DANISH EMISSION INVENTORY FOR WASTEWATER TREATMENT AND DISCHARGE

Results of inventories up to 2023

Scientific Report from DCE – Danish Centre for Environment and Energy No. 689 2025

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Data sheet

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Abstract: This report forms part of the documentation for the emission inventories for waste. The report includes both methodological descriptions for estimating emissions of greenhouse gases and air pollutants and presents the resulting emission data as reported to the United Nations Framework Convention on Climate Change and the United Nations Economic Commission for Europe Convention on Long-Range Transboundary Air Pollution. The results of inventories up to 2023 are included.

Keywords: WWTP, wastewater treatment plants, CH_4, N_2O, NMVOC, National GHG emission inventory, effluent

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List of abbreviations

AD	Anaerobic Digestion
AR5	Fifth Assessment Report of the IPCC
BI_5	Organic matter measured as biochemical oxygen demand over 5 days
BOD	Biological Oxygen Demand. Is an indirect measure of the amount of organic matter that can be oxidised biologically in the wastewater.
CH_4	Methane
CLRTAP	Convention on Long-Range Transboundary Pollutants
COD	Organic matter measured as Chemical Oxygen Demand
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalents
DOC	Degradable Organic Content
DCE	Danish Centre for Environment and energy
DEA	Danish Energy Agency
DEPA	Danish Environmental Protection Agency
DME	Danish Ministry of Environment and Gender Equality
EF	Emission Factor
ENVS	Department of ENVironmental Science, Aarhus University
GHG	Greenhouse gas
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
kt	kiloton, 1,000,000,000 grams
MBNDC	Mechanical, Biological Nitrification, Denitrification and Chemical (In Danish MBNDK)
MCF	Methane Conversion Factor
N_2O	Nitrous oxide
NMVOC	Non-Methane Volatile Organic Compounds
NOVANA	National Monitoring and Assessment Programme for the Aquatic and Terrestrial Environments
SGAV	Agency for Green Transition and Aquatic Environment
QA	Quality Assurance
QC	Quality Control
TOW	Total Organic Waste. Expressed in either BOD (BI_5) or COD
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change
WWTP	Wastewater Treatment Plant

List of annexes

Annexes are only available online at: https://envs.au.dk/en/research-areas/air-pollution-emissions-and-effects/air-emissions/reporting-sectors/waste (at the bottom of the page).

Please note that data found via this link always match the newest version of the sector reporting.

Preface

The Danish Centre for Environment and Energy (DCE), Aarhus University prepares the national inventories of emissions to the atmosphere and is responsible for the reporting to the UNFCCC (United Nations Framework Convention on Climate Change) and to the UNECE CLRTAP (United Nations Economic Commission for Europe Convention on Long-range Transboundary Pollutants) on an annual basis. Furthermore, the greenhouse gas emission inventory is reported to the European Union and the Paris Agreement, while the air pollution inventory forms the basis of the reporting under the NEC directive (National Emission Ceilings Directive for certain atmospheric pollutants).

This report summarises the methods and the data used for quantification of emissions from wastewater treatment and discharge. Data given in this report cover the time-series until 2023. These data formed the basis for the submissions to the international bodies in 2025.

This is the third sectoral report documenting the data and methodologies used in estimating emissions from wastewater treatment and discharge. The report has been reviewed externally by Thomas Frank-Gopolos and Amanda Elmark Christensen from Agency for Green Transition and Aquatic Environment (SGAV) under The Danish Ministry of Green Transition and their comments have been addressed in the report.

Summary

The Danish Centre for Environment and Energy (DCE), Aarhus University prepares the national inventories of emissions to the air and carries out the reporting to the UNFCCC (United Nations Framework Convention on Climate Change) and to the UNECE CLRTAP (United Nations Economic Commission for Europe Convention on Long-range Transboundary Air Pollution) on an annual basis. Furthermore, the greenhouse gas emission inventory is reported to the EU Regulation on the Governance of the Energy Union and Climate Action, while the air pollution inventory is reported under the NEC directive (Directive on the reduction of national emissions of certain atmospheric pollutants).

Denmark has international obligations to annually estimate and report emissions to the atmosphere of a large number of pollutants. Distinct reporting obligations exist for greenhouse gases and air pollution. The Danish greenhouse gas emission inventories follow the IPCC Guidelines. While the air pollution inventories are based on the methodology outlined in the EMEP/EEA Guidebook. The national emission inventory covers six sectors as defined in the reporting formats for the UNECE CLRTAP and the UNFCCC; one of these six sectors being Waste. "Wastewater treatment and discharge" is a subsector in the Waste sector. The Wastewater treatment and discharge subsector covers emissions from the aerobic and anaerobic treatment (biogas production) of wastewater and the emissions related to discharge of effluent wastewater.

Denmark is a Party to two international conventions regarding air emissions: the CLRTAP (the Geneva Convention) and the UNFCCC (the Climate Convention). Air pollutants reported under the CLRTAP are SO_2, NO_x, NMVOC, CO, NH_3, particles, heavy metals (As, Cd, Cr, Cu, Hg, Ni, Pb, Se, Zn) and POPs (PCDD/F, HCB, PCBs, benzo(a)pyrene, benzo(b)fluoranthene, benzo(k)fluoranthene and indeno(1,2,3-cd)pyrene). Greenhouse gasses (CO_2, CH_4, N_2O, and F-gasses) are reported under the UNFCCC. Only methane (CH_4), nitrous oxide (N_2O) and non-methane volatile organic compounds (NMVOC) are relevant for wastewater and therefore the scope of this report. The information contained in this report only relates to Denmark, i.e. excluding Greenland and the Faroe Islands.

Wastewater management in Denmark has changed much over the last decades. In the 1990s, the treatment plants were more numerous, smaller and relatively primitive, but up through the 90s and 00s the treatment plants became more and more advanced and centralised. The sector is also affected by the expansion of the sewer system which includes a larger part of the population and an increase in industrial wastewater being treated centrally at large municipally administrated treatment plants.

This report provides detailed background information on the methodologies and references for the input data used for quantification of emissions from wastewater treatment and discharge. Including information on the methodologies, activity data, emission factors, and emissions for the time series 1990-2023 (1985-2023 for NMVOC). The emission factors are based either on national references or on international guidebooks, while activity data are country specific.

Emissions of CH_4, N_2O and NMVOC are included in the wastewater treatment and discharge sector. CH_4 emissions stem from sewer systems and wastewater treatment, from anaerobic treatment plants, from scattered settlements and from wastewater discharge of both residential, commercial and industrial wastewater. N_2O emissions stem from wastewater treatment and from wastewater discharge of both residential, commercial and industrial wastewater. NMVOC emissions stem from wastewater treatment of both residential, commercial and industrial wastewater.

The total Danish greenhouse gas emission in 2023 is 38,785.4 kt CO_2 equivalents (CO_2e) including Land use, Land use change and forestry (LULUCF) and including indirect CO_2. In the same year, greenhouse gas emissions from Wastewater treatment and discharge are 219.9 kt CO_2e, corresponding to 0.6 % of total national emissions. In 1990, greenhouse gas emission from wastewater was 441.3 kt CO_2e (0.6 % of the total national CO_2 equivalent emission), corresponding to a decrease throughout the time series of 50 %.

As mentioned above NMVOCs are also included in the inventory of wastewater treatment plants. NMVOC emission from wastewater in 2023 is 9.7 t (0.01 % of the national total NMVOC emission of 97.9 kt). This is a decrease of 23 % (from 12.7 t NMVOC) since 1990.

Sammenfatning

Nationalt Center for Miljø og Energi (DCE) på Aarhus Universitet udarbejder de nationale opgørelser for emissioner til luft og rapporterer hvert år til UNFCCC (De Forenede Nationers Rammekonvention om Klimaændringer) og til UNECE CLRTAP (De Forenede Nationers Økonomiske Kommission for Europa Konvention om Langtransporteret Grænseoverskridende Luftforurening). Derudover, rapporteres drivhusgasemissionsopgørelsen til EU's Forordning om forvaltning af energiunionen og klimaindsatsen, og luftforureningsopgørelsen rapporteres under NEC-direktivet (Direktiv om nedbringelse af nationale emissioner af visse luftforurenende stoffer).

Danmark har tilsluttet sig internationale forpligtigelser til årligt at estimere og rapportere emissioner fra en lang række stoffer til atmosfæren. Der er særskilte rapporteringsforpligtelser for drivhusgasser og luftforurening. De danske drivhusgasemissionsopgørelser følger IPCC's retningslinjer. Mens luftforureningsopgørelserne er baseret på EMEP/EEA Guidebogen. Den nationale emissionsopgørelse dækker seks sektorer som defineret i rapporteringsformaterne for UNECE CLRTAP og UNFCCC; en af disse seks sektorer er affald. "Spildevandsrensning og -udledning" er en delsektor i affaldssektoren. Delsektoren "Spildevandsrensning og -udledning dækker emissioner fra aerob og anaerob (biogas produktion) behandling af spildevand og emissioner relateret til udledning af spildevand.

Danmark er part i to internationale konventioner med hensyn til luftemissioner; CLRTAP (Genèvekonventionen) og UNFCCC (klimakonventionen). Luftforurenende stoffer rapporteret under CLRTAP er SO_2, NO_x, NMVOC, CO, NH_3, partikler, tungmetaller (As, Cd, Cr, Cu, Hg, Ni, Pb, Se, Zn) og POP'er (PCDD/F, HCB, PCB'er, benzo(a)pyrene, benzo(b)fluoranthene, benzo(k)fluoranthene and indeno(1,2,3-cd)pyrene). Drivhusgasserne (CO_2, CH_4, N_2O og F-gasser) rapporteres under UNFCCC. Kun metan (CH_4), lattergas (N_2O) og ikke-metan flygtigt organisk kulstof (NMVOC) er relevante for spildevandsrensning og derfor inkluderet i nærværende rapport. Oplysningerne i denne rapport vedrører kun Danmark, dvs. eksklusive Grønland og Færøerne.

Spildevandshåndteringen i Danmark har ændret sig meget i løbet af de seneste årtier. I 1990'erne var renseanlæggene flere, mindre og relativt primitive, men op gennem 90'erne og 00'erne blev renseanlæggene mere og mere avancerede og centraliserede. Sektoren er også påvirket af udbygningen af kloaksystemet, som omfatter en større del af befolkningen, og en stigning i industrielt spildevand, der behandles centralt på store kommunalt administrerede renseanlæg.

Denne rapport giver detaljeret baggrundsinformation om de anvendte beregningsmetoder og referencer for de inputdata, der anvendes til kvantificering af emissioner fra spildevandshåndtering og -udledning. Herunder oplysninger om beregningsmetoder, aktivitetsdata, emissionsfaktorer og emissioner for tidsserien 1990-2023 (1985-2023 for NMVOC). Emissionsfaktorerne og værdier for parametre, der indgår i beregningen af emissioner, er enten baseret på nationale referencer eller på internationale guidebøger, mens aktivitetsdata er specifikke for Danmark.

Emissioner af CH_4, N_2O og NMVOC er inkluderet i spildevandsrensnings- og -udledningssektoren. CH_4-emissioner stammer fra kloaksystemer og spildevandsrensning, fra anaerobe slambehandling, fra spredt bebyggelse og fra spildevandsudledning af både husholdnings-, erhvervs- og industrispildevand. N_2O-emissioner stammer fra spildevandsrensning og -udledning af både husholdnings-, erhvervs- og industrispildevand. NMVOC-emissioner stammer fra spildevandsrensning af både husholdnings-, erhvervs- og industrispildevand.

Den samlede danske drivhusgasemission i 2023 er 38.785,4 kt CO_2-ækvivalenter inklusive Arealanvendelse og Skovbrug (LULUCF) og inklusiv indirekte CO_2. Samme år er drivhusgasemissionerne fra spildevandsrensning og -udledning 219,9 kt CO_2-ækvivalenter, hvilket svarer til 0,6 % af de samlede nationale drivhusgasemissioner. I 1990 var drivhusgasemissionen fra spildevand 441,3 kt CO_2-ækvivalenter (0,6 % af den samlede nationale CO_2-ækvivalente emission), svarende til et fald i hele tidsserien på 50 %.

Som nævnt ovenfor er NMVOC også inkluderet i opgørelsen over spildevandsrensningsanlæg. NMVOC-emissioner herfra er 9,7 t i 2023 (0,01 % af den nationale samlede NMVOC-emission på 97,9 kt). Dette er et fald på 23 % (fra 12,7 t NMVOC) siden 1990.

1 International obligations

Denmark has international obligations to annually estimate and report emissions to the atmosphere of a large number of pollutants. Distinct reporting obligations exist for greenhouse gases and air pollution. The national emission inventories follow internationally agreed guidelines for the format, quality and timeline of the reporting.

The Danish greenhouse gas emission inventories follow the IPCC Guidelines (IPCC, 2006 and 2019). The inventories are based on the European programme for emission inventories, the CORINAIR system, which includes methodology, structure and software. The methodology is outlined in the EMEP/EEA Guidebook (EEA, 2023). The emission data are stored in MS Excel and the CollectER database from where it is transferred to the reporting formats. In the national inventory, the emissions are organised in six categories, according to the reporting formats for the Convention on Long-range Transboundary Pollutants (UNECE CLRTAP) and the United Nations Framework Convention on Climate Change (UNFCCC). These categories cover emissions from Energy, Industrial Processes and Product Use (IPPU), Agriculture, Land use - Land use change and forestry (LULUCF), Waste, and Other. The Danish emission database is organised according to the Selected Nomenclature for Air Pollution (SNAP) as defined in the CORINAIR system. The emission inventories are prepared from a complete emission database based on the SNAP sectors. Aggregation to the sector codes used for both the CLRTAP in accordance with the Nomenclature for Reporting (NFR) and the UNFCCC in accordance with the Common Reporting Tables (CRT) is based on a correspondence list between SNAP and NFR or CRT sectors.

Documentation reports for the National Emission Inventory 2025 are published on the homepage for The Danish Centre for Environment and Energy (DCE), Aarhus University, as are annual updated figures on emissions and emission factors: https://envs.au.dk/en/research-areas/air-pollution-emissions-and-effects/air-emissions

Furthermore, the data reported can be found on the EIONET homepage:

UNFCCC reporting: https://cdr.eionet.europa.eu/dk/Air_Emission_Inventories/Submission_UNFCCC

CLRTAP reporting: https://cdr.eionet.europa.eu/dk/un/clrtap/inventories/

1.1 International conventions and reduction targets

Denmark is a party to two international conventions with regard to air emissions: the CLRTAP (the Geneva Convention) and the UNFCCC (the Climate Convention).

CLRTAP is a framework convention and has expanded to cover eight protocols:

- EMEP Protocol, 1984 (Geneva).
- Protocol on the Reduction of Sulphur Emissions, 1985 (Helsinki).

- Protocol concerning the Control of Emissions of Nitrogen Oxides, 1988 (Sofia).
- Protocol concerning the Control of Emissions of Volatile Organic Compounds, 1991 (Geneva).
- Protocol on Further Reduction of Sulphur Emissions, 1994 (Oslo).
- Protocol on Heavy Metals, 1998 (Aarhus) and its 2012 amended version.
- Protocol on Persistent Organic Pollutants (POPs), 1998 (Aarhus) and its 2009 amended version.
- Protocol to Abate Acidification, Eutrophication and Ground-level Ozone, 1999 (Gothenburg) and its 2012 amended version.

The Climate Convention (UNFCCC) is a framework convention from 1992. The objective of the convention is "to achieve (…) stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". The convention does not hold obligations concerning reduction of emissions but encourage the parties to reduce the emissions of greenhouse gases to their 1990 level. An important point is that the Parties to the convention are obligated to make national inventories of anthropogenic emissions of sources and removals by sinks of greenhouse gases. Denmark has ratified the Climate Convention without territorial exceptions for Greenland and the Faroe Islands, and the national reporting to UNFCCC therefore includes the entire Kingdom of Denmark.

The Paris Agreement was adopted at the Paris Climate Change Conference of Parties (COP21) in 2015, establishing nationally determined contributions (NDCs) to have targets for 2030. The Paris Agreement entered into force on 4 November 2016. The EU submitted a provisional target under the Paris Agreement, called the Intended Nationally Determined Contribution (INDC), to reduce its greenhouse gas emissions by at least 40 % by 2030 compared to 1990. The Nationally Determined Contributions (NDCs) have to be updated or renewed every fifth year, next time in 2025. In December 2020, the EU submitted its updated and enhanced NDC of 55 % reduction by 2030 from 1990 levels. Thereby the EU and its Member States, acting jointly, are committed to a binding target of a net domestic reduction of at least 55 % in greenhouse gas emissions by 2030 compared to 1990.

To meet this international obligation, the EU has implemented regulations to ensure the compliance at Member State level. For the period 2021 to 2030, the EU established new reduction commitments for Member States in Regulation (EU) 2023/857. This regulation sets a target for Denmark of a reduction of 50 % in the non-ETS sector. For the ETS, there is a reduction in allowances of 43 % compared to 2005. A separate target exists for the land-use sector in Regulation (EU) 2023/839, where Denmark has a reduction target of 441 kt CO_2 equivalents compared to the average of 2016-2018.

The information contained in this report only relates to Denmark. The greenhouse gas emissions of the pollutants are converted to CO_2 equivalents, which can be summarised to total greenhouse gas (GHG) emissions. According to the IPCC Fifth Assessment Report, which has been used from this submission and will be used by all Parties in the reporting under the Paris Agreement, the global warming potentials for a 100-year time horison are:

- Carbon dioxide (CO_2): 1
- Methane (CH_4): 28
- Nitrous oxide (N_2O): 265

Based on weight and a 100-year period, CH_4 is thus 28 times more powerful a greenhouse gas than CO_2 and N_2O is 265 times more powerful than CO_2. (Myhre et al., 2013).

2 Total Danish emissions

The national Danish emissions in 2023 as reported to the conventions are summarised in Table 2.1, 2.2, 2.3 and 2.4. The emissions are aggregated on sector level according to the reporting formats.

Table 2.1 GHG emission 2023 as reported to UNFCCC (Nielsen et al., 2025a).

Sector	CO_2	CH_4	N_2O	HFCs	PFCs	SF_6	NF_3	Total GHG
				kt CO_2 equivalents				
Energy	24,362	323	280					24,965
Industrial Processes and Product Use	1,215	3	60	261	0.5	13	NO,NA	1,553
Agriculture	201	7,140	3,881					11,223
Land Use, Land-Use Change and Forestry	-939	397	42					-500
Waste	12	1,085	172					1,270
Denmark Total excl. LULUCF	25,790	8,552	4,394	261	0.5	13	NO,NA	39,010
Denmark Total incl. LULUCF	24,851	8,948	4,436	261	0.5	13	NO,NA	38,509
Indirect CO_2	276							

NA: Not applicable, NO: Not occuring

Table 2.2 Danish emissions of other air pollutants in 2023 as reported to CLRTAP (Nielsen et al., 2025b).

Sector	NO_x	NMVOC	SO_2	NH_3	$PM_{2.5}$	PM_{10}	TSP	BC	CO
	kt	kt	kt	kt	kt	kt	kt	kt	kt
Energy	63.92	22.11	7.10	1.65	9.11	10.34	11.82	1.55	171.70
Industrial Processes and Product Use	0.06	29.97	0.70	0.34	0.77	2.72	6.67	0.01	3.07
Agriculture	16.88	45.34	0.01	63.03	1.05	8.04	63.33	0.01	1.03
Waste	0.14	0.52	0.33	0.67	0.28	0.29	0.30	0.02	2.33
Other	NO	NO	NO	0.57	NO	NO	NO	NO	NO
Denmark Total	81.01	97.94	8.14	66.26	11.22	21.39	82.11	1.59	178.13

Table 2.3 Danish emissions of other air pollutants in 2023 as reported to CLRTAP (Nielsen et al., 2025b)

Sector	Pb	Cd	Hg	As	Cr	Cu	Ni	Se	Zn
	t	t	t	t	t	t	t	t	t
Energy	9.26	0.55	0.20	0.15	2.10	59.63	3.71	0.42	48.95
Industrial Processes and Product Use	1.85	0.02	0.01	0.06	0.22	3.25	0.25	0.03	2.51
Agriculture	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Waste	1.59	0.01	0.00	0.00	0.01	0.05	0.01	0.00	6.32
Other	NO	NO	NO	NO	NO	NO	NO	NO	NO
Denmark Total	12.70	0.59	0.21	0.21	2.33	62.93	3.97	0.45	57.79

Table 2.4 Danish emissions of other air pollutants in 2023 as reported to CLRTAP (Nielsen et al., 2025b)

Sector	PCDD/F	Benzo(a)-pyrene	Benzo(b)-flouranthene	Benzo(k)-flouranthene	Indene-(1,2,3-cd)-pyrene	HCB	PCB
	g	t	t	t	t	kg	kg
Energy	20.62	1.25	1.36	0.77	0.75	1.72	0.30
Industrial Processes and Product Use	0.15	0.02	0.02	0.01	0.01	0.01	0.06
Agriculture	0.03	0.01	0.02	0.01	0.01	0.36	0.00
Waste	4.19	0.06	0.09	0.05	0.08	0.01	0.03
Other	NO	NO	NO	NO	NO	NO	NO
Denmark Total	25.00	1.34	1.49	0.84	0.86	2.10	0.39

The waste sector generally only has minor contributions to the total emissions, but with noticeable exceptions, e.g. for CH_4, N_2O, SO_2, Pb, Zn and dioxins.

However, for wastewater treatment and discharge the only relevant pollutants are CH_4, N_2O and NMVOC. Only the emission of CH_4 and N_2O are significant compared to the national total emissions.

Table 2.5 Comparison of emissions from wastewater treatment and discharge and national Danish emissions.

	Unit	1990	1995	2000	2005	2010	2015	2020	2023
CH_4									
National emission, excl. LULUCF	kt	354.5	375.3	375.5	369.2	354.7	336.5	334.1	305.4
Wastewater treatment and discharge	kt	8.6	4.7	4.2	3.8	3.6	3.6	3.7	3.5
Fraction of national total	-	2.4%	1.3%	1.1%	1.0%	1.0%	1.1%	1.1%	1.1%
N_2O									
National emission, excl. LULUCF	kt	29.8	26.7	25.0	20.4	19.5	19.4	19.7	16.6
Wastewater treatment and discharge	kt	0.8	0.7	0.6	0.5	0.4	0.5	0.5	0.5
Fraction of national total	-	2.5%	2.6%	2.3%	2.6%	2.3%	2.6%	2.4%	2.8%
NMVOC									
National emission	kt	218.3	219.3	190.9	160.6	136.1	118.2	106.9	97.9
Wastewater treatment and discharge	kt	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Fraction of national total	-	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%

While methane emissions from wastewater have been decreasing since 1990, due to improved efficiency of the wastewater treatment, the national emissions have been more stable, causing methane emissions from wastewater treatment and discharge to become less noticeable on a national scale; from 2.4 % in 1990 to 1.1 % in recent years.

For nitrous oxide, national emissions have decreased at about the same rate as emissions from wastewater, leaving the fraction of nitrous oxide emitted on a national scale rater constant at 2.1-2.8 % for 1990-2023.

Although national emissions of NMVOC have decreased significantly more since 1985 than emissions from wastewater, NMVOC emissions from wastewater are insignificant on a national level for all years (0.005-0.011 %).

3 Wastewater handling and discharge

This report presents the methodological approach used in the emission inventory for wastewater treatment and discharge and provides improved information regarding the country level methodology. Chapter 4 presents the methodology and emission calculations for estimating the CH_4, N_2O and NMVOC emissions from Danish wastewater treatment plants (WWTPs), scattered settlements and wastewater discharge to waterbodies, including updated information on activity data and emission factor values. Chapter 5 presents all input data relevant for the emission calculations and Chapter 6 presents a verification of the activity data, input parameters and model approach for estimating emissions from Danish wastewater handling and discharge. Lastly, Chapter 7 presents uncertainties.

3.1 Source category description

Wastewater can be a source of methane (CH_4) when treated or disposed anaerobically or when dissolved CH_4 enters aerated treatment systems. It can also be a source of nitrous oxide (N_2O) emissions. Carbon dioxide (CO_2) emissions from wastewater are not considered here because these are generally derived from biogenic organic matter in human excreta or food waste and should not be included in national total emissions. (IPCC, 2019).

In addition to greenhouse gasses (CH_4 and N_2O), wastewater handling can also be a source of non-methane volatile organic compounds (NMVOC) and ammonia (NH_3). NH_3 emissions are related to latrines and open sewers which are not relevant for Denmark (EEA, 2023).

This source category includes an estimation of the emission of CH_4, N_2O and NMVOC from wastewater handling, i.e. wastewater collection and treatment. CH_4 is produced during anaerobic conditions and treatment processes, while N_2O may be generated and emitted as a by-product from nitrification (aerobic processes) and denitrification (anaerobic processes) during biological treatment (Adouani et al., 2010; Kampschreur et al., 2009).

This source category also includes CH_4 and N_2O emissions from effluent wastewater. Dissolved CH4 and N2O in discharges, have the potential to be released in the receiving waters where emissions will depend on the nutrient level of the receiving waters. Emissions are higher when wastewater is discharged into nutrient-impacted/eutrophic conditions, e.g. in lakes where carbon accumulates in sediments, giving a higher potential for methane generation (IPCC, 2019). No information on the types of receiving waters for wastewater effluent are available for Denmark.

For the N_2O emissions, starting material in the influent may be urea, ammonia, and proteins, which are converted to nitrate by nitrification. Denitrification is an anaerobic biological conversion of nitrate into dinitrogen. N_2O is an intermediate of both processes. A Danish investigation indicates that N_2O is formed during aeration steps in the sludge treatment processes as well as during anaerobic treatments, the former contributing most to the N_2O emissions during sludge treatment (Gejlsbjerg et al., 1999; DEPA, 2015).

3.1.1 Organic matter in wastewater treatment

Emission factors for estimating the methane emissions are provided in units of biological or chemical oxygen demand (BOD or COD) in the wastewater in accordance with the IPCC guidelines (IPCC, 2019). In simple terms, the difference between COD and BOD may be explained as follows: 1 kg COD corresponds to the amount of organic matter that consumes 1 kg O_2 by total digestion, while BOD consumes an amount of O_2 corresponding to the biochemical degradable fraction of carbon.

The uncertainty in BOD data is higher than COD data. This is because different standard methodologies exist for measuring BOD (ISO 5815-2:2003; 5815-1:2019). Some BOD measurements include the biochemical oxidation of not only carbonaceous, but also nitrogenous compounds, potentially making the BOD measures inconsistent. This adds further to the uncertainty in the reported BOD data (SGAV, 2024). With C:N ratios in wastewater of about 1:10 to 1:20, the latter BOD measurement standard results in an 5-10 % overestimation of TOW. However, upon accurate knowledge on the BOD measurement standard applied, it would be possible to correct for such overestimation.

Plant level TOW data are generally available in both COD and BOD, allowing for the calculation of a country specific COD per BOD ratio. The Danish COD per BOD ratio ranges between 2.3-2.8 for 1990-2023, with an average for the time series of 2.4; this is in line with the IPCC (2019) default value of 2.4.

3.1.2 Nitrogen in wastewater treatment processes

Sources to N_2O emissions during wastewater treatment processes reveal that 90 % of the nitrous oxide emission originates from activated sludge processes, i.e. denitrification and nitrification processes (Kampschreur et al., 2009). When bacteria and microorganisms break down proteins contained in the sludge, ammonium is released. At aerobic conditions, other bacteria transform ammonium to nitrate. Yet other bacteria can convert nitrate into free nitrogen, if fed with easily degradable organic matter under anoxic conditions. Upon successive denitrification, free nitrogen is a gas that bubbles out of the wastewater. However, challenges in the design of alternating aerobic and anoxic conditions in the bio-tank result in the emission of nitrous oxide (Kimochi et al., 1998 and Tallec et al., 2008).

The N_2O emission depends on several factors, such as pH, temperature, NO_3^-, oxygen and COD content in a complex pattern (Kampschreur et al., 2009). Studies of the biological denitrifying processes verify the complexity of processes and parameters influencing the resulting N_2O emission. Several studies found that N_2O emissions are strongly reduced at influent COD/N ratios above 3.5; at high ratios the N_2O emissions were below 1 % while at COD/N ratios below 3.5 the N_2O emission were at 20-30 % of the influent N load (Hanaki et al., 1992; Itokawa et al., 2001; Kampschreur et al., 2008; Park et al., 2000). Pointing in the opposite direction, a study by Van Niel et al. (1993) showed that a COD/N ratio above 10 could lead to enrichment of aerobic denitrification bacteria and increased N_2O emissions. The latter is supported by a study of Tallec et al. (2008), NO_3 - and C/N ratios and found a distribution of respectively 96-99 %, 0 reporting the N_2O emissions to be positively related to oxygenation during nitrification. Danish wastewater treatment plants have COD/N ratios in the influent wastewater in the range of 10-14, since 2010 the ratio was 13-14 (Please refer to Table 5.1 of this report, TOW_{inlet} and $m_{N,influent,municipal}$).

Chiu and Chung (2003) measured the distribution of N_2, N_2O and CO_2 under different NO_3^- and C/N ratios and found a distribution of respectively 96-99 %, 001-0.006 % and 1.1-3.8 %. This study does not report on the amount of inflowing N, whereas Adouani et al. (2010) reports on N_2O and NO emissions corresponding to up to 74 % and 19 % of denitrified N-NO_3^-. Sharma et al. (2008) reports N_2O emissions up to 4000 ppm, which is the same range in the study of Chiu & Chung (2003). The CO_2, as reported by Chiu and Chung (2003), is short-cycle CO_2, not originating from fossil fuels, and therefore not to be included as a contribution to greenhouse gas in the emission inventory (Kampschreur et al., 2009). Kampschreur et al. (2009) gives an overview of studies of N_2O emissions from wastewater treatment, showing a huge variation and uncertainty in the N_2O emission ranging between 0 and 95 % at lab-scale and in the range of 0-14.6 % of the nitrogen load at the full-scale level, in agreement with the differences in reported studies above.

In general, literature reveals insight into specific N_2O production mechanisms, however due to the complexity involved, no clear patterns in physiochemical operational condition, micro-organisms composition and activity exist (Sivret et al., 2008). Nitrous oxide emission occurs due to incomplete conversion of nitrate to free nitrogen and relies on a wide range of process conditions such as low oxygen levels in the process tanks, lack of COD for denitrification and fluctuating loads and modes of operation (Thomsen et al., 2015).

A Danish study (DEPA, 2020) measuring nitrous oxide emissions from wastewater treatment plants in 2018–2020, includes nine Danish plants across a wide range of sizes, nitrogen loads, aeration strategies, sludge-handling, and reject water handling. Real-time amperometric (liquid-phase) sensors were installed in the water to measure nitrous oxide concentrations. These data were processed through emission models to estimate gaseous emissions. Plants using surface aeration showed significantly higher uncertainty in emission calculation and were therefore excluded from the national average factor, leaving data from six plants with bottom aeration. In DEPA (2020, Chapter 9.2) it is assessed that the data does not indicate a general difference in emission factors between the two types of plant. Therefore, it is recommended that the same emission factor is used for both. The resulting national N_2O emission factor was 0.84 % N_2O-N per Total-N inlet, equating to 0.0084 kg N_2O-N per kg T-N inlet, with observed variation from 0.24 to 1.24 %. Emissions varied substantially between plants and day-to-day for each plant, but a weak correlation was found between daily nitrogen loading and N_2O emissions—higher ammonium loading tended to increase emissions. Facilities with greater residual biological capacity generally emitted less N_2O than those operating near full capacity (DEPA, 2020).

3.2 Wastewater in Denmark

All wastewater in Denmark is treated in either centralised wastewater treatment plants (WWTPs), at industries with separate wastewater treatment or in septic systems. During cloudbursts, there may be discharge without treatment, but emissions from this is included through measurement of rain-related effluents.

In this report, as in the point source reports from the Agency for Green Transition and Aquatic Environment (SGAV)[1], WWTPs are defined as plants with an approved capacity of more than 30 person equivalents (PE). WWTPs can be managed by municipalities or private owners. WWTPs of over 30 PE are obligated to take samples of e.g. N, P and TOW according to MIM (2025, §26). For WWTPs with an approved capacity of 30 PE or less, there is no requirement for sampling, and data for these are therefore not readily available. In 2022, 93 WWTPs with 30 PE or less load existed in Denmark, these treated 0.1 % of the total amount of wastewater. (SGAV, 2024).

The Danish wastewater treatment system has over time developed from many smaller WWTPs to fewer bigger and more advanced WWTPs, and this centralisation continues. From 1989 to 2023, the number of WWTPs with at least 30 PE has decreased from 1980 to 656 (SGAV, 2024). The amount of wastewater treated at the most technologically advanced WWTPs in Denmark has likewise increased, from 10 % in 1989 to above 90 % since 2013 (DME, 1995 and SGAV, 2024). Improvements of the centralised- and decentralised wastewater treatment systems as well as the sewer system are on-going in Denmark.

Wastewater streams from households and industries are mixed in the sewer system prior to treatment at centralised WWTPs. The contribution from the industry to the influent wastewater at the centralised WWTPs is known for the years 1998-2003 and has an average of 40.7 % (37 % - 48 %) with the highest influent contribution occurring at the biggest and most advanced technological WWTPs in Denmark (DME, 2010).

For the part of the population, which is not connected to the collective sewer system (i.e. scattered houses), septic systems are applied. A septic system is usually composed of a septic tank buried in the ground, and a soil dispersal system for liquids. Solid-, dense- and floatable materials contained in the influent, are retained in the septic tanks as sludge, where it undergoes anaerobic digestion until emptied. The gas produced from anaerobic sludge digestion (mainly CH4 and largely biogenic CO2) are usually released through vents (IPCC, 2019, 6.1.2). Septic sludge is collected and transported for treatment at the centralised WWTPs. Municipal collection of sludge from septic tanks occurs at a frequency set by the local authorities and in general, septic tanks are emptied once a year.

The number of houses not connected to the sewer system is known from SGAV (2024) and the total number is known from Statistics Denmark (2024). From this information, the trend in the fraction of population not connected to the sewer system is calculated. The fraction of the population not connected to the sewer system decreased from 11.5% in 1990 to 7.0% in 2023.

Regarding diffuse emissions from the sewer system, very little data are available (e.g. Lyngby-Taarbæk Kommune, 2014). It is known that centralised wastewater treatment plants are associated with increased residence times, which increases the risk of the occurrence of bottom sediments and thus biological decomposition of organic matter in the sewage system. However, the sewer system is hydraulically designed to prevent the accumulation of bottom sediments and under such conditions, temporary anaerobic processes will be

[1] Point source reports 2023-2024 are published by Agency for Green Transition and Aquatic Environment (SGAV) under the Ministry of Green Transition (MGTP), before that, the reports were published by Danish Environmental Protection Agency (DEPA) under the Danish Ministry of the Environment (DME).

dominated by fermentation and sulphate reduction, which means that the possibility of methane formation may be ignored (DANVA, 2008; DANVA, 2011; Hvitved-Jacobsen, 2001).

The discharges of nitrogen and organic matter from point sources were significantly reduced in the period 1990 to the mid-1990s due to the expansion of treatment plants with nutrient removal, as well as efforts to reduce discharges from industries (SGAV, 2024).

In connection with the Aquatic Environment Plan I from 1987, reduction targets were set for the discharge of nutrients and organic matter from treatment plants, as well as corresponding reduction targets for nutrients from industry. The targets for point sources in the Aquatic Environment Plan I were achieved in the 1990s. The Aquatic Environment Plan II from 1998 and the Aquatic Environment Plan III from 2004 had no specific requirements for point sources, but the River Basin Management Plans set requirements for the reduction of discharges from point sources in selected areas. The reduction from the other point sources; aquacultures, scattered settlements and rain-related effluent, represents – compared to treatment plants and industry – only a small proportion of the total reduction since 1989. The total discharge of nitrogen, phosphorus and organic matter from point sources has been decreasing over the past 20 years despite the fact that the population growth during the period is just over half a million people. This is due to several factors (SGAV, 2024):

- Centralisation of wastewater treatment at larger, more advanced treatment plants with more efficient nutrient removal.
- Better pre-treatment of wastewater from many companies.
- Fewer households with direct discharges and the water plans' increased requirements for treatment measures for dispersed settlements.
- Reduction of the phosphorus content in detergents. The reduction has given rise to an update of the phosphorus unit figure in the discharge calculations from 2018 onwards.

In total, the total discharge of nitrogen, phosphorus and organic matter in the period 1989-2023 has been reduced by approximately 80%, 90% and 90%, respectively. In recent years, efforts have been made to improve the data quality for rain-related effluent. The calculated discharge for this point source type therefore shows a slight increase in the period from 2012 to 2023 compared to the period before. This is not considered to be a real significant increase in the discharge from rain-related effluent, but a calculation adjustment based on significantly improved data quality in the form of better registration of data about the outlets and the areas that drain to them. The section on rain-related discharges shows that an average of 51 % (43 % in 2022) of the total discharged water volume from this point source type is calculated with an uncertainty of 55 % or less. In addition, the discharge from rain-related effluent fluctuates with the year's precipitation. Work is continuing to improve the basis for the calculation from rain-related effluents (SGAV, 2024).

Latrines are no longer commonly used in Denmark. Latrines can still be found in some remote allotment associations (tiny holiday houses), at public forest shelters or temporarily at large events like music festivals. The use of latrines in Denmark is negligible and not considered further in this report.

Sludge from wastewater treatment plants is only spread on agricultural land. Emissions from sludge spreading on fields, is part of the Agricultural sector and is hence not included in this report.

3.3 COD pathway

A flow chart of the treatment pathways in Denmark is visualised in Figure 3.1 in units of COD flows and corresponding points of emissions.

Because a COD analysis oxygenates practically all organic material, while nitrogen compounds are not oxidised, this makes COD the best estimate of the maximum methane conversion potential. Furthermore, in Denmark the wastewater is a mixture of industrial and municipal household wastewater in which case COD may be the only feasible measure due to the presence of bacterial inhibitors or other chemical interferences, which interfere with the BOD determination.

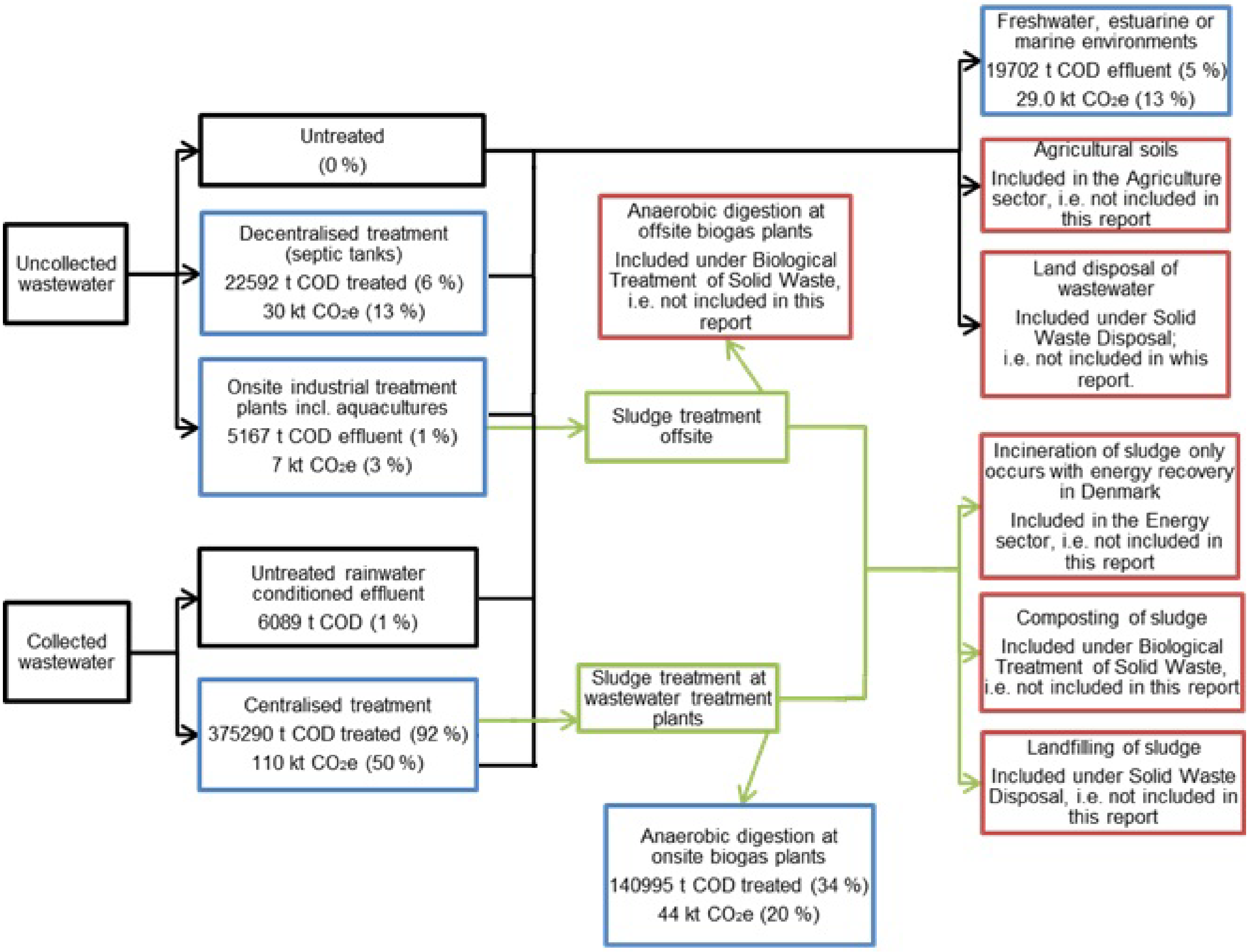

Figure 3.1 Overview of the COD flow through the treatment systems and discharge pathways in Denmark in 2023. Green arrows represent separated sludge. Points of emissions with blue frames are included in this report, while those with red frames fall outside the scope of this report.

IPCC (2019) recognises CH_4 and N_2O as the only greenhouse gas emissions from wastewater treatment processes and discharges while CO_2 process emissions are defined as biogenic carbon neutral. Therefore, only methane and nitrous oxide emissions have been included in Figure 3.1. Emissions presented in Figure 3.1 are not caused alone by methane from the organic matter content but also by N_2O from the N content.

The total national COD of 409,138 tonnes in 2023 is calculated from the influent COD in centralised WWTPs, influent COD to decentralised treatment (septic tanks), effluent from aquacultures, effluent from treatment at separate industries and from rain-related effluent. Of the total COD (100 %) produced, 93 % is collected in the sewer systems where 92 % is treated in WWTPs and the remaining 1 % is rain-related effluent (untreated). Of the 7 % of the total COD that is uncollected, 6 % of the COD is produced within scattered settlements not connected to the sewer system, these are modelled as septic tank systems. The remaining 1 % is effluent COD from separate industries and aquacultures.

Of the 92 % COD treated at centralised WWTPs in 2023, 58 % (216,915 tonnes COD) enters WWTPs with anaerobic sludge digestion, but only 65 % of this is utilised in the biogas reactor (140,995 tonnes COD). The remaining sludge goes through aerobic stabilisation.

Emissions from aerobic mechanical and biological treatment processes occur prior to anaerobic digestion or aerobic sludge stabilisation at all WWTPs in Denmark. Of the 375 kt COD entering the centralised Danish WWTPs, a greenhouse gas emission (primarily N_2O) of 110 kt CO_2e results from the aerobic biological treatment step common to both WWTPs with anaerobic and aerobic sludge management strategies. This emission is equal to 50 % of all greenhouse gas emissions from wastewater treatment and discharge in Denmark in 2023.

The main source of methane emission occurs from anaerobic sludge digestion corresponding to 44.5 kt CO_2e in 2023 (6.9 % leakage rate). Approximately 25 % of the COD in the influent wastewater remains in the final sludge from anaerobic and aerobic stabilisation while 5 % of the total COD produced in Denmark is lost to the aquatic system (rivers, lakes and sea) resulting in emissions summing up to 29.0 kt CO_2e or 13 % of the total greenhouse gas emissions from wastewater treatment and discharge.

3.4 Technologies

Today, the majority (96 %) of Danish wastewater is treated in advanced and well managed treatment plants that reduce the content of organic matter and nitrogen to a minimum, the so called MBND(K) (Mechanical, Biological, Nitrification, Denitrification and Chemical) plants (SGAV, 2024).

Figure 3.2 and Annex 1 present the percent of wastewater treated at centralised WWTPs with advanced technology treatment for the removal of organic matter, nitrogen and phosphorus, i.e. wastewater treatment plants of the type MBNDK. Figure 3.2 also presents the environmental performance for the time series since 1990, quantified as the reduction efficiencies of organic matter (BOD) and total-N in the effluent wastewater with reference to the influent wastewater at national level (DMP, 2010 and SGAV, 2024 and earlier versions).

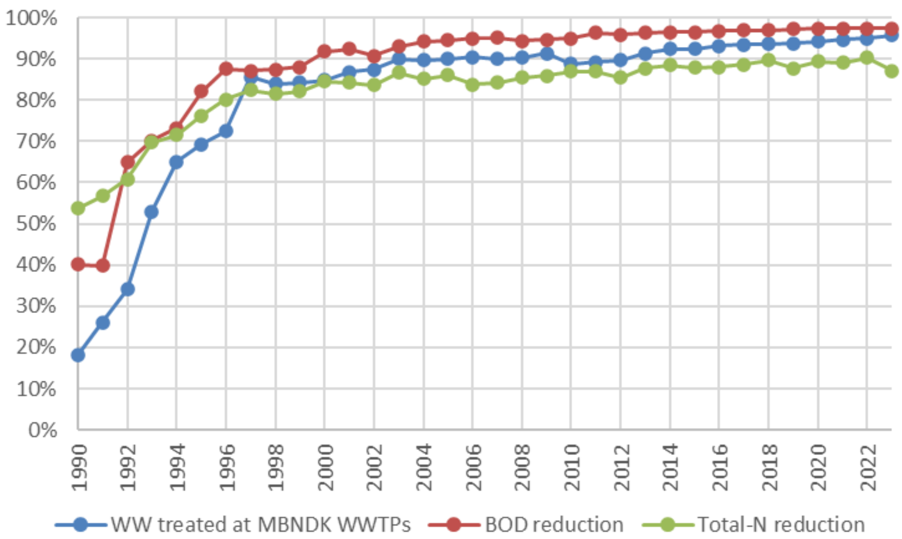

Figure 3.2 Degree of utilisation of modern, centralised WWTPs and degrees of reduction of BOD and total-N.

The increase in treatment efficiency is reflected in the number of plants having the most advanced treatment technologies installed, which was 0.5 % before the first Water Environment Action Plan in 1987. As shown in Figure 3.2 and Annex 1, the fraction of influent wastewater at the Danish WWTPs treated by advanced organic matter, nitrogen and phosphorus removal technologies has increased further from 18 % in 1990 to 96 % in 2023 (SGAV, 2024).

The technological development of the Danish WWTPs has been accompanied by a centralisation of the wastewater treatment at fewer and bigger plants. In 2023, about 50 % of the wastewater is treated at 32 WWTPs and 90 % of the wastewater is treated at the 173 biggest WWTPs (SGAV, 2024).

The centralisation of wastewater treatment at WWTPs using advanced treatment technologies have resulted in an increase in the N and organic matter reduction efficiencies. As such, 54 % and 40 % of the N and organic matter respectively, in the influent wastewater was reduced in the effluent wastewater in 1990 and the efficiencies wave increased to 87 % for N and 97 % for organic matter in 2023. The above-described technological development for improved quality of the effluent wastewater has caused a reduction in the emissions originating from the discharge of effluent wastewater. As such, 51 % of greenhouse gas emissions originated from effluent in 1990 compared to only 13 % in 2023.

4 Methodology and emission calculations

This section includes methodological issues, input data and calculated emissions related to the CH_4, N_2O and NMVOC emissions from wastewater treatment and discharge.

4.1 Methodological issues

The following contributions to the wastewater sector are included in the Danish emission inventories:

- CH_4 from sewer systems and wastewater treatment
- CH_4 from anaerobic treatment plants
- CH_4 from septic tanks
- CH_4 from wastewater discharge
- N_2O from wastewater treatment
- N_2O from wastewater discharge
- NMVOC from wastewater treatment

The methodologies developed for estimating emissions from wastewater treatment and discharge follows the IPCC Guidelines (IPCC, 2006 and 2019) for methane and nitrous oxide and the EEA Guidebook (EEA, 2023) for NMVOC.

4.1.1 Methodologies from international guidelines

The IPCC 2019 guidelines provide default methodologies for estimating both methane and nitrous oxide emissions from both domestic - and industrial wastewater. Three tier methods are available. The Tier 1 methods apply default values for the emission factors and activity parameters. This method is considered good practice for countries with limited data. The Tier 2 method generally follows the same method as Tier 1 but allows for incorporation of a country specific emission factor and country specific activity data. For a country with good data and advanced methodologies, a country specific method could be applied as a Tier 3 method. IPCC (2019). Denmark applies Tier 3 methodologies.

Methane emissions from domestic/commercial wastewater are calculated from the methane emission factors for the individual treatment technologies, multiplied by the amount of organic material disappearing during treatment, i.e. influent TOW minus the final sludge, to derive a sum of emission, i.e. gross methane emission. The amount of recovered methane is subtracted to arrive at a net methane emission (IPCC guidelines 2006, Equation 6.1, page 6.11).

Denmark is a small country with a very high level of equality in living standards; there is no difference between centralised wastewater treatment in different areas of Denmark. Calculations are therefore not split into different income groups. (IPCC, 2019, eq. 6.3A). The Danish emission inventory for wastewater treatment and discharge is a country level methodology based on plant level monitoring activity data in the influent and effluent wastewater. At the present stage of development, the country level methodology applies national activity data and a mix of default and country specific emission factors.

IPCC (2019) – Equation 6.1 (Updated): CH_4 emissions from domestic wastewater for each treatment/discharge pathway:

$$CH_4\ Emissions_j = \left[\left(TOW_j - S_j\right) \bullet EF_j - R_j\right]$$

The principle of equation 6.1 in the IPCC (2019) is to allocate different emission factors to the different treatment pathways. Treatment pathways occurring in Denmark are mixed industrial and household wastewater transported via the collective sewer system (92 %) to 1) WWTPs using biological treatment processes and aerobic sludge stabilisation as sludge management strategy, or 2) WWTPs using biological treatment processes and anaerobic sludge digestion. A minor fraction of the total COD content in Danish wastewater is comprised by domestic wastewater, produced within scattered settlements not connected to the collective sewer system (6 %). Such wastewater is modelled as being managed in 3) septic tanks accompanied by sludge collection used as ingestate (initial substrate) at anaerobic WWTPs. Finally, small contributions to emissions occur from separate industries (1 %) or rain-related effluents (1 %).

The method for estimating methane emissions from industrial wastewater is similar to the one used for municipal wastewater and includes on-site industrial wastewater with significant carbon loading that is treated under anaerobic conditions. Relevant industries are e.g. slaughterhouses, breweries, dairy production etc. (IPCC, 2019). Methane from the on-site treatment of industrial wastewater is not currently included in the Danish inventory, see Chapter 9.

According to the IPCC (2019) Guidelines, nitrous oxide emissions from domestic/commercial wastewater can be calculated from emission factors for the individual treatment technologies, multiplied by the amount of influent nitrogen (IPCC guidelines 2006, Equation 6.9, page 6.37). The guidance provides the option of differentiating between three income groups when estimating emissions (rural, urban high income and urban low income). As Denmark is a small country with a very high level of equality in living standards; there is no difference between different areas of Denmark. Calculations are therefore not split into different income groups. (IPCC, 2019, eq. 6.9). The Danish emission inventory for wastewater treatment and discharge is a country level methodology based on plant level monitoring activity data in the influent and effluent wastewater. The country level methodology applies national activity data and a country specific emission factor.

The general guidance on the calculation of nitrous oxide emissions from industrial wastewater, is the same as that for municipal wastewater. Denmark applies the same country specific emission factor as for municipal wastewater, and plant level monitoring data are available for effluent wastewater.

Lastly, IPCC (2019) provides guidance on estimating emissions from both domestic/commercial and industrial effluent. Calculations are the same for municipal and industrial effluent. Denmark applies default IPCC emission factors for both methane and nitrous oxide emission calculations.

4.1.2 Country specific approach

Compared to many other countries, Denmark is in a good position regarding the availability of monitoring data quantifying the input activity data at plant level. This implies that monitoring data on BOD, COD and total-N are available for all WWTPs in Denmark. Therefore, Denmark applies Tier 3 methodologies for all source categories within the wastewater sector – except for effluent wastewater (indirect) emissions.

The IPCC guidelines distinguish between domestic- and industrial wastewater. Since wastewater entering the Danish sewer system is a mix of domestic-, commercial- and industrial wastewater, sewered wastewater treated centrally is in this report generally referred to as municipal wastewater.

Denmark experiences significant seasonal temperature variations, and as recommended by IPCC (2019, page 6.19) therefore uses a country specific emission factor for decentralised treatment systems of domestic wastewater, i.e. septic tanks.

Monitoring data on the influent and effluent resources, i.e. waste flow, N, P, biological oxygen demand (BOD) and chemical oxygen demand (COD) for the wastewater are available for all WWTPs in Denmark and reported by the Danish Ministry of Green Transition (SGAV), the National Focal Point for point sources. SGAV collects all point source data from the National Monitoring and Assessment Programme for the Aquatic and Terrestrial Environments (NOVANA) (SGAV, 2024). Since the late eighties, annual reports have documented results from the monitoring of point sources, i.e. wastewater treatment plants, industries, rain-related effluent (storm water), scattered houses, freshwater aquacultures and maricultures.

Data on energy production from Danish wastewater treatment plant with anaerobic sludge digestion are available from the energy statistics (DEA, 2024) and presented in Table 4.1 and Annex 2 (Biogas production, TJ). These data do not include any information on venting or flaring.

The following descriptions of methodological issues are presented separately for each contribution to the wastewater treatment and discharge emissions.

4.2 Methane emission from municipal wastewater treatment

Centralised wastewater treatment plants are sources of methane emissions. These emissions primarily arise from the anaerobic decomposition of organic matter in wastewater and sludge. While Denmark utilises centralised aerobic treatment, the resulting biosolids can still lead to substantial methane release during handling where anaerobic areas will occur to some degree.

4.2.1 Methodology

The fugitive emissions from the sewer system, primary (and secondary) settling tanks and biological N and P removal processes, $CH_{sewer+MB}$, are estimated as:

$$CH_{4,sewer+MB} = TOW_{inlet} \cdot EF_{sewer+MB} = TOW_{inlet} \cdot B_0 \cdot MCF_{sewer+MB} \quad \text{Eq. 7.5.1}$$

Where TOW_{inlet} equals the influent organic degradable matter measured as the chemical oxygen demand (COD) in the influent wastewater flow. B_o is the default maximum CH_4 producing capacity, i.e. 0.25 kg CH_4 per kg COD (IPCC, 2019). $MCF_{sewer+MB}$ is the fraction of DOC that is anaerobically converted to CH_4 in sewers and WWTPs, i.e. 0.003 based on the expert knowledge on the state and technological management of the Danish wastewater by Vollertsen (2012). The $MCF_{sewer+MB}$ value from Vollertsen (2012) is a conservative estimate of the fugitive methane emission from the settling tanks (clarifiers) and aerobic biological treatment processes, based on the knowledge that the factor is well below 0.1 % of influent COD. The fugitive emission from the sewer system is judged to be negligible or zero by DANVA (DANVA, 2008 and 2011).

The emission factor, $EF_{sewer+MB}$, for these three processes and systems, i.e. sewer system, clarifiers and biological N and P removal processes equals 0.75 g CH_4 per kg COD in the inlet wastewater. In comparison, Johansen (2013) assumes that the contribution from the sewer system is insignificant, which is in agreement with the IPCC guidelines reporting a default MCF for open and closed flowing sewer of 0 (IPCC, 2019).

Furthermore, Johansen (2013, page 30) reports a total methane emission from pumping and storage of digested sludge to be around 0.1 %-0.2 % of the total methane production, corresponding to a maximum emission factor of 0.3 g CH_4 per kg COD from other processes than dedicated anaerobic digestion.

In conclusion, in the context of well-managed WWTPs, the applied country specific value for $EF_{sewer+MB}$, i.e. 0.75 g CH_4 per kg COD in the inlet wastewater, represents a conservative estimate of methane from sewer and mechanical and biological treatment processes.

The methane emissions from sewer, mechanical and aerobic biological treatment are common treatment steps for all WWTPs whether they apply anaerobic digestion or aerobic stabilisation as sludge management strategy (Thomsen et al., 2015). For this reason, the activity data used for calculating the methane emission from sewer, mechanical, and biological treatment processes at centralised treatment plants is the total national COD in the influent wastewater.

4.2.2 Emission calculation

Table 4.1 presents the activity data and calculated methane emissions from centralised wastewater treatment. Further information on the activity data is available in Chapter 5 Input data.

Table 4.1 Activity data and emissions for centralised treatment of wastewater.

Parameter	Abbr.	Unit	1990	1995	2000	2005	2010	2015	2020	2023
Influent TOW at municipal WWTPs	TOW_{inlet}	kt COD	349	354	390	353	370	387	388	375
Methane emission	$CH_{4,sewer+MB}$	kt	0.26	0.27	0.29	0.26	0.28	0.29	0.29	0.28

4.3 Methane emission from anaerobic digestion

Anaerobic digestion is a biological process used to stabilize wastewater sludge by breaking down organic matter in the absence of oxygen. This process produces biogas and reduces the volume and pathogen content of the sludge.

4.3.1 Methodology

Anaerobic treatment in terms of sludge digestion occurs with capture of the CH_4 generated during digestion. The biogas produced contains between 55 and 70 % methane used for energy production (DEA, 2015). Most WWTPs combusts the produced biogas in a biogas-driven engine to produce heat and electricity, however upgrading of the biogas by CO_2 extraction is performed at Biofos A/S which is the largest wastewater utility in Denmark. This upgrading of biogas allows for the production of bio-natural gas that may be sold and distributed in the natural gas grid or gasworks gas grid (Biofos, 2025). Emissions from the consumption of biogas are included in the Energy sector and hence not treated in this report.

The methane emission from anaerobic sludge digestion may occur via venting and from storage of the digestate (Johansen, 2013).

The net methane emission from anaerobic treatment processes of sludge in closed systems with biogas extraction for energy production is estimated according to Equation 7.5.2:

$$CH_{4,AD,net} = EF_{AD} \cdot CH_{4,AD,recovered} = EF_{AD} \cdot E_{recovered}/NCV_{CH_4} \qquad \text{Eq. 7.5.2}$$

Where the emission factor, EF_{AD}, is the gross energy production leakage rate, based on measured data at biogas facilities at wastewater treatment plants. $CH_{4,AD,recovered}$ is the collected methane which can be calculated from the measured biogas recovery ($E_{recovered}$) and the net calorific value of methane (NCV_{CH4}) of 52.04 MJ per kg CH_4. $E_{recovered}$ is available from the energy statistics (DEA, 2024).

The leakage rate EF_{AD} of 6.9 % is calculated from Gudmundsson et al. (2021, Tabel 15 and Tabel 18), where the methane emission from WWTPs excluding emissions from gas engines are divided by the gas production at WWTPs.

Sludge storage tanks without gas collection are considered to be a significant source of emissions. As there is typically no gas collection at sludge storage tanks, this may partly explain the relatively high measured methane emissions at sewage treatment plants compared to other plant types (Gudmundsson et al., 2021).

The country specific methane content in biogas (NCV_{CH4}) of 52.04 MJ per kg CH_4, is calculated from the calorific value 23 GJ per 1,000 m^3 biogas provided by the DEA (2024), a percent volume content of methane in biogas of 65 % (Johansen, 2013, T4.9) and a density of 0.68 kg CH_4 per Nm^3 (Dutt, 2003).

$$NCV_{CH_4} = 23GJ/(1000\ m^3)\ /\ (0{,}68\ kg\ CH_4/Nm^3 \cdot 65\%) = 52.04\ MJ/kg\ CH_4$$

Methane emissions from separate industries are included in the inventory as all WWTPs with bio-gasification of sludge are included in the Energy Statistics (DEA, 2024).

4.3.2 Emission calculation

Table 4.2 presents the activity data and calculated methane emissions from anaerobic digestion. Further information on the activity data is available in Chapter 5.

Table 4.2 Activity data and emissions for anaerobic digestion of wastewater sludge.

Parameter	Abbr.	Unit	1990	1995	2000	2005	2010	2015	2020	2023
Biogas production	$E_{recovered}$	TJ	458	598	857	913	840	901	1293	1198
Methane emission	$CH_{4,AD,net}$	kt	0.6	0.8	1.1	1.2	1.1	1.2	1.7	1.6

4.4 Methane emission from septic tanks

Methane emissions from septic tanks occur as a byproduct of the breakdown of organic matter by microbes in anaerobic conditions. This process primarily happens in the septic tanks' sludge layer, where organic material from household waste settles and decomposes.

4.4.1 Methodology

For the part of the population not connected to the collective sewer system, simple decentralised wastewater handling is assumed and modelled as septic tanks. Only few measurements are available of the methane emissions from septic tanks and information on the pumping and management of septate, including its transportation to a wastewater treatment facility is sparse. Variations in measured methane emissions are likely linked to temperature and emptying frequency (Nielsen et al., 2018). A septic tank should be emptied at least once a year, but the frequency may vary depending on the size of the tank, the number of residents, and the amount of wastewater consumed. Septic tanks located at vacation homes may be emptied less frequently than those located at year-round residences. The emptying of septic tanks is regulated by the municipalities and may therefore vary across Denmark.

The methane emission is calculated as:

$$CH_{4,ST} = EF_{ST} \cdot f_{nc} \cdot P \qquad \text{Eq. 7.5.3}$$

Where P is the population number. f_{nc} is the fraction of the population that is not connected to the sewer system, i.e. scattered houses, which is a time series that steadily decreases from 11.5 % in 1990 to 7.0 % in 2023. And EF_{ST} is the emission factor for septic tanks.

f_{nc} is calculated from data on total existing Danish housings (available for the entire time series from Statistics Denmark, 2024) and the distribution of property types for the scattered settlement (available for 1993, 1995, 2002, 2008 and 2010-2022 from SGAV, 2024, and earlier versions). The data on total housings include year-round residences in both regular houses and holiday homes, and holiday homes that are not used as primary residences. The data on scattered housings include residences, holiday homes, allotment houses (tiny houses) and other. In both datasets, holiday homes and allotment houses that are not used as primary residences are weighted 25 %. The intermediate years (1994, 1996-2001 and 2003-2007) are calculated via interpolation and 1990-1992 are set to equal 1993.

A country specific EF_{ST} has been calculated based on measured methane emission of 0.695 g CH_4 per PE per day (Nielsen et al., 2018), as shown in Equation 7.5.4:

$$EF_{ST} = 0.695 \, \frac{\text{g } CH_4}{\text{PE} \cdot \text{d}} \cdot 10 \cdot 365 \, \frac{d}{y} = 2.54 \, \frac{\text{kg } CH_4}{\text{PE} \cdot \text{y}} \qquad \text{Eq. 7.5.4}$$

The country specific EF_{ST} value is derived by applying an uncertainty factor of 10 to account for the fact that the general state of installed septic tanks is of older date and may not be functioning optimal (Vollertsen, 2018).

Methane emission factors are generally expressed as g CH_4 per kg COD (like for wastewater treatment and - discharge). For easier comparison between emission factors, EF_{ST} can be calculated into the unit of per COD, using the default DOC_{ST} of 54.31 kg COD per person per year. The default DOC_{ST} is derived from the default value of 62 g BOD per person per day and the default COD per BOD conversion factor of 2.4 (both from IPCC, 2019). The EF_{ST} value is then 46.7 g CH_4 per kg COD, which is the value presented in Chapter 5.2. The IPCC emission factor for septic tanks is 0.3 kg CH_4 per kg BOD or 0.125 kg CH_4 per kg COD (IPCC, 2019, V5C6 Table 6.3), which is 168 % higher than the applied country specific value.

4.4.2 Emission calculation

Table 4.3 presents the activity data and calculated methane emissions from anaerobic decomposition in septic tanks. Further information on the activity data is available in Chapter 5.

Table 4.3 Activity data and emissions for septic tanks.

Parameter	Abbr.	Unit	1990	1995	2000	2005	2010	2015	2020	2023
Population	P	1000s	5135	5216	5330	5411	5535	5660	5823	5933
People outside sewage system	f_{nc}	-	11.5%	11.1%	10.7%	10.3%	9.4%	8.5%	7.4%	7.0%
Methane emission	$CH_{4,ST}$	kt	1.5	1.5	1.5	1.4	1.3	1.2	1.1	1.1

4.5 Methane emissions from wastewater discharge

Methane emissions from wastewater discharge are a significant, but often overlooked, source of greenhouse gases from wastewater treatment. Methane is generated during the anaerobic decomposition of organic matter in the effluent wastewater. Emissions from this source decreases as wastewater treatment efficiencies increase as this leads to decreased TOW content in the effluent wastewater.

4.5.1 Methodology

The fugitive CH_4 emission from effluent wastewater includes discharge from both:

Municipal wastewater, including effluents from municipal wastewater treatment plants, rain-related effluents and effluents from scattered houses not connected to the sewage system.

Industrial wastewater, including effluents from wastewater treatment plants at separate industries and effluents from aquaculture.

Emissions are calculated according to Equation 7.5.5:

$$CH_{4,discharge} = TOW_{effluent} \cdot EF_{CH_4,discharge} = TOW_{effluent} \cdot B_0 \cdot MCF_{discharge}$$

$$= TOW_{effluent} \cdot 0.25 \frac{kg\ CH_4}{kg\ COD} \cdot 0.11 = TOW_{effluent} \cdot 27.5 \frac{g\ CH_4}{kg\ COD} \qquad \text{Eq. 7.5.5}$$

Where $TOW_{effluent}$ equals the effluent organic degradable matter measured as the chemical oxygen demand (COD) in the effluent wastewater flow. B_o is the default maximum CH_4 producing capacity, i.e. 0.25 kg CH_4 per kg COD (IPCC, 2019). $MCF_{discharge}$ is the fraction of DOC that is discharged to water-bodies. IPCC (2019, Table 6.3) distinguishes between discharge into environments like lakes where carbon accumulates in sediments (higher emissions) and environments like fjords/seas (lower emissions). Since the Danish monitoring data does not include a categorisation of wastewater discharge by the type of waterbody, the default Tier 1 value of 0.11 from IPCC (2019) is applied.

$TOW_{effluent}$ is available from DEPA (2024) for each of the five contributions mentioned above Equation 7.5.5 separately, these are summed into municipal- and industrial wastewater streams and emissions are calculated and reported in the CRT tables separately for the two streams. The emission factor for discharge $EF_{CH4,discharge}$, regardless of whether the effluent wastewater is from municipal or industrial sources, equals 27.5 g CH_4 per kg COD.

4.5.2 Emission calculation

Table 4.4 presents the activity data and calculated methane emissions from wastewater discharge. Further information on the activity data is available in Chapter 5 Input data.

Table 4.4 Activity data and methane emissions for wastewater discharge.

Parameter	Abbr.	Unit	1990	1995	2000	2005	2010	2015	2020	2023
Effluent TOW from municipal sector	$TOW_{effluent,municipal}$	kt COD	72.2	34.4	22.5	19.2	20.5	24.7	15.5	14.5
Effluent TOW from industrial sector	$TOW_{effluent,industrial}$	kt COD	154.0	44.9	24.4	13.3	12.6	7.3	4.8	5.2
Methane emission	$CH_{4,discharge}$	kt	6.2	2.2	1.3	0.9	0.9	0.9	0.6	0.5
Of which municipal	$CH_{4,discharge,municipal}$	kt	2.0	0.9	0.6	0.5	0.6	0.7	0.4	0.4
Of which industrial	$CH_{4,discharge,industrial}$	kt	4.2	1.2	0.7	0.4	0.3	0.2	0.1	0.1

4.6 Nitrous oxide emission from wastewater treatment

Nitrous oxide is mainly produced during biological nitrogen removal processes, particularly during nitrification (aerobic process) where N_2O is produced as a by-product when there is low dissolved oxygen or high nitrite accumulation, and during denitrification (anoxic process) where N_2O is an intermediate product.

4.6.1 Methodology

All Danish wastewater treatment plants have implemented biological N-removal treatment processes, which are associated with some loss of N_2O due to incompleteness in the denitrification step (Thomsen et al., 2015). The N_2O emission from wastewater treatment processes is calculated according to Equation 7.5.6:

$$N_2O_{WWT} = EF_{N_2O,WWT} \cdot m_{N,influent} \qquad \text{Eq. 7.5.6}$$

Where the process related $EF_{N2O,WWT}$ is 13.2 kg N_2O per tonne N load in the influent wastewater. This value is calculated from 8.4 kg N_2O-N per tonne N (DEPA, 2020) and the stochiometric relation between nitrous oxide and N_2 (44/28). $m_{N.influent}$ is the influent N load flow of either municipal or industrial wastewater, as the two streams are calculated and reported in the CRT tables separately. The influent N load is monitored and annually reported by SGAV (2024 and earlier versions).

The national emission factor from DEPA (2020) is the product of a Danish monitoring campaign running on six wastewater treatment plants in the period 2018 to 2020, covering a range variety of plants in terms of size, nitrogen loading, sludge treatment configuration and reject water handling. The national N_2O emission factor of 0.84 % N_2O-N per Total-N inlet is about half of the IPCC (2019) default value (1.6 %), but within the IPCC range (0.02 % to 4.5 %). The national value is also verified by a study from the LaGas-project on the biggest WWTP in Denmark, as this study found an emission factor of 0.4-1.2 % N_2O-N per Total-N (Delre et al., 2017).

DEPA (2020) found that emissions varied substantially between plants and day-to-day for each plant, but a weak correlation was found between daily nitrogen loading and N_2O emissions—higher ammonium loading tended to increase emissions. Facilities with greater residual biological capacity generally emitted less N_2O than those operating near full capacity. The emission factor results in emissions from commercial/residential wastewater treatment of 62-89 g N_2O per capita for 1990-2023. The emission factor value in units of g N_2O per capita has decreased from 85 g N_2O per capita in 1990 to 65 g N_2O per capita in 2023. This decrease reflects an improvement in technology with lower emissions as a result. This development has happened despite the increase in industrial wastewater being connected to the sewer system and contributing to the N load entering the municipal treatment plants, throughout the time series.

The country specific emission factor of 0.84 % N_2O-N per Total-N inlet is kept constant throughout the time series.

For separate industrial wastewater treatment plants, influent N load is not available from the monitoring programme but only the effluent total-N load. The influent N load is therefore estimated from the effluent time series, by assuming that the industrial treatment plants have the same average N-removal efficiency as municipal treatment plants.

4.6.2 Emission calculation

Table 4.5 presents the activity data and calculated nitrous oxide emissions from wastewater treatment. Further information on the activity data is available in Chapter 5.

Table 4.5 Activity data and nitrous oxide emissions for wastewater treatment.

Parameter	Abbr.	Unit	1990	1995	2000	2005	2010	2015	2020	2023
Influent N load at municipal WWTPs	$m_{N,influent,municipal}$	kt	33.2	33.0	31.7	32.4	27.4	30.5	30.3	29.3
Influent N load at industrial WWTPs	$m_{N,influent,industrial}$	kt	9.7	10.4	5.8	3.2	2.6	2.7	2.6	1.9
Nitrous oxide emission	$N_2O_{,WWT}$	t	567	572	495	470	395	439	435	412
Of which municipal	$N_2O_{,WWT,municipal}$	t	439	435	418	428	361	403	400	387
Of which industrial	$N_2O_{,WWT,industrial}$	t	128	137	77	42	34	36	35	25

4.7 Nitrous oxide emission from wastewater discharge

After the treated wastewater is discharged to aquatic environments, the nitrification and denitrification processes continue both in-stream and as sediment-based. The transformation of the N remaining in the effluent will lead to additional N_2O emissions when discharged into rivers, lakes or oceans.

4.7.1 Methodology

The N_2O emission from effluent wastewater includes discharge from both:

Municipal wastewater, including effluents from municipal wastewater treatment plants, rain-related effluents and effluents from scattered houses not connected to the sewage system

Industrial wastewater, including effluents from wastewater treatment plants at separate industries and effluents from aquaculture

Emissions are calculated according to Equation 7.5.7:

$$N_2O_{discharge} = D_N \cdot EF_{N_2O,discharge} \qquad \text{Eq. 7.5.7}$$

Where D_N is the effluent discharged sewage nitrogen load monitored by the National monitoring program of the aquatic environment and nature and $EF_{N2O,discharge}$ is 7.9 kg N_2O per tonne N load in the effluent wastewater. This emission factor value is calculated from the IPCC Tier 1 default emission factor of 0.005 kg N_2O-N per kg N (IPCC, 2019, V5C6, Table 6.8A) and the stochiometric relation between nitrous oxide and N_2O-N (44/28). The IPCC Guidelines also provides a Tier 3 emission factor of 0.019 kg N_2O-N per kg N, relevant for "nutrient-impacted and/or hypoxic freshwater, estuarine, and marine environments". This emission factor will be relevant for some locations in Denmark in some periods of the year. However, as it is not currently possible to divide the effluent wastewater between different discharge pathways, the default Tier 1 emission factor is applied for all effluent wastewaters.

D_N is available from DEPA (2024) for each of the five contributions mentioned above Equation 7.5.7, these are summed into municipal - and industrial wastewater streams and emissions are calculated and reported in the CRT tables separately for the two streams.

4.7.2 Emission calculation

Table 4.6 presents the activity data and calculated nitrous oxide emissions from wastewater discharge. Further information on the activity data is available in Chapter 5.

Table 4.6 Activity data and nitrous oxide emissions for wastewater discharge.

Parameter	Abbr.	Unit	1990	1995	2000	2005	2010	2015	2020	2023
Discharged N from municipal sector	$D_{N,municipal}$	kt	18.3	10.9	6.4	5.4	5.2	6.0	4.6	5.6
Discharged N from industrial sector	$D_{N,industrial}$	kt	6.0	4.2	3.6	1.7	1.3	1.4	1.2	1.0
Nitrous oxide emission	$N_2O_{,discharge}$	t	191	119	79	55	51	58	46	52
Of which municipal	$N_2O_{,discharge,municipal}$	t	48	33	28	13	10	11	10	8
Of which industrial	$N_2O_{,discharge,industrial}$	t	144	86	50	42	41	47	36	44

4.8 NMVOC emission from wastewater treatment

During the breakdown of organic matter in the wastewater treatment processes, the vast majority of the emitted carbon is released as methane, but a small quantity is also released as non-methane volatile organic compounds (NMVOC). A comparison of the calculated output data (Table 6.1) shows that NMVOC emissions from municipal wastewater treatment plants is below 0.5 mass% of the methane emission.

4.8.1 Methodology

A Tier 2 approach from EEA (2023) is applied for the calculation of NMVOC emissions from wastewater treatment. The emission factor is the same for the Tier 1 and Tier 2 methodologies, but the relevant activity data for a Tier 2 methodology is applied, i.e. the amount of wastewater handled (cf. Equation 7.5.8).

$$NMVOC_{WWT} = EF_{NMVOC,WWT} \cdot V_{influent} \qquad \text{Eq. 7.5.8}$$

The amount of wastewater handled ($V_{influent}$) is available from the "Point sources" report series for 1992-2023 from DEPA (2024). Data are available for municipal wastewater plants and industrial plants separately. Activity data for 1985-1991 are estimated from 1992-1994 data as a constant average.

$EF_{NMVOC,WWT}$ is available from EEA (2023, 5.D, Chapter 3.3.2, Table 3-3) as 15 mg NMVOC per m^3 wastewater handled. This emission factor is the same for both the default Tier 1 and Tier 2 methodologies (EEA, 2023).

4.8.2 Emission calculation

Table 4.7 presents the activity data and calculated NMVOC emissions from wastewater handling. Further information on the activity data is available in Chapter 5.

Table 4.7 Activity data and NMVOC emissions for wastewater handling.

Parameter	Abbr.	Unit	1985	1990	1995	2000	2005	2010	2015	2020	2023
Influent WW at municipal WWTPs	$V_{influent,municipal}$	mill. m^3	788	757	802	825	701	683	767	693	607
Influent WW at industrial WWTPs	$V_{influent,industrial}$	mill. m^3	86	88	79	74	62	54	49	40	40
NMVOC emission	$NMVOC_{WWT}$	t	13.1	12.7	13.2	13.5	11.4	11.1	12.2	11.0	9.7
Of which municipal	$NMVOC_{WWT,municipal}$	t	11.8	11.4	12.0	12.4	10.5	10.2	11.5	10.4	9.1
Of which industrial	$NMVOC_{WWT,industrial}$	t	1.3	1.3	1.2	1.1	0.9	0.8	0.7	0.6	0.6

5 Input data

All input data applied in this report are presented in this chapter.

5.1 Activity data

The Danish EPA is responsible for monitoring and annual reporting of plant level (point sources) data within the national water quality database under the programme NOVANA (the National Monitoring and Assessment Programme for the Aquatic and Terrestrial Environments). Influent and effluent water quality monitoring data on nitrogen, phosphorous, biological and chemical oxygen demand (COD and BOD) are available for all WWTPs in Denmark with more than 30 PE. For separate industrial wastewater, mainly data on effluent wastewater are reported (SGAV, 2024 and earlier versions, and DEPA 2024). The Danish aquatic monitoring programme also includes measurements of emissions to the aquatic environment from aquaculture, rain-related effluents, and scattered settlements.

The time series for activity data on population, biogas production, volume of wastewater handled, TOW and N load are presented in Table 5.1. These same data are also presented in Chapter 4, where they are relevant for the individual calculations. The full time series is presented in Annex 2.

Table 5.1 Activity data for wastewater treatment and discharge.

	Abbr.	Unit	1985	1990	1995	2000	2005	2010	2015	2020	2023
Population	P	1000s	-	5135	5216	5330	5411	5535	5660	5823	5933
People outside sewage system	f_{nc}	%	-	11.5	11.1	10.7	10.3	9.4	8.5	7.4	7.0
Biogas production	$E_{recovered}$	TJ	-	458	598	857	913	840	901	1293	1198
Influent WW at municipal WWTPs	$V_{influent,municipal}$	mill. m^3	788	757	802	825	701	683	767	693	607
WW treated at industrial WWTPs[1]	$V_{influent,industrial}$	mill. m^3	86	88	79	74	62	54	49	40	40
Influent TOW at municipal WWTPs	TOW_{inlet}	kt COD	-	349	354	390	353	370	387	388	375
Effluent TOW from municipal sector[2]	$TOW_{effluent,municipal}$	kt COD	-	72.2	34.4	22.5	19.2	20.5	24.7	15.5	14.5
Effluent TOW from industrial sector[3]	$TOW_{effluent,industrial}$	kt COD	-	154.0	44.9	24.4	13.3	12.6	7.3	4.8	5.2
Influent Total-N at municipal WWTPs	$m_{N,influent,municipal}$	kt	-	33.2	33.0	31.7	32.4	27.4	30.5	30.3	29.3
Influent Total-N at industrial WWTPs	$m_{N,influent,industrial}$	kt	-	9.7	10.4	5.8	3.2	2.6	2.7	2.6	1.9
Effluent Total-N from municipal sector[2]	$D_{N,municipal}$	kt	-	18.3	10.9	6.4	5.4	5.2	6.0	4.6	5.6
Effluent Total-N from industrial sector[3]	$D_{N,industrial}$	kt	-	6.0	4.2	3.6	1.7	1.3	1.4	1.2	1.0

[1]Set equal to the amount of reported effluent wastewater from separate industries

[2]Municipal WWTPs, scattered houses and rain-related effluent

[3]Industrial WWTPs and aquaculture farming

The discharges of nitrogen and organic matter from point sources were significantly reduced in the period 1990 to the mid-1990s due to the expansion of wastewater treatment plants with nutrient removal, as well as efforts to reduce discharges from industries. (SGAV, 2024 and earlier versions).

Monitoring data on the influent BOD and COD are available for mixed industrial and household wastewater treated at municipal WWTPs. These data are used for calculating the total organic waste (TOW) in the influent wastewater. For 1999-2004, 2007-2013 and 2015-2023, plant level TOW data exists for Danish WWTPs. These data are verified by comparing them with calculated TOW values, see Annex 3. Data for the three missing intermediate years are interpolated. The selected TOW values for 1990-1998, are estimated from data on population, the default BOD production, default COD per BOD ratio and default fraction of industrial and commercial co-discharged protein ($F_{IND\text{-}COM}$), all default values are from IPCC (2019) (cf. Table 7.5.2). All calculated TOW data are presented in Annex 3.

Influent and effluent data on TOW and N content are available from DEPA (2024).

Plant level TOW data are generally available in both COD and BOD, allowing for the calculation of a country specific COD per BOD ratio. The Danish COD per BOD ratio ranges between 2.3-2.8 for 1990-2023, with an average for the time series of 2.4; this is in line with the IPCC (2019) default value of 2.4.

For the anaerobic digestion of sludge, the biogas production from the Danish energy statistics (DEA, 2024) were used to quantify the amount of methane lost by venting/leakage (Equation 7.5.2).

Population data and data on the total number of different housing types in Denmark are available from Statistics Denmark (2024) and the distribution of property types for the scattered settlement is available from SGAV (2024).

5.1.1 Industrial effluent

Wastewater from industries originates from either separate industries (i.e. outside the municipal sewer system and treatment plants) or from aquaculture.

Table 5.2 presents the effluent data for each of the industrial contributions.

Table 5.2 Effluent data for industrial wastewater.

	Unit	1990	1995	2000	2005	2010	2015	2020	2023
Effluent TOW from industrial sector	kt COD	154.0	44.9	24.4	13.3	12.6	7.3	4.8	5.2
- of which separate industries	kt COD	143.4	33.0	11.8	2.8	2.6	2.2	1.0	1.1
- of which aquaculture farms	kt COD	10.6	11.9	12.6	10.5	10.0	5.1	3.8	4.0
Effluent Total-N from industrial sector	kt	6.0	4.2	3.6	1.7	1.3	1.4	1.2	1.0
- of which separate industries	kt	4.5	2.5	0.9	0.4	0.3	0.3	0.3	0.2
- of which aquaculture farms	kt	1.6	1.7	2.7	1.2	0.9	1.0	1.0	0.8

The total effluent amount of COD from 57 of the biggest industries in Denmark were reported to be around 88,000 tonne in 1985 corresponding to approximately 2-million-person equivalents (DEPA, 1990a, C3.1). Since 1989, more comprehensive examinations of the separate industries have been performed annually.

In the period 1985- 1995, industries have implemented wastewater treatment technologies and less polluting processes resulting in reductions in the total industrial effluent amount of TOW, but part of the reduction is also a result of an increase in industries connected to municipal treatment plants. Organic matter in the effluent from separate industries measured in BOD (BI_5), peaked in 1991 with 75,800 tonnes and rapidly decreased to only 13,800 tonnes in 1995 (82 % decrease). The discharged organic matter continues to decrease and is at 477 tonnes BOD in 2022, which is a 99 % decrease compared to 1990. (DEPA, 1990b and DME, 1998 and SGAV, 2024).

In 1989, there were 483 active aquacultures in Denmark, discharging 6,246 tonnes BOD and 2,192 tonnes N (DEPA, 1990b page 37 and 127). In 2022, there were only 157 active aquacultures left, discharging 1,676 tonnes BOD and 822 tonnes N. Although only 24 aquacultures (15 %) were saltwater based, these make up roughly half of the nitrogen effluent and two thirds of the organic matter effluent from aquacultures in 2022. (SGAV, 2024, C7-8).

The total organic matter and nitrogen discharge from industrial sources was reduced by 97 % and 82 % respectively through the period 1990-2022 (DEPA, 1990 and SGAV, 2024).

5.1.2 Municipal effluent

Table 5.3 presents the effluent data for each of the residential wastewater and other sewered contributions.

Table 5.3 Effluent data for sewered and other residential wastewater.

	Unit	1990	1995	2000	2005	2010	2015	2020	2023
Effluent TOW from municipal sector	kt COD	72.2	34.4	22.5	19.2	20.5	24.7	15.5	14.5
- of which centralised WWTPs	kt COD	54.8	18.7	7.9	5.9	6.3	6.7	5.3	4.8
- of which scattered houses	kt COD	12.5	10.5	9.3	8.5	8.3	6.6	3.9	3.6
- of which rain-related effluent	kt COD	4.9	5.2	5.3	4.7	5.8	11.4	6.3	6.1
Effluent Total-N from municipal sector	kt	18.3	10.9	6.4	5.4	5.2	6.0	4.6	5.6
- of which centralised WWTPs	kt	15.4	8.9	4.7	3.8	3.6	3.7	3.2	3.8
- of which scattered houses	kt	2.0	1.1	1.0	0.9	0.9	0.7	0.5	0.4
- of which rain-related effluent	kt	0.9	0.9	0.8	0.6	0.8	1.5	0.9	1.4

Improved technology at the centralised WWTPs has resulted in decreases in the effluent of both TOW and N.

As the number of people living outside the sewer system areas decrease, so do the effluent from scattered houses. The fraction of the population modelled with septic tanks has decreased from 591 thousand in 1990 to 416 thousand in 2023.

Rain-related effluent shows no trend as it varies with the annual rainfalls. However, improved documentation of rain-related effluent results in a slightly higher average level for both COD and N from 2014 and forward.

5.2 Emission factor

The applied emission factors are presented in Table 5.4 below. Details on the calculation of the calculated emission factors and on the general choice of emission factors, are given in Chapter 4, where the emission factors are presented as part of the description on applied methodology.

Table 5.4 Emission factors applied in the Danish inventories for wastewater.

Emission factor	**Description**	**Unit**	**Value**	**Source**
B_o	Max. CH_4 producing capacity	kg CH_4/kg COD	0.25	IPCC (2019), V5C6, Table 6.2
$MCF_{sewer+MB}$	CH_4 correction factor	-	0.003	Vollertsen (2012)
$MCF_{discharge}$	CH_4 correction factor (Tier 1)	-	0.11	IPCC (2019), V5C6, Table 6.3+6.8
NCV_{CH4}	Net calorific value	MJ/kg CH_4	52.04	Calculated in Chapter 4.3.1
BOD	Default biochemical oxygen demand production	g/person/day	62	IPCC (2019), V5C6, Table 6.4
BOD/COD ratio	Default biological- per chemical oxygen demand ratio	-	2.4	IPCC (2019), V5C6, page 6.18
$F_{IND-COM}$	Default fraction of industrial and commercial co-discharged protein	-	1.25	IPCC (2019), V5C6, Table 6.11
$EF_{sewer+MB}$	CH_4 EF for sewers + WWTPs	kg CH_4/t COD	0.75	Calculated in Chapter 4.2.1
EF_{AD}	CH_4 EF for biogas plants	-	6.9 %	Gudmundsson et al. (2021)*
EF_{ST}	CH_4 EF for septic tanks	kg CH_4/t COD	46.7	Calculated in Chapter 4.4.1
$EF_{CH4,discharge}$	CH_4 EF for discharge of effluent	kg CH_4/t COD	27.5	Calculated in Chapter 4.5.1
$EF_{N2O,direct}$	N_2O EF from WWT	kg N_2O/t N in influent	13.2	DEPA (2020)**
$EF_{N2O,discharge}$	N_2O EF from discharge of effluent	kg N_2O/t N in effluent	7.9	Calculated in Chapter 4.7.1
$EF_{NMVOC,WWT}$	NMVOC EF from WWT	Mg NMVOC/m^3 ww	15	EEA (2023, C3.3.2, Table 3-3)

*The emission factor is not directly available in the reference, see Chapter 4.3.1 for details.

**The emission factor is not directly available in the reference, see Chapter 4.6.1 for details.

6 Emissions

The main pollutants from wastewater treatment and discharge are CH_4 and N_2O followed by NMVOC.

Figure 6.1 presents the greenhouse gas emissions from wastewater treatment and discharge in Denmark divided in the seven contributions.

Emissions are also summarised in Table 6.1, while emissions for the full time series are shown in Annex 4.

Emissions of CH_4 and N_2O are calculated into CO_2 equivalents (CO_2e) using the global warming potentials (GWP) from the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC); these are 28 for CH_4 and 265 for N_2O (Myhre et al., 2013).

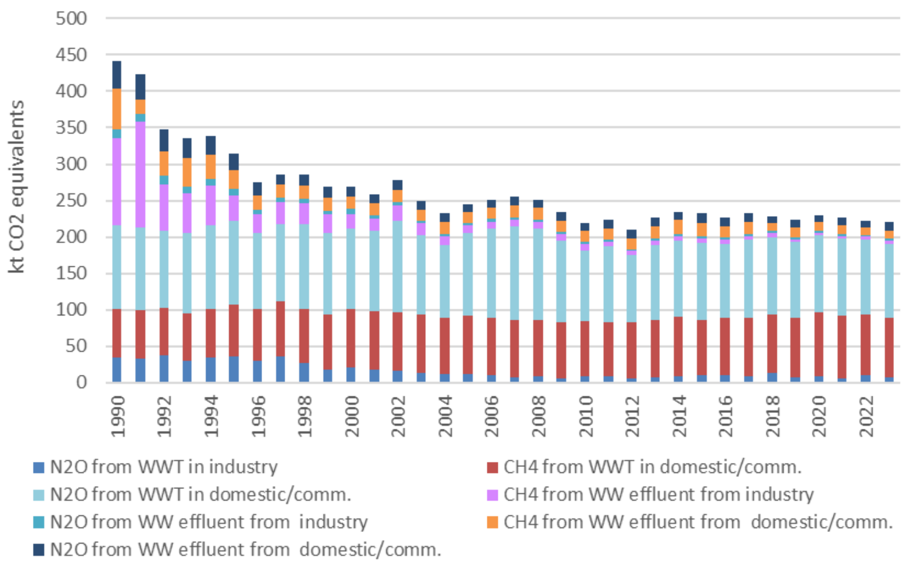

Figure 6.1 Greenhouse gas emissions. WWT = wastewater treatment, WW = wastewater.

Table 6.1 Emissions from wastewater treatment and discharge.

	Unit	1985	1990	1995	2000	2005	2010	2015	2020	2022	2023
$CH_{4, \text{anaerobic digestion, net}}$	kt		0.6	0.8	1.1	1.2	1.1	1.2	1.7	1.6	1.6
$CH_{4, \text{sewers + MB}}$	kt		0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
$CH_{4, \text{septic tanks}}$	kt		1.5	1.5	1.5	1.4	1.3	1.2	1.1	1.1	1.1
$CH_{4, \text{domestic/comm. effluent}}$	kt		2.0	0.9	0.6	0.5	0.6	0.7	0.4	0.4	0.4
$CH_{4, \text{industrial effluent}}$	kt		4.2	1.2	0.7	0.4	0.3	0.2	0.1	0.1	0.1
$CH_{4, \text{total}}$	kt CO_2e		241	132	117	106	101	100	102	98	97
$N_2O_{, \text{plants, domestic/comm.}}$	t		439	435	418	428	361	403	400	391	387
$N_2O_{, \text{effluent, domestic/comm.}}$	t		144	86	50	42	41	47	36	33	44
$N_2O_{, \text{plants, separate industries}}$	t		128	137	77	42	34	36	35	39	25
$N_2O_{, \text{effluent, separate industries}}$	t		48	33	28	13	10	11	10	9	8
$N_2O_{, \text{total}}$	kt CO_2e		201	183	152	139	118	132	128	125	123
Total greenhouse gas	kt		441	315	269	245	220	232	230	222	220
$NMVOC_{\text{municipal WWTPs}}$	t	11.8	11.4	12.0	12.4	10.5	10.2	11.5	10.4	9.2	9.1
$NMVOC_{\text{industrial WWTPs}}$	t	1.3	1.3	1.2	1.1	0.9	0.8	0.7	0.6	0.6	0.6
$NMVOC_{\text{total}}$	t	13.1	12.7	13.2	13.5	11.4	11.1	12.2	11.0	9.8	9.7

Regarding the methane time trend, the net CH_4 emission, $CH_{4.anaerobic\ digestion.net}$, from anaerobic treatment (i.e. after biogas recovery) has increased 162 % from 1990 to 2023. A less significant increase of 8 % is observed in the CH_4 emission, $CH_{4.sewer+MB}$, from the sewer system (incl. mechanical and biological treatment at WWTPs). CH_4 emissions, $CH_{4.septic\ tanks}$, from scattered houses not connected to the collective sewer system have decreased with 30 % reflecting the increase in the number of people connected to the collective sewer system. Lastly, CH_4 emissions from discharge have decreased with 80 % and 97 % respectively for municipal and industrial effluent, this reflecting the improved efficiency of WWTPs during the time series. In total, CH_4 emissions, $CH_{4.total}$, quantified as the sum of the five contributions to CH_4 emissions, have decreased by 60 % from 1990 to 2023.

Regarding the nitrous oxide time trend, the N_2O emission from the effluent wastewater has decreased 83 % and 69 % from 1990 to 2023 for centralised sources and separate industries respectively, while the N_2O emission from wastewater treatment plants has decreased by 12 % and 80 % for centralised and separate sources respectively. The decrease in the emission from effluent wastewater is due to the technical upgrade and centralisation of the Danish WWTPs following the adoption of the Action Plan on the Aquatic Environment in 1987. The effluent related emission from wastewater effluent has decreased from 191 tonnes N_2O in 1990 to 52 tonnes N_2O in 2023 corresponding to a reduction of 73 %. The trend in plant related N_2O emissions only decreases from 567 tonnes in 1990 to 412 tonnes in 2023 (-27 %), this is due to the influent N measurements to the centralised treatment plants only decreasing 12 % from 1990 to 2023, part of the reason being the increased fraction of industrial wastewater being treated at municipal WWTPs.

The N_2O emissions are mainly caused by WWTPs, contributing with between 75 % (1990) and 91 % (2022) of total N_2O emission from this sub-sector.

The N_2O emissions from municipal effluent wastewater, includes WWTP effluents, rain-related effluents as well as effluents from scattered houses, while N_2O emissions from separate industries includes separate industrial discharges and effluent from aquaculture.

The annual fluctuations in N_2O may be caused by several factors, e.g. climatic condition such as variations in precipitation and as a result varying contributions to the influent N and varying characteristics of especially the industrial contributions to the influent. Furthermore, infiltration of groundwater, as well as exfiltration of overload rainwater and wastewater (DEPA, 2024 and Vollertsen et al., 2002), may contribute to the fluctuation in the trend of the calculated N_2O emission.

7 Uncertainties

Uncertainty estimates include uncertainty with regard to the total emission inventory as well as uncertainty with regard to trends. Uncertainties are reported annually for both greenhouse gases and for other pollutants.

7.1 Methodology

The uncertainty for greenhouse gas emissions have been estimated according to the 2006 IPCC Guidelines (IPCC, 2006). The uncertainty has been estimated by the "Approach 1" methodology, this is further described in Nielsen et al. (2025a, Chapter 1.7).

The Approach 1 calculation is based on a normal distribution and a confidence interval of 95 %.

The input data for the Approach 1 estimate are:

- Emission data for the base year and the latest year
- Uncertainties for emission factors
- Uncertainties for the activity data

7.2 Uncertainty input data

The uncertainty levels used in the models are shown in Table 8.1. Uncertainties have been derived from IPCC Guidelines values, EEA Guidebook values and uncertainties in country specific parameters respectively. The uncertainties are assumed valid for all years 1990-2023.

Table 8.1 Estimated uncertainty rates for activity data and emission factors, %.

95 % confidence interval uncertainties	CH_4	N_2O	NMVOC
Municipal wastewater treatment			
Activity	10 %	10 %	10 %
Emission factor	900 %	70 %	100 %
Anaerobic treatment plants			
Activity	5.6 %		
Emission factor	25 %		
Septic tanks			
Activity	20 %		
Emission factor	101 %		
Municipal wastewater effluent			
Activity	10 %	10 %	
Emission factor	104 %	100 %	
Industrial wastewater treatment			
Activity		40 %	10 %
Emission factor		70 %	100 %
Industrial wastewater effluent			
Activity	10 %	10 %	
Emission factor	104 %	100 %	

Activity data are generally collected from monitoring data (SGAV, 2024 and earlier versions) and these are given an uncertainty of ±10%. Activity data for industrial wastewater treatment (influent) are estimated from effluent data and uncertainties are therefore higher (±40 %). Activity data for the use of septic tanks are calculated from population data (uncertainty <1 %) and the estimated fraction of population outside the sewer system (uncertainty estimated at ±20 %). Activity data for biogas production at wastewater treatment plants are calculated from the biogas production (available from the energy statistics with uncertainty of ±1 %) and the net calorific value for methane (uncertainty ±5.5 %).

When uncertainties are combined as is the case for e.g. the uncertainty for the activity data for the use of septic tanks, the input uncertainty presented in Table 8.1 is calculated following Equation 7.5.8 (IPCC, 2019 V1C3 Equation 3.1).

$$U_{total} = \sqrt{U_1^2 + U_2^2 + \ldots + U_n^2} \quad \text{Eq. 7.5.8}$$

The applied nitrous oxide emission factor for wastewater treatment is from DEPA (2020), the spread of performed measurements in the source, leads to an uncertainty of ±70 %. The nitrous oxide emission factor for effluent is the default IPCC (2019) value, and the uncertainty is set at 100 %.

The methane emission factor for wastewater effluent is calculated from IPCC default values B_0 (uncertainty ±30 %) and Tier 1 MCF (uncertainty ±100 %), the resulting uncertainty calculation input value is 104.4 %.The methane emission factor for the use of septic tanks is calculated from the country specific measured methane emission factor from Nielsen et al. (2018) (uncertainty ±100 %) and the IPCC BOD_5 value (uncertainty ±10 %), the resulting uncertainty of this input is ±100.5 %. The applied country specific methane emission factor from biogas production is available from ENS (2021) and has an uncertainty of ±25 %. The methane emission factor for treatment of wastewater calculated from the country specific MCF from Vollertsen (2012) (uncertainty ±900 %) and the IPCC B_0 value (uncertainty ±30 %).

The NMVOC emission factor is available from EEA (2023) and has an uncertainty of ±100 %.

7.3 Uncertainty results

The Tier 1 uncertainty estimates for the waste sector are calculated from 95 % confidence interval uncertainties; results are shown in Table 8.2.

Table 8.2 Tier 1 uncertainty estimates for wastewater.

Pollutant	2023 emission		2023 emission uncertainty, %	Trend* 1990-2023, %	Trend uncertainty, %-point
GHG**	219.9	kt CO_2e	49.1	-50.2	18.4
CH_4	3.5	kt	81.4	-59.6	27.9
N_2O	0.5	kt	59.9	-38.8	15.5
NMVOC	9.7	t	94.5	-23.5	11.2

*Percent change in emission in 2023 with respect to the base year 1990.

**GHG emissions are calculated in units of CO_2 equivalents.

8 QA/QC and verification

A list of QA/QC tasks are performed directly in relation to the emissions from the waste sector part of the Danish emission inventories. The following procedures are carried out to ensure the data quality:

- Checking of time series in the NFR and SNAP source categories. Considerable changes are controlled and explained
- Comparison with the inventory of the previous year. Any major changes are verified
- A manual log table is applied to collect information about recalculations
- Some automated checks have been prepared for the emission databases
- Check of units for fuel rate and emission factors
- Additional checks on database consistency.

For greenhouse gases, the Wastewater treatment and discharge sector is covered by the QA/QC manual guiding the quality work for the Danish greenhouse gas inventory, see Nielsen et al. (2020) for specific information on the QA/QC plan for the Danish greenhouse gas inventory. For specific information on the implementation of the QA/QC plan for the Wastewater treatment and discharge sector, please refer to the National Inventory Document (Nielsen et al., 2025a).

Documentation concerning verification of the Danish emission inventories has been published in Fauser et al. (2007). An updated verification report for the Danish emission inventories for GHGs is published in 2013 (Fauser et al., 2013).

This report serves as a key part of the QA of the emission inventory for the Waste sector. The previous version of this report was reviewed by Riitta Pipatti from Statistics Finland, Greenhouse Gas Inventory unit and Hans Oonk from “OonKAY!”. The comments received have been incorporated in the report or have been listed as future improvements.

The QC work will continue in future years.

8.1 Time series consistency and completeness

Consistency and completeness have been improved by integrating plant level data from the Danish Energy Statistics with plant level COD data from the Danish monitoring program and plant level environmental reports. All emission calculations have consistent methodologies throughout the time series.

Data regarding industrial on-site wastewater treatment processes have been achieved and included.

9 Source specific planned improvements

Following is a list of planned improvements for this sector:

- It is possible, from currently available data, to estimate methane emissions from on-site anaerobic treatment of industrial wastewater. There emissions are to be included in the future. The resulting increase in emissions will be about 1.4 tonne CH_4 per year.
- Based on the latest UNFCCC review, the documentation for the national emission factor for CH_4 from wastewater treatment is insufficient. Therefore, the factor will be updated to the IPCC default. This is an increase in the emission factor from 1.8 g CH_4 per kg BOD to 18 g CH_4 per kg BOD, resulting in an increase in emissions of around 2.5 - 3 kt CH_4 for each year in the time series 1990-2024.

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Appendix

Appendix can be found here.

DANISH EMISSION INVENTORY FOR WASTEWATER TREATMENT AND DISCHARGE

Results of inventories up to 2023

This report forms part of the documentation for the emission inventories for waste. The report includes both methodological descriptions for estimating emissions of greenhouse gases and air pollutants and presents the resulting emission data as reported to the United Nations Framework Convention on Climate Change and the United Nations Economic Commission for Europe Convention on Long-Range Transboundary Air Pollution. The results of inventories up to 2023 are included.

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