: Biological Treatment of Solid Waste) and for land application (Volume 4, Chapter 11: Agriculture, Forestry and Other Land Use) are reported separately. Emissions from on-site wastewater and sludge treatment processes, such as AD, commonly situated within the WWTP boundary are considered further in this coverage of accounting methodologies. Other sludge treatment processes such as composting, incineration and the application of biosolids to land are not considered further in this discussion of accounting methodologies.

For CH_4 emissions from AD due to unintentional leakages as a result of pipework, valve and tank roof leaks, where biogas is lost and not recovered for valorization and/or is not combusted, the IPCC states in the 2006 Guidelines, Volume 5, Chapter 4, that emissions will generally be between 0% and 10% of the amount of CH_4 generated and that 5% should be used, in the absence of other information. It does not include an emission factor for these unintentional leakages. It also suggests that where technical standards for biogas plants ensure that unintentional emissions are flared, emissions are likely to be close to zero. Emissions from flaring are not considered significant, as the majority of CO_2 emissions are of biogenic origin, and the CH_4 and N_2O emissions are very small. Therefore, *good practice*, according to the 2019 Refinement does not require estimation of emissions from flaring of biogas. However, if estimating these emissions is desired, they should be reported under the Waste sector and the IPCC Guidelines refer to Volume 2 (Energy), Chapter 4 for guidance on flaring (Bartram *et al.*, 2019). This guidance assumes a conversion of 98% efficiency for combustion of methane in Equation (4.2.4). This figure is also implemented in the Water and Wastewater Companies for Climate Mitigation (WaCCliM) tool, ECAM, which uses a 2% methane loss due to incomplete combustion due to flaring, based on technical judgment and Volume 2 of the IPCC

There are no further considerations for CH_4 emissions in either the 2019 Refinement or 2006 Guidelines. A number of other fugitive sources of CH_4 emissions from sludge treatment which are not currently considered under the IPCC guidelines could be significant. These are likely to be very site specific and limited industry level data exists to support emission factors. A number of these have been subject to published research, as highlighted below and as recently summarized by UKWIR (United Kingdom Water Industry Research, 2020):

- Sludge storage and processing: Storage, thickening and dewatering of sludges with or without anaerobic digestion facilities, could be a significant source of fugitive CH_4 emissions from WWTPs. Type of sludges, their extent of treatment, the nature of storage and venting/extraction, and general asset operation are all likely to influence fugitive emissions.
- Gas line: Leakages in the gas line are highly dependent on on-site maintenance and gas measurement control and could be a potentially important source of fugitive emissions from WWTPs.
- Combined Heat and Power (CHP): CHP engines can reach an efficiency of up to approximately 42% conversion of biogas into electricity by burning CH_4, with high- and low-grade heat making up most of the leftover energy in the biogas (9% is parasitic energy). The percentage of unburned CH_4 measured in combustion that will be released as emissions has been found to be between 1.5% (Daelman *et al.*, 2012) and 1.8% (Woess-Gallash *et al.*, 2010).
- Dewatering digestate: The dissolved CH_4 remaining in digestate will be released to a great extent in the dewatering process. Digestate is blended with polymer for flocculation for fast

gravity water release. Here some of the CH_4 will stay in the centrate (the water released) or stay in the flocculated sludge, with very little going into the atmosphere. It is in the next step, dewatering, where pressure is applied, either by belts pressing against each other (e.g., belt presses) or by centrifugal forces (e.g., centrifuges), where more dissolved CH_4 is likely to be released. Centrifuges are believed to release more CH_4 from digestate due to the high forces being applied. It has been reported that dewatering and storing digestate might lead to emissions of 2–4.5% the total CH_4 production (Daelman *et al.*, 2012; Schaum *et al.*, 2015).

- Maturation pads and digestate storage: Further to the above, any storage of digestate prior to land spreading or landfill will have potential for CH_4 emissions – this may be in addition to secondary digestion emissions and could add additional emissions to existing conventional AD sites with the common storage of sludge cake. There has been limited research, but this could be considered a potentially significant source of CH_4 (Daelman *et al.*, 2012).
- Biogas upgrading: There is increasing interest in the potential economic benefits of injecting biogas into existing gas networks. There are a number of biogas-to-grid projects being implemented in several countries. In order to inject biogas into the grid, the biogas needs to be cleaned up and processing technologies, for example membrane or water wash based removal of impurities in biomethane, will have a potential fugitive emission consideration. The potential slippage is subject to ongoing investigation but may be in the order of 1–3% of produced biogas for grid injection.

4.3.2.2 Nitrous oxide

4.3.2.2.1 Nitrous oxide emissions from wastewater treatment

The methodology to estimate N_2O emissions from wastewater treatment was first introduced by the IPCC in the 2006 Guidelines Refinement, Volume 5: Waste, Chapter 6: Wastewater Treatment and Discharge. Based on limited data quantification of N_2O emissions from full-scale WWTPs, the 2006 Guidelines recommended a default EF of 3.2 g N_2O/person/year from a single study carried out at a small domestic activated sludge WWTP (4 Ml/day) in the University of New Hampshire, USA (Czepiel *et al.*, 1995). It stated that direct N_2O emissions from WWTPs were considered as a minor source in comparison with the indirect N_2O emissions from effluent discharges. Since then, this EF has been used to estimate direct N_2O emissions from different treatment processes around the world for countries where emissions from WWTPs are considered.

The 2006 Guidelines methodology did not provide any higher tier guidance. It noted that it was considered *good practice* to estimate total N_2O emission from domestic wastewater treatment only for countries that have predominantly advanced, centralized, WWTPs with nitrification and denitrification steps. For these, it suggested, using the following equation, in kg N_2O/year:

$$N_2O_{WWTP} = P \times T_{WWTP} \times F_{IND\text{-}COM} \times EF_{WWTP} \tag{4.7}$$

where P is the human population; T_{WWTP} is the degree of utilization of modern, centralized WWTPs (%, country-specific), $F_{IND\text{-}COM}$ is the fraction of industrial and commercial co-discharged protein (default = 1.25, based on data in Metcalf and Eddy (2003) and expert judgment), and EF_{WWTP} is 3.2 (2–8) g N_2O/person/year.

After several years of research and national monitoring campaigns at full-scale WWTPs employing different treatment processes in various countries, there has been a consensus that the 2006 Guidelines methodology with the applicability of a single EF to represent N_2O emissions from different processes presented several limitations, including:

- N_2O emission was attributed to denitrification as the dominant source of N_2O, with nitrification being considered a minor contributor. Research has shown that nitrification is a significant contributor to N_2O emissions from aerobic zones, and that the importance of one pathway over another will depend on the environmental and operational conditions of the WWTP (Ahn *et al.*, 2010; Pan *et al.*, 2016).

- *It did not consider spatial and diurnal variability in N_2O emissions*. Significantly high spatial and diurnal variability is observed in all studies, by monitoring N_2O emissions at across the secondary treatment tanks and for longer periods of time (Ni *et al*., 2015; Pan *et al*., 2016; Vasilaki *et al*., 2019).
- It did not make a distinction between WWTPs with different treatment types or different operational conditions and the associated effect on N_2O production. The production pathways of N_2O in wastewater treatment are highly complex and vary depending on the type of treatment but also on the operational conditions – even within the same treatment processes. For instance, SBRs and step-feed plug flow reactors are generally associated with higher N_2O emissions compared to other process configurations due to sudden operational changes (Pan *et al*., 2016; Pijuan *et al*., 2014; Vasilaki *et al*., 2019).
- *It did not consider WWTPs that are located in different climate zones*. It has been shown that N_2O emissions from tropical climate zones are higher than from temperate zones, as a factor of temperature and bacterial activity (Brotto *et al*., 2015b).

In 2018/2019, the IPCC Guidelines went through a peer-review of the science developed since the 2006 Guidelines, providing significantly more guidance, in particular with respect to N_2O from wastewater treatment (Bartram *et al*., 2019). In recognition of the high variability of N_2O production and its dependency on the treatment design and operations, a new significantly higher EF of 0.016 (with range minimum 0.00016 – maximum 0.045) kg N_2O-N/kg N load is recommended in the 2019 Refinement (Bartram *et al*., 2019). This represents a change of two orders of magnitude in the default EF for the Tier 1 method application, from 0.00035 kg N_2O-N/kg N load (conversion of 3.2 g N_2O/person/year based on the IPCC protein/N conversion of 0.16 g N/g protein) to 0.016 kg N_2O-N/kg N load.

The new EF is derived from linear regression of 29 full-scale monitoring data on N_2O emissions and influent nitrogen load from a variety of the most common suspended growth (e.g. activated sludge, including continuous and batch operating modes) treatment processes in Australia, Brazil, China, Japan, the Netherlands, Spain, and the USA – regarding these as *the most typically and widely used treatment processes globally* (Bartram *et al*., 2019). A summary of the studies included is provided in Table 4.3 however there is some evidence that the originally cited references may require review due to some apparent variation in conversion of units and other issues – these are shown as footnote comments. Recent analysis also includes discussion of data points and the IPCC 2019 Refinement method and considers the extent to which larger treatment plants (treating greater than 300 000 population equivalent, e.g.,) drive the linear regression and resultant emission factor derivation as well as the recognition that treatment performance, in particular in terms of nitrogen removal, likely requires further consideration (de Haas & Ye, 2021). Work by others (e.g., Valkova *et al*., 2020) also discusses the importance of considering nitrous oxide emissions with respect to total nitrogen removed though for higher levels of total nitrogen removed (∼50–92%). Conversely, sector-level work in Denmark does not exhibit a similar correlation with total nitrogen removal and highlights significant variability for a similar (∼60–95%) degree of total nitrogen removal (Lake *et al*., 2021 (unpublished)). Chapter 11 provides further discussion of this and other emerging issues.

Chapter 5 covers more details on the different types of monitoring methodologies (e.g. online off-gas, grab sampling) as specified in Table 4.3 and Chapter 11 provides further discussion on the derivation of emission factors from site measurement campaigns with emerging research and practical application of methods and consideration of best practice.

The 2019 Refinement provides a three-tier methodology for assessment of greenhouse gas emission factors and a decision tree to help identify which tier should be applied depending on the available data and activity parameters. Historically, the three-tier methodology was not applied to N_2O emissions assessment, but the 2019 Refinement provides for the following methods which are subsequently discussed:

Table 4.3 Summary of N_2O studies considered in the 2019 IPCC refinement (adapted from Bartram *et al.*, 2019).

Treatment Type[a]	Category	EF (kg N_2O-N/kg $N_{influent}$)	Country	Frequency/sampling method	Reference
AO	BNR	0.028	Netherlands	16-months on-line monitoring period (1-month interruption due to technical failure)	Daelman *et al.* (2015)
AO	BNR	0.021	Australia	2 days, twice a day off-line grab sample	Foley *et al.* (2010)
AO	BNR	0.045	Australia	2 days, twice a day off-line grab sample	Foley *et al.* (2010)
A2O	BNR	0.013	Australia	2 days, twice a day off-line grab sample	Foley *et al.* (2010)
SBR	BNR	0.023	Australia	2 days, twice a day off-line grab sample	Foley *et al.* (2010)
OD	BNR	0.008	Australia	2 days, twice a day off-line grab sample	Foley *et al.* (2010)
IA	BNR	0.0005	Japan	Short-term, off-line grab samples	Kimochi *et al.* (1998)
EA	BNR	0.015	Australia	2 days, twice a day off-line grab sample	Foley *et al.* (2010)
A2O	BNR	0.013	China	24-h monthly, 1 year, online off-gas monitoring	Wang *et al.* (2016)
CAS	BNR	0.00036	UK	8 weeks, online off-gas measurement	Aboobakar *et al.* (2013)
AO[b]	BNR	0.12[c]	Spain	10 weeks, 2–3 days a week, online off-gas measurement	Rodriguez-Caballero *et al.* (2014)
OD	BNR	0.00016	Japan	4 times throughout the year, off-gas grab samples	Masuda *et al.* (2018)[d]
AO	BNR	0.0013	Japan	4 times throughout the year, off-gas grab samples	Masuda *et al.* (2018)
AO	BNR	0.0049	Japan	4 times throughout the year, off-gas grab samples	Masuda *et al.* (2018)
Separate-stage	BNR	0.00019	USA	5 days, summer and winter, online off-gas measurement	Ahn *et al.* (2010)
Bardenpho	BNR	0.0036	USA	5 days, summer and winter, online off-gas measurement	Ahn *et al.* (2010)

Step-feed	BNR	0.011	USA	5 days, summer and winter, online off-gas measurement	Ahn *et al.* (2010)
MLE	BNR	0.0007	USA	5 days, summer and winter, online off-gas measurement	Ahn *et al.* (2010)
MLE	BNR	0.0006	USA	5 days, summer and winter, online off-gas measurement	Ahn *et al.* (2010)
OD	BNR	0.0003	USA	5 days, summer and winter, online off-gas measurement	Ahn *et al.* (2010)
Step-feed	BNR	0.015	USA	5 days, summer and winter, online off-gas measurement	Ahn *et al.* (2010)
Step-feed, plug flow	BNR	0.019	Australia	7 weeks, online off-gas measurement	Ni *et al.* (2015); Pan *et al.* (2016)
SBR	BNR	0.029[e]	China	Short-term (undefined), off-gas grab samples	Bao *et al.* (2016)
SBR	BNR	0.038	Spain	33 days, online off-gas measurement	Rodriguez-Caballero *et al.* (2015)
Plug flow	non-BNR	0.004	USA	5 days, summer and winter, online off-gas measurement	Ahn *et al.* (2010)
Plug flow	non-BNR	0.0062	USA	5 days, summer and winter, online off-gas measurement	Ahn *et al.* (2010)
Step-feed	non-BNR	0.0018	USA	5 days, summer and winter, online off-gas measurement	Ahn *et al.* (2010)
Plug flow	non-BNR	0.023[f]	Japan	5 times throughout the year, off-gas grab samples	Masuda *et al.* (2015)
AO	non-BNR	0.013[f]	China	Short-term (undefined), off-gas grab samples	Bao *et al.* (2016)
IA	non-BNR	0.0016	Brazil	1-day, off-line grab samples	de Mello *et al.* (2013)

[a]BNR: biological nutrient removal, AO: anaerobic-oxic activated sludge process, A2O: anaerobic-anoxic-oxic activated sludge process, SBR: sequencing batch reactor, OD: oxidation ditch, IA: intermittent aeration process, EA: extended aeration process, CAS: conventional activated sludge process, MLE: modified Ludzack-Ettinger.
[b]Reference not considered for the derivation of the new EF but considered as an outlier.
[c]It appears this value was incorrectly cited and should be 0.0012 kg N_2O-N/kg $N_{influent}$ based on influent TN.
[d]It appears Masuda *et al.* (2018) considered TN removed (and TN still in final effluent) in their analysis, thus factors from Masuda *et al.* (2018) should be considered further.
[e]It appears this value was incorrectly cited and should be 0.019 kg N_2O-N/kg $N_{influent}$.
[f]Review (unpublished) suggests that the derivation and/or citation of these factors from original studies may require further review.

4.3.2.2.1.1 Tier 3 – asset-specific EFs

Asset-specific EFs are emissions estimated using bottom-up, on-site measurements at the facility-level, are recognized as a 'Tier 3' methodology and are advocated as most preferable in the IPCC Guidelines. Although direct monitoring is now recognized by the IPCC methodology as the preferable option, few water utilities have undertaken direct monitoring historically. Most of the available data are the result of research to investigate the pathways and process conditions leading to N_2O emissions, and not to derive an EF. The 2019 Refinement does not provide a methodology to develop site-level emission monitoring campaigns and guidance for deriving emission factors from these which is a recognized area for ongoing work. Given the substantial variation in EFs calculated across WWTPs, even where these are very similar treatment process types, a focus on Tier-3-level assessment and long-term study to develop robust WWTP-level EFs is likely to remain a key area of focus for the water sector – with key recent discussions considering that the use of emission factors relative to the extent of total nitrogen removal may be most applicable (de Haas & Ye, 2021; Valkova *et al.*, 2020).

4.3.2.2.1.2 Tier 2 – country-specific EFs

The 2019 Refinement guidelines suggest that if asset-specific EFs are not available, country-specific EFs are most preferable (i.e., Tier 2). Few countries have currently taken this route, as further discussed in Section 4.4. Given the high number of WWTPs, the variety of treatment processes and variability of N_2O emissions, deriving a single country-specific emission factor is also challenging, requiring long-term measurements of representative WWTPs and a methodology to normalize the EF.

Similarly for Tier 3 monitoring, the 2019 Refinement does not provide a methodology to develop a Tier 2 country-level EF from an in-country dataset. The basis for statistical assessment of EF data from multiple WWTPs is not well established in research to date – for example whether data is normally distributed, the most suitable analysis to apply (e.g. linear regression) and basis for analysis and EF (e.g., total nitrogen load influent or total nitrogen removed).

4.3.2.2.1.3 Tier 1 – global EFs

If country-specific EFs are not available, the global EF derived in the 2019 Refinement should be applied (i.e., Tier 1). By implication, under the Paris Agreement, the first global emission inventory report in 2023 from signatory Parties should be either in line with this Tier 1 as international best practice, set out by the IPCC, or by a derived country-specific EF.

The implications of the change in the Tier 1 EF are significant, especially as many water utilities that account for process emissions as part of their carbon footprint apply the IPCC methodology to estimate N_2O emissions. An increasing number of water utilities in countries with centralized WWTPs are working towards Scope 1 process emissions reduction to provide emissions reduction in their sector in alignment with the Paris Agreement, as reflected in country-level carbon reduction targets. It is important to note that applying a global EF will provide little value in supporting these water utilities to quantify and mitigate their contribution to National emissions. A Tier 2 or Tier 3 approach is critical to both measure existing emissions and derive EFs but, most importantly, to allow mitigation interventions to be measured and monitored.

4.3.2.2.2 Nitrous oxide emissions from wastewater effluent

The IPCC also provides the methodology to estimate N_2O emissions from wastewater after disposal of untreated or treated wastewater effluent into aquatic environments by accounting for the removal of nitrogen through treatment processes prior to wastewater effluent disposal. Similarly, this methodology has been in place since the 2006 Guidelines, Volume 5: Waste, Chapter 6: Wastewater Treatment and Discharge, and has been revised in the 2019 Refinement to incorporate wastewater discharge into nutrient-impacted aquatic environments (eutrophic or hypoxic), where emissions can be significantly higher in comparison to relatively clean and/or well-oxygenated environments (Bartram *et al.*, 2019).

Table 4.4 Nitrous oxide emission factors by type of discharge aquatic environment with 95%ile limits shown in brackets (Bartram *et al.*, 2019).

Type of discharge environment	$EF_{Effluent}$ (kg N_2O-N/kg N)
Freshwater, estuarine, and marine discharge (Tier 1)	0.005 (0.0005–0.075)
Nutrient-impacted and/or hypoxic freshwater, estuarine and marine environment (Tier 3, if needed)	0.019 (0.0041–0.091)

The following equation (from Equation (6.7) in the 2019 IPCC Refinement) is used to estimate N_2O emissions from the discharge of treated or untreated wastewater into aquatic environments:

$$N_2O_{\text{Effluent,DOM}} = N_{\text{Effluent,DOM}} \times EF_{\text{Effluent}} \times 44/28 \tag{4.8}$$

where, $N_2O_{\text{Effluent,DOM}}$ is the N_2O emission from domestic wastewater effluent (kg N_2O/year); $N_{\text{Effluent,DOM}}$ is the nitrogen in the effluent discharged to aquatic environments (kg N/year). The 2019 IPCC Refinement provides a methodology to estimate $N_{\text{Effluent,DOM}}$ based on total nitrogen influent (TN_{DOM}), degree of utilization of the treatment system (T_j), and fraction of total nitrogen removed (N_{REM}). EF_{Effluent} is the emission factor for N_2O emissions from wastewater discharged to aquatic environments (kg N_2O-N/kg N), as depicted below in Table 4.4. The factor 44/28 is the stoichiometric conversion from N to molecular N_2O.

The 2019 Refinement notes that the EFs are based on limited field data and on specific assumptions regarding occurrence of nitrification and denitrification in rivers and estuaries. For well-oxygenated environments, a total of 62 data points were reviewed, while 59 studies were evaluated for low-oxygen environments.

4.4 NATIONAL GUIDELINES

The majority of signatory countries of the Kyoto Protocol use the IPCC Guidelines as the basis for their national GHG inventory assessment. Some countries have developed country-based methodologies to provide greater clarity on the use of EFs and activity data – examples of this being country-level derivation of country- or facility-specific EFs.

4.4.1 Methane

There are limited national guidelines for estimation of CH_4 emissions from WWTPs at national level.

4.4.1.1 Australia

A Tier 2 approach for Australia is described in the National Greenhouse and Energy Reporting (Measurement) Determination 2008 made under sub-section 10(3) of the *National Greenhouse and Energy Reporting Act 2007*. This legislation provides four methods for GHG emissions assessment (Department of Industry, Science, Energy & Resources, 2021; OPC, 2017b):

The Determination provides three methods for estimating CH_4 emissions from treatment and emissions from flaring in Part 5.3 Wastewater Handling (Domestic and Commercial). The methods, which align with Tier 2 and 3 approaches, are summarized below:

- Method 1: based on the estimated quantity of CH_4 in biogas produced, considering standard per capita COD contributions. This subtracts biogas which is utilized on site, flared or exported and provides a separate emissions calculation for wastewater and for sludge – in each case with a default MCF and default EF for CH_4. Wastewater and sludge MCFs are based on the 2006 IPCC Guidelines correction factors (e.g. from 2006 IPCC Volume 5, Table 6.3). Separate consideration of sludge types – that is volatile solids in primary and waste activated sludge – is given.

- Method 2: considers an approach aligned with Method 1 but with more specific consideration of a facility. This is based on designation of sub-facility levels based on treatment areas and the use of measured data (e.g. COD or BOD) with considerations for the operator in designating a sub-facility, considerations of representative sampling (which must be on at least a monthly basis), and description of requirements for certification of samples taken by accredited laboratories.
- Method 3: aligns with Method 2 but provides for different sampling laboratory certification.

The methods meet IPCC Tier 2 and 3 approaches in part – in that they allow for facility type and site level calculations through Methods 1, 2 and 3. The Determination provides for Method 4 in GHG emissions assessment – defined as facility-specific measurement of emissions by continuous or period emissions monitoring – but this is not included as a method for CH_4 emissions estimation in the present approach.

4.4.1.2 United Kingdom

Water Companies in the UK are required to report their GHG emissions to the economic regulator for water companies in England and Wales, Ofwat, using country-developed EFs and a peer-reviewed industry-wide tool for operational carbon assessment – the Carbon Accounting Workbook (CAW). Sector-level reporting has been required by Ofwat since 2007 (Ofwat, 2010). Emissions reported in the CAW are in part used for compilation in UK National Inventory Reporting.

The CAW provides for calculation of fugitive CH_4 emissions from sludge storage, thickening and treatment in anaerobic digesters. The EFs included for mass of CH_4 per mass of raw dry solids of sewage sludge consider losses from digesters, venting due to ignition failure and downtime at flare stacks, fugitive emissions and secondary digester emissions. They also consider advanced AD processes including the thermal hydrolysis process (THP) and acid phase digestion (APD). A recent review of the applied EFs highlights their derivation is based on theoretical assessments only – and is not from measured datasets. It concludes with the need to further review and revise these which is currently ongoing (United Kingdom Water Industry Research, U 2020).

Whilst considering EFs that have been derived for national use by the water sector, the UK methodology is not well aligned with the IPCC methodology and has been recommended for review and revision through an industry monitoring program (United Kingdom Water Industry Research, U 2020).

4.4.1.3 Other country considerations

Elsewhere, there is evidence of voluntary program approaches to quantify and reduce CH_4 emissions which include the water sector. For example, the Swedish biogas industry have focused on leak detection and operational controls for CH_4 emissions reduction for biogas systems as a voluntary mechanism since 2007 (Holmgren *et al.*, 2012).

Implementation of future regulations, such as the European Union Best Available Techniques 14 (BAT 14) for the waste sector (Commission Implementing Decision (EU) 2018/1147 of 10 August 2018) (European Union, 2020) will likely require interventions for AD sites to reduce fugitive CH_4 emissions through on-site measurements, such as leakage detection and repair (LDAR), including for AD and associated processes at WWTPs. Industry initiatives and regulatory requirements could potentially result in better estimation of CH_4 emissions from WWTPs for more accurate national guidelines for estimation based on bottom-up measurements.

4.4.2 Nitrous oxide

4.4.2.1 Australia

A Tier 2 approach for Australia is described in the National Greenhouse and Energy Reporting (Measurement) Determination 2008 made under sub-section 10(3) of the *National Greenhouse and*

Energy Reporting Act 2007. It provides four methods for GHG emissions assessment (Department of Industry, Science, Energy and Resources, 2021; OPC 2017a):

- Method 1 (known as the default method): derived from the National Greenhouse Accounts methods and based on national average estimates.
- Method 2: a facility-specific method, generally, using industry practices for sampling and Australian or equivalent standards for analysis.
- Method 3: the same as method 2 but based on Australian or equivalent standards for both sampling and analysis.
- Method 4: provides for facility-specific measurement of emissions by continuous or periodic emissions monitoring.

Three of these – Methods 1, 2 and 3 are described for N_2O determination. These three methods included in the Determination provide for a Tier 2, country-specific assessment based on national data, EFs and facility-specific nitrogen loads. Work is ongoing to develop in-country facility-specific emissions measurement for use by the industry to develop improved country-level EFs.

All methods adopt a mass balance approach to calculate the removal of organic material, or nitrogen, considering country-specific factors for protein, nitrogen in sludge and disposal routes (to landfill or other disposal), and emissions differentiated by three types of discharge environment as per Equation (4.9) below. See the published Determination Section 5.31 for full method detail, a summary of which is provided below.

$$E_j = (N_{\text{in}} - N_{\text{trl}} - N_{\text{tro}} - N_{\text{outdisij}}) \times EF_{\text{secij}} + N_{\text{outdisij}} \times EF_{\text{disij}} \tag{4.9}$$

where E_j is the emissions of N_2O released from human sewage treated by the plant during the year, measured in tonnes of N_2O and expressed in CO_2e tonnes, N_{in} is the quantity of nitrogen entering the plant during the year, measured in tonnes of nitrogen and calculated according to whether the plant has treatment to a primary or secondary standard, population served, a per capita protein intake of 0.036 tonnes per year and a nitrogen protein fraction of 0.016 tonnes of nitrogen per tonne of protein. N_{trl} is the quantity of nitrogen in sludge transferred out of the plant and removed to landfill during the year, measured in tonnes of nitrogen and calculated using a mass flow of dry sludge and assumed fraction of nitrogen of 0.05, N_{tro} is the quantity of nitrogen in sludge transferred out of the plant and removed to a site other than landfill during the year, measured in tonnes of nitrogen and calculated using a mass flow of dry sludge and nitrogen fraction of 0.05, N_{outdisij} is the quantity of nitrogen leaving the plant, differentiated by discharge environment as described by EF_{disij} factors to different discharge environments.

The EF for wastewater, EF_{secij}, is currently 4.9 tonnes of N_2O, measured in CO_2e per tonne of nitrogen 'produced' from the wastewater treatment process (i.e. N_2O removed through the WWTP) or 0.016 kg N_2O/kg TN removed in secondary treatment based on the 2017 Determination (with N_2O GWP of 298). This was based historically on international literature sources and work of the IPCC. This is currently in revision and a proposed revised factor following consultation in July 2020 is 2.082 tonnes of N_2O measured in CO_2e per tonne of nitrogen produced or 0.0079 kg N_2O/kg TN.

For Methods 2 and 3, the same EF applies but laboratory sampling methods are specified (see Determination Sections 5.33, 5.34, 5.35, 5.36). The Determination requires that samples be representative, sufficient in coverage, free from bias, sampled in accordance with quoted international or Australian standards and, in the case of wastewater, sampled on a monthly basis.

Work continues in the Australian water sector to estimate in-country EFs and develop in-country monitoring methodologies which might allow for future development of a Method 4 approach.

4.4.2.2 Austria

A Tier 2 country-specific EF of 43 g N_2O/PE/year is used to estimate N_2O emissions from wastewater treatment for their national GHG inventory assessment for WWTPs serving over 2 000 PE. Water utilities are not required to report GHG emissions at the sector-level to their regulator.

The estimation of a country-specific EF was developed based on a national measuring program conducted in 2012–2014 with 20 field measurements at 8 representative activated sludge WWTPs (BMLFUW, 2015). The monitoring campaigns were carried out with long-term online measurements of several weeks, with both off-gas measurement (flux chamber) and liquid measurement (Unisense micro-sensor). The results concluded that nitrification was the main source of N_2O emissions, and an observed correlation with the TN removal degree confirmed the role of the denitrification as N_2O sink. The country-specific EF was derived through linear regression of N_2O emissions and nitrogen removal for 18 of the 20 campaigns and extrapolated to include nitrogen removal consideration for WWTPs with an organic design capacity larger than 5 000 PE (94%) and less than 2 000 PE (~6%) (BMLFUW, 2015). This draws on work previously discussed by Valkova *et al.* (2020) and Parravicini *et al.* (2016) which draws attention to the link between N_2O emissions and the extent of total nitrogen reduction. Based on the Austrian wastewater emission ordinance a 70% minimum reduction degree on annual average basis is required for municipal WWTPs > 5 000 PE (EVO, 1996).

In addition, to estimate the N_2O emissions from the discharge of wastewater to aquatic environments, the Austrian methodology considers country-specific measured/reported values for $N_{\text{Effluent,DOM}}$ (Equation (4.8)) for both WWTP effluent and for effluent of the population not connected to the WWTP (less than 5%). The total N_2O emissions for the inventory is the following:

$$N_2O_{\text{TOTAL}} = N_2O_{\text{WWTP}} + N_2O_{\text{EFFLUENT}} \tag{4.10}$$

where, N_2O_{WWTP} is N_2O emissions from advanced WWTPs for the population connected to WWTPs with controlled nitrification and denitrification; N_2O_{EFFLUENT} is N_2O emissions from WWTPs effluent and from effluent of the population not connected to WWTPs.

4.4.2.3 Denmark

Denmark has completed a national survey of N_2O emissions from representative WWTPs and is applying mitigation strategies to reduce N_2O emissions across the sector (VTU, 2016). This was achieved through monitoring across 10 facilities and analysis of data (including removal of facility N_2O emission pertaining to sidestream treatment) has resulted in a new country-specific EF of 0.84% N_2O based on influent TN (noting that all WWTPs achieve very high degrees of total nitrogen removal). This is significantly higher than the previous in-country EF of 0.32% N_2O based on influent TN (The Danish EPA, 2020). Regulatory incentives are being discussed to reduce emissions to a target value and provide a mechanism for the water companies to fund this, which is likely to result in a focus on online continuous monitoring and mitigation for large facilities.

4.4.2.4 Japan

Different Tier 2 EFs are used to estimate N_2O emissions in Japan based on research conducted in WWTPs in the country for specific treatment types, as detailed in Table 4.5.

The EFs for high load denitrification and membrane separation were derived based on the median value of on-site measurements at 13 WWTPs (National Institute for Environmental Studies (2006)). For other treatment processes, the EF was obtained by dividing the upper limit value for standard denitrification from Tanaka *et al.* (1995) by treated nitrogen concentration in fiscal year 1994 (GIO, 2019).

Table 4.5 Nitrous oxide emission factors by wastewater treatment plant.

Wastewater treatment process	N_2O EF_{WWTP} (kg N_2O-N/kg N load)
High load denitrification	0.0029
Membrane separation	0.0024
Other (including anaerobic, aerobic and standard denitrification treatment processes)	0.0000045

High load denitrification facilities treat ‘night soil’ and black water ‘sludge’ from different wastewater treatment configurations through ‘high-load denitrification devices, solid-liquid separation devices and flocculation separation devices’; standard denitrification facilities include grey water which results in a more diluted wastewater and comprises a biochemical denitrification process (Ministry of Environment, 2018). Membrane separation processes also appear to be high-load denitrification facilities where membrane separation devices are adopted for solid-liquid separation instead of traditional sedimentation tanks or mechanical devices (Ministry of Environment, 2019).

4.4.2.5 United States of America

In the USA mandatory GHG emissions reporting from water companies can occur at different levels, depending on the State. For instance, in California, water companies emitting from 10 000 to 25 000 tCO_2e/year need to report at a State level to the California Air Resources Board (CARB) Regulation for the Mandatory Reporting of GHG Emissions (MRR), and also choose to report at a sector-level to The Climate Registry (TCR) voluntary reporting program (McGuckin *et al.*, 2013).

For the national level GHG inventory assessment, in addition to using the 2006 IPCC Guidelines EF of 3.2 g N_2O/person/year (0.00035 kg N_2O-N/kg N load) for WWTPs without intentional denitrification (Czepiel *et al.*, 1995), the United States Environmental Protection Agency (USEPA) have introduced a country-developed EF for WWTPs with intentional nitrification and denitrification due to the degree of biological nutrient removal (BNR) WWTPs in the country, which serves a population of 21.3 million people (Scheehle & Doorn, 2001; USEPA, 2019). The EF of 7.0 g N_2O/person/year (0.00074 kg N_2O-N/kg N load) was adopted based on a study conducted in Germany in 1993, and thus not derived from in-country estimates (Schon *et al.*, 1993). Per capita protein intake figures are considered specific to dietary intake in the US whilst the IPCC 2006 estimate of 16 kg N/kg protein is applied. This results in an incoming TN of 16 g N/PE/day.

4.4.2.6 United Kingdom

In the United Kingdom (UK), emissions from the water sector are reported both at the national level based on the Department for Environment, Food & Rural Affairs (Defra) Guidelines, and at the sector level to the economic regulator for water companies in England and Wales, Ofwat.

For the national reporting, N_2O emissions from wastewater treatment are not reported, only indirect N_2O from discharge of effluent based on the 2006 IPCC Guidelines is reported. The NIR specifies that ‘the UK GHG inventory mostly follows the UK water industry GHG emission estimation methodology developed by [the UK Water Industry Research] UKWIR and used by all UK water companies to generate their annual emission estimates from all sources/activities’ (Brown *et al.*, 2019).

For sector-level reporting, water companies have been required to report their annual operational GHG emissions to the regulator, Ofwat, since 2007 (Ofwat, 2010). The reporting is done using the industry-wide tool, CAW, which provides a framework for harmonized estimation and reporting of the annual GHG emissions from the UK water sector (UKWIR, 2005). Since its first publication by UKWIR in 2005, the CAW has been reviewed each year to include the latest available information and reviews in 2009 and 2020 considered process EFs. The latest review undertaken in 2020 was aimed at addressing the need for an improved understanding of process emissions, specifically CH_4 and N_2O emissions (UKWIR, 2020a, 2020b).

For estimation of N_2O emissions from wastewater treatment, the latest review updated the country-developed EF to its original value of 0.004 kg N_2O-N/kg N load in secondary treatment, which was originally derived from the simple statistical average of nine studies (lab-, pilot-, and full-scale) conducted globally between 1994 and 2002 (UKWIR, 2008; (United Kingdom Water Industry Research, U 2020). The UK water sector have acknowledged that accurate estimation and mitigation of process emissions is one of the main challenges in their pathway to achieving net zero by 2030. Work is underway to develop an approach for industry wide monitoring of N_2O from representative WWTPs to develop country-specific EFs across fixed-film and suspended growth process types (United Kingdom Water Industry Research, U 2020).

REFERENCES

Aboobakar A., Cartmell E., Stephenson T., Jones M., Vale P. and Dotro G. (2013). Nitrous oxide emissions and dissolved oxygen profiling in a full-scale nitrifying activated sludge treatment plant. *Water Research*, **47**, 524–534, https://doi.org/10.1016/j.watres.2012.10.004

Ahn J.-H., Kim S., Park H., Rahm B., Pagilla K. and Chandran K. (2010). Emissions from activated sludge processes, 2008–2009: results of a National Monitoring Survey in the United States. *Environmental Science and Technology*, **44**, 4505–4511, https://doi.org/10.1021/es903845y

Aizawa, T., Sato A. and Nojiri, (2006). National Greenhouse Gas Inventory Report of Japan (August, 2006). National INstitute for Environmental STudies. Available at https://www.nies.go.jp/gio/en/archive/nir/jqjm1000000kannj-att/I069.pdf

Bao Z., Sun S. and Sun D. (2016). Assessment of greenhouse gas emission from A/O and SBR wastewater treatment plants in Beijing, China. *International Biodeterioration & Biodegradation*, **108**, 108–114, https://doi.org/10.1016/j.ibiod.2015.11.028

Bartram D., Short M. D., Ebie Y., Karkas J., Gueguen C., Peters G. M., … Karthik M. (2019). 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, IPCC.

Bellucci F., Kozak J. A., Heraty L., Carbone J., Sturchio N. C., Connor C., … Lanyon R. (2010). Greenhouse Gas Emissions from Three Chicago Wastewater Treatment Plants. Water Environment Federation (p. 417904199). WEFTEC.

BMLFUW (2015). Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft. Retrieved from Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft: https://www.bmlfuw.gv.at/service/publikationen/wasser/Lachgasemissionen---Kl-ranlagen.html

Brotto A. C., Huosheng L., Muriel D., Gabarro J., Colprim J., Murthy S. and Chandran K. (2015a). Characterization and mitigation of nitrous oxide (N2O) emissions from partial- and full-nitrification BNR processes based on post-anoxic aeration control. *Biotechnology & Bioengineering*, **9999**, 1–7.

Brotto A. C., Kligerman D. C., Andrade S. A., Ribeiro R. P., Oliveira J. L., Chandran K. and de Mello W. Z. (2015b). Factors controlling nitrous oxide emissions from a full-scale activated sludge system in the tropics. *Environmental Science Pollution Research*, **22**, 11840–11849, https://doi.org/10.1007/s11356-015-4467-x

Brown P., Broomfield M., Cardenas L., Choudrie S., Jones L., Karagianni E., … Wakeling D. (2019). UK Greenhouse Gas Inventory, 1990 to 2017. Department of Business, Energy and Industrial Strategy, London.

C40 (2020, October 19). C40 Cities. Retrieved from https://www.c40.org/

Czepiel P., Crill P. M. and Harris R. C. (1995). Nitrous oxide emissions from municipal wastewater treatment. *Environmental Science and Technology*, **29**, 2352–2356, https://doi.org/10.1021/es00009a030

Daelman M. R., van Voorthuizen E. M., van Dongen U. G., Volcke E. I. and van Loosdrecht M. C. (2012). Methane emission during municipal wastewater treatment. *Water Research*, **46**, 3657–3670, https://doi.org/10.1016/j.watres.2012.04.024

Daelman M. R., van Voorthuizen E. M., van Dongen L., Vockle E. I. and van Loosdrecht M. C. (2013). Methane and nitrous oxide emissions from municipal wastewater treatment – results from a long-term study. *Water Science and Technology*, **67**, 2350–2355, https://doi.org/10.2166/wst.2013.109

Daelman M. R., van Voorthuizen E. M., van Dongen U. G., Volcke E. I. and van Loosdrecht M. C. (2015). Seasonal and diurnal variability of N2O emissions from a full-scale municipal wastewater treatment plant. *Science of the Total Environment*, **536**, 1–11, https://doi.org/10.1016/j.scitotenv.2015.06.122

de Haas D. and Ye L. (2021). Nitrous oxide emissions from wastewater treatment: a case for variable emission factors. *e-journal*, **6**(2). https://doi.org/10.21139/wej.2021.008

Delre A., Monster J. and Scheutz C. (2017). Greenhouse gas emission quantification from wastewater treatment plants, using a tracer gas dispersion method. *Science of The Total Environment*, **605–606**, 258–268, https://doi.org/10.1016/j.scitotenv.2017.06.177

de Mello W. Z., Ribeiro R. P., Brotto A. C., Kligerman D. C., Piccoli A. S. and Oliveira J. L. (2013). Nitrous oxide emissions from an intermittent aeration activated sludge system of an urban wastewater treatment plant. *Quimica Nova*, **36**, 16–20. Retrieved from: https://www.scielo.br/j/qn/a/KH9PdV5YM6Fp8fhRxLS3bQR/

Department of Industry, Science, Energy and Resources (2021) National Greenhouse and Energy Reporting (Measurement) Determination 2008 made under subsection 10(3) of the National Greenhouse and Energy Reporting Act 2007, Compilation No. 13, dated 1 July 2021.

Doorn M. R., Strait R. P., Barnard W. and Eklund B. (1997). Estimate of Global Greenhouse Gas Emissions from Industrial and Domestic Wastewater Treatment, EPA-600/R-97-091, U.S. EPA Office of Research and Development, Air Pollution Prevention and Control Division, Research Triangle Park, NC.

Doorn M. R., Towprayoon S., Vieira S. M., Irving W., Palmer C., Pipatti R. and Wang C. (2006). Chapter 6: wastewater treatment and discharge. In: 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Simon E., Leandro B., Kyoko M., Todd N. and Kiyoto T. Volume 5: Waste. IPCC. Japan by Institute for Global Environmental Strategies (IGES), Hayama, Japan. https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/0_Overview/V0_0_Cover.pdf

European Union (2020, September 15). EUR_Lex. Retrieved from EUR_Lex: https://eur-lex.europa.eu/eli/dec_impl/2018/1147/oj

EVO (1996). Allgemeine Emissionsverordnung für kommunales Abwasser /emission ordinance for municipal wastewater, adaptation to the EU guideline for municipal wastewater 271/91 (accessed 5 January 2021).

Federici S. (2019). 2019 Refinement to the 2006 IPCC Guidelines for National GHG Inventories. UN Climate Change Conference. IPCC, Madrid.

Foley J., de Haas D., Yuan Z. and Lant P. (2010). Nitrous oxide generation in full-scale biological nutrient removal wastewater treatment plants. *Water Research*, **44**, 831–844, https://doi.org/10.1016/j.watres.2009.10.033

GIO (2019). National Greenhouse Gas Inventory Report of JAPAN, Ministry of the Environment/Japan Greenhouse Gas Inventory Office of Japan (GIO)/Center for Global Environmental Research (CGER)/National Institute for Environmental Studies (NIES). National Institute for Environmental Studies.

Greenhouse Gas Protocol (2021). GHG Protocol Global Protocol for Community-Scale Greenhouse Gas Inventories. Published by World Resources Institute. Retrieved from: https://ghgprotocol.org/sites/default/files/standards/GPC_Full_MASTER_RW_v7.pdf

Greenhouse Gas Protocol (2015). Revised Edition, A Corporate Accounting and Reporting Standard. World Resources Institute.

Greenhouse Gas Protocol (2020b). Greenhouse Gas protocol. Retrieved from: https://ghgprotocol.org/

Holmgren M., Hellstrom H. and Petersson A. (2012). The Swedish Voluntary Agreement for Control of Methane Emissions From Biogas Plants. Orbit 2012.

IPCC (2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. In: H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara and K. Tanabe (eds.). Published: IGES, Japan. https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/0_Overview/V0_0_Cover.pdf.

IPCC (2014a). Climate change 2014: synthesis report. In: Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Core Writing Team, R. K. Pachauri and L. A. Meyer (eds.), IPCC, Geneva.

IPCC (2014b). 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands, T. Hiraishi, T. Krug, K. Tanabe, N. Srivastava, J. Baasansuren, M. Fukuda and T. G. Troxler (eds.), IPCC, Switzerland.

IPCC (2018a). IPCC Factsheet: What is the IPCC. IPCC.

IPCC (2018b). Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.). World Meteorological Organization, Geneva, Switzerland, 32 pp.

IPCC (2020a). AR6 Synthesis Report: Climate Change 2022. Retrieved from IPCC: https://www.ipcc.ch/report/sixth-assessment-report-cycle/#:~:text=The%20IPCC%20is%20currently%20in,due%20for%20release%20in%202022

IPCC (2020b). The Paris agreement. Retrieved from United Nations Climate Change: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (accessed 5 January 2021).

IPCC (2021). Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. V. Masson - Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds). Cambridge University Press. In Press.

Kimochi Y., Inamori Y., Mizuochi M., Kai-Qin X. and Matsumara M. (1998). Nitrogen Removal and N_2O Emission in a Full Scale Domestic Wastewater Treatment Plant with Intermittent Aeration. *Journal of Fermentation and Bioengineering*, **86**, 202–206.

Kozak J. A., O'Connor C., Granato T., Kollias L., Bellucci F. and Sturchio N. (2009). Methanes and nitrous oxide emissions from wastewater treatment plant processes. 5347–5361. Available at https://accesswater.org/publications/-296015/methane-and-nitrous-oxide-emissions-from-wastewater-treatment-plant-processes

Kyung D., Kim M., Chang J. and Lee W. (2015). Estimation of greenhouse gas emissions from a hybrid wastewater treatment plant. *ournal of Cleaner Production*, **95**, 117–123.

Lake A., Brotto A., Porro J., Holmen Andersen M. and Sandino J. (2021). Nitrous oxide – no laughing matter – lessons from Europe. unpublished.

Masuda S., Suzuki S., Sano I., Li Y.-Y. and Nishimura O. (2015). The seasonal variation of emission of greenhouse gases from a full-scale sewage treatment plant. *Chemosphere*, **140**, 167–173, https://doi.org/10.1016/j.chemosphere.2014.09.042

Masuda S., Sano I., Hojo T., Li Y.-Y. and Nishimura O. (2018). The comparison of greenhouse gas emissions in sewage treatment plants with different treatment processes. *Chemosphere*, **193**, 581–590, https://doi.org/10.1016/j.chemosphere.2017.11.018

McGuckin R., Oppenheimer J., Badruzzaman M., Contreras A. and Jacangelo J. G. (2013). Toolbox for Water Utility Energy and Greenhoyse Gas Emission Management, Water Research Foundation, Denver.

Metcalf & Eddy (2003). Wastewater Engineering: Treatment and Reuse. McGraw-Hill, New York.

Miljøstyrelsen (English translation Danish Environmental Protection Agency) (2020). MUDP Lattergaspulje Dataopsamling på måling og reduktion af lattergasemissioner fra renseanlæg, Retrieved from https://www2.mst.dk/Udgiv/publikationer/2020/12/978-87-7038-254-0.pdf

Ministry of the Environment (2018). Night Soil Treatment and Decentralised Wastewater Treatment Systems in Japan. Retrieved from https://www.jeces.or.jp/en/downroad/pdf/nightsoilsystems_en.pdf

Ni B.-J., Pan Y., van den Akker B., Ye L. and Yuan Z. (2015). Full-scale modeling explaining large spatial variations of nitrous oxide fluxes in a step-feed plug-flow wastewater treatment reactor. *Environmental Science and Technology*, **49**, 9176–9184.

Ofwat (2010). Playing Our Part – Reducing Greenhouse Gas Emissions in the Water and Sewarage Sectors. Supporting Information, Ofwat, Birmingham.

OPC: Office of Parliamentary Counsel (2017a). National Greenhouse and Energy Reporting (Measurement) Determination 2008 made under subsection 10(3) of the National Greenhouse and Energy Reporting Act 2007, compilation No. 9 dated 1 July 2017, Office of Parliamentary Counsel, Canberra.

OPC (2017b). National Greenhouse and Energy Reporting (Measurement) Determination 2008, Compilation No. 9, Office of Parliamentary Council, Canberra.

Pan Y., van den Akker B., Ye L., Ni B.-J., Watts S., Reid K. and Yuan Z. (2016). Unravelling the spatial variation of nitrous oxide emissions from a step-feed plug flow full scale wastewater treatment plant. *Scientific Reports*, **6**, 20792. https://doi.org/10.1038/srep20792

Parravicini V., Svardal K. and Krampe J. (2016). Greenhouse gas emissions from wastewater treatment plants. *Energy Procedia*, **97**, 246–253, https://doi.org/10.1016/j.egypro.2016.10.067

Pijuan M., Tora J., Rodriguez-Caballero A., Carrera C. E. and Perez J. (2014). Effect of process parmeters and operational mode on nitrous oxide emissions from anitritation reactor treating reject wastewater. *Water Research*, **49**, 23–33, https://doi.org/10.1016/j.watres.2013.11.009

Rodriguez-Caballero A., Aymerich I., Poch M. and Pijuan M. (2014). Evaluation of process conditions triggering emissions of green-house gases from a biological wastewater treatment system. *Sci Total Environ* **493**, 384–391.

Rodriguez-Caballero A., Aymerich I., Marques R., Poch M. and Pijuan M. (2015). Minimizing N_2O Emissions and Carbon Footprint on a Full-Scale Activated Sludge Sequencing Batch Reactor. *Water Research* **71**, 1–10.

Rogelj J., Shindell D., Jiang K., Fifita S., Forster P., Ginzburg V., Handa C., Kheshgi H., Kobayashi S., Kriegler E., Mundaca L., Séférian R. and Vilariño M. V. (2018). Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds). In Press, pp. 93–174.

Schaum C., Fundneider T. and Cornel P. (2016). Analysis of methane emissions from digested sludge. *Water Science and Technology*, **73**, 1599–1607, https://doi.org/10.2166/wst.2015.644

Scheehle E. A. and Doorn M. R. (2001). Improvements to the US Wastewater Methane and NItrous Oxide Emissions Estimate.

Schon M., Walz R., Angerer G., Bohm E., Hillenbrand T., Hiessl H. and Reichert J. (1993). Emissionen der Treibhausgase Distickstoffoxid und Methan in Deutschland. Emissionsbilanz, Identifikation von Forschungs- und Entwicklungsbedarf Sowie Erarbeitung von Handlungsempfehlungen. Phase 1. Erich Schmidt Verlag,

Berlin, Germany. Retrieved from: http://publica.fraunhofer.de/documents/PX-46292.html (accessed 5 January 2021)
Tanaka M., Inoue Y., Matsuzawa Y. and Watanabe I. (1995). B2-(1)Research into Volumes Released from Waste Treatment Plants, 1994 Global Environment Research Fund Outcome Report.
UKWIR (2005). Workbook for Quantifying Greenhouse Gas Emissions, 05/CL/01/3, UKWIR, London.
UKWIR (2008). Carbon Accounting in the UK Water Industry: Methodology for Estimating Operating Operational Emissions, 08/CL/01/5, UKWIR, London.
UKWIR (2020a, September 15). How do we remove more carbon than we emit by 2050. Retrieved from UK Water Industry Research: https://ukwir.org/How-do-we-remove-more-carbon-than-we-emit-by-2050 (accessed 5 January 2021)
UKWIR (2020b). Quantifying and Reducing Direct Greenhouse Gas Emissions From Waste and Water Treatment Processes, CL/01/E/201, UKWIR, London.
United Kingdom Water Industry Research (2020). Quantifying and Reducing Direct Greenhouse Gas Emissions From Waste and Water Treatment Processes, UKWIR, London.
United Nations (2020, September 15). What is the kyoto protocol. Retrieved from United Nations Climate Change: https://unfccc.int/kyoto_protocol (accessed 5 January 2021)
USEPA (2019). Inventory of the U.S Greenhouse Gas Emissions and Sinks. 1990–2017, US Environmental Protection Agency.
Valkova T., Parravicini V., Saracevic E., Tauber J., Svardal K. and Krampe J. (2020). A method to estimate the direct nitrous oxide emissions of municipal wastewater treatment plants based on the degree of nitrogen removal. *Journal of Environmental Management*, **279**, 1–10.
Vasilaki V., Massara T. M., Stanchev P., Fatone F. and Katsou E. (2019). A decade of nitrous oxide (N2O) monitoring in full-scale wastewater. *Water Research*, **161**, 392–412, https://doi.org/10.1016/j.watres.2019.04.022
VTU (2016). Intelligent og miljømæssig bæredygtig energieffektivisering af renseanlæg – Emissionsminimering af drivhusgasser.
Wang J., Chen N., Yan W., Wang B. and Yang L. (2015). Effect of dissolved oxygen and nitrogen on emission of N2O from rivers in China. *Atmospheric Environment*, **103**, 347–356, https://doi.org/10.1016/j.atmosenv.2014.12.054
Wang Y., Fang H., Zhou D., Han H. and Chen J. (2016). Characterization of nitrous oxide and nitric oxide emissions from a full-scale biological aerated filter for secondary nitrification. *Chemical Engineering Journal*, **299**, 304–313.
Woess-Gallash S., Bird S., Enzinger P., Jungmeier G., Padinger R., Pena N. and Zanchi G. (2010). Greenhouse gas benefits of a biogas plant in Austria, Joanneum Research Forschungsgesellschaft mbH, Resources – Institute of Water, Energy and Sustainability, Graz, Austria.
World Resources Institute (2021). Global Protocol for Community Scale Greenhouse Gas Inventories. World Resources Institute: Washington DC, USA, https://ghgprotocol.org/sites/default/files/standards/GPC_Full_MASTER_RW_v7.pdf (accessed 20 March 2022)
World Resources Institute and World Business Council for Sustainable Development, (2011). Corporate Value Chain (Scope 3) Accounting and Reporting Standard. Place of publication WRI – Washington DC, USA. ISBN 978-1-56973-772-9 Retrieved from: https://ghgprotocol.org/sites/default/files/standards/Corporate-Value-Chain-Accounting-Reporing-Standard_041613_2.pdf. (Accessed 20 March 2022)

NOMENCLATURE

AD	Anaerobic digestion
BAT	Best available technology
BNR	Biological nutrient removal
BOD	Biological oxygen demand
CARB	California Air Resources Board Regulation for the Mandatory Reporting of GHG Emissions
COD	Chemical oxygen demand

EF	Emission factor
EU	European Union
GHG	Greenhouse gas
GWP	Global warming potential
IPCC	Intergovernmental Panel on Climate Change
LDAR	Leakage detection and repair
MCF	Methane correction factor
NDC	Nationally determined contributions
NIR	National Inventory Report
PE	Population equivalents
TCR	The Climate Registry
TN	Total nitrogen
UK	United Kingdom
UKWIR	United Kingdom Water Industry Research
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
USEPA	United States Environmental Protection Agency
WWTP	Wastewater treatment plant