# WASTEWATER TREATMENT AND DISCHARGE

Scientific Report from DCE – Danish Centre for Environment and Energy No. 193 2016

AARHUS UNIVERSITY
DCE – DANISH CENTRE FOR ENVIRONMENT AND ENERGY

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# Data sheet

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Abstract: This sector report present a verification of the country-specific methane emissions factor of 1.3 % of the reported methane recovery in terms of biogas production at Danish wastewater treatment plants from anaerobic sludge treatment. The verification is based on a combination of national level COD balance, as recommended by the UNFCCC review team, supplemented by plant level reported data. Secondary, the correctness of the percentage of the Danish population not connected to the collective sewer system is documented. Lastly a first approach for including direct $N_2O$ emissions from separate industries is presented.

Keywords: WWTP, $CH_4$, $N_2O$, National GHG emission inventory

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# List of abbreviations

AD Anaerobic Digestion

BAT Best Available Techniques

BOD Biological Oxygen Demand

$CH_4$ Methane

COD Chemical Oxygen Demand

$CO_2$ Carbon dioxide

$CO_2e$ Carbon dioxide equivalents

DCA Danish Centre for food and Agriculture

DCE Danish Centre for Environment and energy

DEA Danish Energy Agency

DEPA Danish Environmental Protection Agency

DM Dry Matter

DME Danish Ministry of Environment

DMEE Danish Ministry of Environment and Energy

EF Emission Factor

ENVS Department of ENVironmental Science, Aarhus University

Gg Giga gram

GHG Greenhouse gas

GWP Global Warming Potential

IPCC Intergovernmental Panel on Climate Change

MBNDC Mechanical, Biological Nitrification, Denitrification and Chemical

MCF Methane Conversion Factor

$N_2O$ Nitrous oxide

NIR National Inventory Report

NOVANA National Monitoring and Assessment Programme for the Aquatic and Terrestrial Environments

QA Quality Assurance

QC Quality Control

TOW Total Organic Waste

UNECE United Nations Economic Commission for Europe

UNFCCC United Nations Framework Convention on Climate Change

VS Volatile Solids

WWTP WasteWater Treatment Plant

# Preface

The Danish Centre for Environment and Energy (DCE) at Aarhus University is contracted by the Ministry of the Environment and Food, and the Ministry of Energy, Utilities and Climate, to report yearly emission inventories for Denmark. Department of Environmental Science, Aarhus University is responsible for calculation and reporting of the Danish national emission inventory to EU and the UNFCCC (United Nations Framework Convention on Climate Change) and UNECE CLRTAP (Convention on Long Range Transboundary Air Pollution) conventions.

This report forms part of the documentation for the inventories and documents the methodology for calculating emissions from wastewater handling. The results of inventories up to 2013 are included. The report updates the report published in 2005 by Thomsen and Lyck.

The previous version of this report was reviewed by Niels Iversen, Section of Environmental Engineering, Department of Life Sciences, Aalborg University, Denmark, and Mette Wolstrup Pedersen, Water office, Danish Environmental Protection Agency.

This report has been reviewed by Riitta Pipatti, Statistics Finland, Helsinki · Greenhouse Gas Inventory unit and Hans Oonk, OonKAY!, Apeldoorn, The Netherlands.

# Summary


The Danish emission inventory for wastewater treatment and discharge is based on plant level monitoring data in the influent and effluent wastewater, reported data on flaring and methane loss at plant level and reported energy recovery data. For this reason, a country-specific methodology for calculating the national emissions from wastewater treatment and discharge have been developed (Thomsen & Lyck, 2005) as the default IPCC methodology do not fit countries having input-output monitoring data (IPCC, 2006, Chapter 5). The focus of the present sector report is to verify the country-specific methane ($CH_4$) emission factor calculated at 1.3 % of the reported methane recovery from biogas production at Danish wastewater treatment plants with anaerobic sludge treatment.

This report presents the status of methodological development within the sub-sector *5.D Wastewater treatment and discharge*. Focus of the report is to present a COD (Chemical Oxygen Demand) mass balance for the Danish wastewater treatment plants, verifying the country-specific methane emission factor, and the resulting level of methane emission from anaerobic sludge digestion, at the Danish wastewater treatment plants (WWTP). The latter requested for by the UNFCCC expert review team.

Varying plant design and sludge management strategies at the individual WWTPs results in varying methane production efficiencies and emissions, which has initiated an ongoing process of collection and combining activity data at plant level with the aim of documenting a country-specific emission inventory – optimally at plant level.

The present report presents status of COD mass balance for verification of the country-specific methane emission factor based on available information according to the status on the development of a plant level database. Plant level monitoring data extracted from reports published by: 1. The individual WWTPs, i.e. Environmental Reports, 2. Yearly reports published by the Danish Nature Agency, i.e. results obtained from National Monitoring and Assessment Programme for the Aquatic and Terrestrial Environments (NOVANA) and 3. Energy Producer Account data received by the Danish Energy Agency.

Plant and National level COD mass balances and methane emission calculations is presented with the aim of data gap filling and verification of the emissions factor for methane emissions from anaerobic sludge digestion.

Another aspect that has been addressed by the UNFCCC expert review team is improved documentation of the fraction of the population, which are not connected to the collective sewer system. For this reason, the report includes a verification of the fraction of the population living within the scattered settlements, i.e. not connected to the collective sewer system, and the associated septic tank modelling approach used to calculate the methane emission from scattered settlements.

Lastly, a first evaluation of the possibility to include direct $N_2O$ emissions from separate industries in future emission inventories to EU and the UNFCCC for the sub-sector *5.D Wastewater treatment and discharge* is presented.

The main objective of this report is to document the accuracy of the country-specific emission factor (EF) value for methane emissions from anaerobic treatment of sludge, i.e. 1.3% of the recovered methane. The latter is obtained by setting up COD mass balances and associated methane budgets at national and plant level based on Danish monitoring data.

There is a general tendency for the methane recovered as calculated from the Energy Producer Account data to be lower than the reported methane recovery data in the Environmental Reports published by the individual WWTPs. There may be several reasons for this tendency. One reason may be that the methane conversion efficiency is lower than the IPCC default value of 80 % of the maximum $CH_4$ producing capacity ($B_o$). The error of propagation is within the range of uncertainty reported at tier 1 and 2 (Nielsen et al., 2014) justifying the country-specific EF of 1.3 % of the recovered methane.

The value of the country-specific methane emission factor for WWTPs with anaerobic sludge digestion is sufficiently justified at plant level. However, national and plant level COD balances indicate that it is important to take into account external carbon when calculating the EF value from COD mass balances and associated $CH_4$ budgets at plant level.

# Sammenfatning

Danmark anvender en dansk udviklet metode til opgørelser af drivhusgasemissioner fra den danske spildevandssektor (Thomsen & Lyck, 2005; Nielsen et al., 2016). Baggrunden er den, at vi i Danmark har et moniteringsprogram, som skal sikre kvaliteten af vores vandmiljø og natur, en Energistatistik som årligt rapporterer energiproduktionen fra fossile og biomasse ressourcer, ligesom flere af de danske forsyningsselskaber årligt udgiver en miljørapport, som ligeledes indeholder information om vandkvalitetsparametre i indløbs- og udløbsspildevand, samt biogas til energiproduktion og gasafbrænding i fakkel, og tab fra rådnetanken. Sådanne datakilder udgør baggrundsdata for inputparametre i den danske model til beregning af de nationale emissioner fra spildevandsrensning og -udledning i modsætning til IPCC-standardmetoden, som er designet til lande, der ikke har relevante moniteringsdata og andre aktivitetsdata til brug for udarbejdelse af inputparametre i emissionsopgørelserne (IPCC, 2006, kapitel 5). Fokus for nærværende sektorrapport er at verificere den danske metan($CH_4$)-emissionsfaktor opgjort til 1,3% af mængden af nyttiggjort metan fra biogasproduktionen på danske renseanlæg, som gør brug af slamudrådning (anaerob slambehandling) som slam behandlingsteknologi (Nielsen et al., 2015).

Denne rapport præsenterer status for metodeudvikling i emissionsopgørelserne for sektoren 5.D Spildevandsrensning og -udledning. Rapporten præsenterer COD (Chemical Oxygen Demand) massebalancer for de danske renseanlæg, på nationalt såvel som på anlægsniveau i det omfang datatilgængelighed tillader dette. Formålet er at verificere den danske metanemissionsfaktor, og dermed dokumentere korrektheden af den resulterende metanemission fra danske renseanlæg med anaerob slamudrådning. Danmark er igennem de sidste års review af UNFCCC's eksperthold, blevet anmodet om at levere en verifikation af den danske metanemissionsfaktor via opstilling af en komplet COD-massebalance.

Varierende anlægsdesign og slamforvaltningsstrategier på de enkelte renseanlæg resulterer i varierende metanproduktion og -emissioner. Dette har afstedkommet et behov for løbende indsamling af aktivitetsdata på anlægsniveau med henblik på at opstille anlægsspecifikke COD massebalancer og tilhørende emissionsfaktorer. Det oparbejdede datagrundlag er repræsentativt for de danske rensningsanlæg med anaerob slambehandling, og dokumenterer den nationale emissionsfaktor og muliggør endvidere anlægsspecifikke opgørelser som tager hensyn til de stadigt mere avancerede og varierende anlægsdesign (Thomsen et al., 2015).

Status for COD-massebalancer på nationalt hhv. anlægsniveau til brug for en verifikation af den danske metanemissionsfaktor er baseret på en sammenkobling af følgende datakilder: 1. Data fra de enkelte renseanlæg, dvs. årlige miljørapporter, 2. Årlige rapporter udgivet af Naturstyrelsen baseret på overvågningsdata fra det danske overvågningsprogram for vandmiljøet og naturen (NOVANA) og 3. Energiproducenttællingsdata fra Energistyrelsen.

COD-massebalancer baseret på anlægsniveaudata hhv. data på nationalt niveau anvendes, foruden verificering af den nationale beregning af metanemissionen, også til metodeforbedring, idet der i den anlægsspecifikke opgørelse over COD i indløb til anlæg med anaerob slambehandling opnås en verificering og forbedring af aktivitetsdata som kvantificerer fraktionen af slam, som behandles på anlæg med anaerob udrådning af slam.

Et andet aspekt, der er blevet adresseret af UNFCCC´s eksperthold, er ønsket om en forbedret dokumentation for den del af befolkningen, som ikke er forbundet et kloaksystem. Derfor indeholder rapporten en forbedret dokumentation for den del af befolkningen, der hører ind under spredt bebyggelse. Spredt bebyggelse modelleres p.t. via septiktankmodellen, som er IPPC´s standardmetode til at beregne metanemission fra den spredte bebyggelse.

Sidst præsenterer rapporten en metode til at inkludere den direkte $N_2O$-emission fra særskilt industri i fremtidige emissionsopgørelser til EU og UNFCCC, som grundet manglende data ikke tidligere har været inkluderet i emissionsopgørelsen for kategorien *5.D Spildevandsrensning og udledning*.

Der er en generel tendens til, at den mængde metan der produceres beregnet ud fra energiproducenttællingen, er noget lavere end den rapporterede metanproduktion afrapporteret i de anlægsspecifikke miljørapporter. Der kan være flere grunde til denne tendens. En årsag kan være, at metanomdannelsesfaktoren er lavere end IPCC's standardværdi på 80 % af den maksimale $CH_4$-produktionskapacitet (Bo). Forskellen ligger dog indenfor usikkerhedsintervallet på tier 1 og 2 (Nielsen et al., 2014), hvilket understøtter korrektheden af den nationale emissionsfaktor på 1.3% af den producerede metan som genvindes.

Værdien af den nationale metanemissionsfaktor for renseanlæg med anaerob slambehandling vurderes tilstrækkeligt dokumenteret. Dog indikerer forskellen imellem COD-balancer baseret på nationale hhv. anlægsspecifikke data, at det er vigtigt at medregne tilførslen af eksternt kulstof til biogastanken i en beregning af anlægsspecifikke emissionsfaktorer fra COD-massebalancer og tilhørende $CH_4$-budgetter.

# 1 Introduction

The Danish wastewater treatment system is characterised by a few big and advanced wastewater treatment plants (WWTPs) and many smaller WWTPs. From 1993 to 2010, the amount of wastewater treated at the most technologically advanced WWTPs in Denmark has increased from 53 % to more than 90 %. Improvements of the decentralised wastewater treatment system as well as the sewer system are ongoing in Denmark (DEPA, 2010). For the part of the population not connected to the sewer system, i.e. scattered settlements, sludge from septic tanks are collected once per year or as appropriate by judgement of the local authorities (DME, 1999). Municipal collection and transportation of sludge from septic tanks for treatment at the centralised WWTPs occurs with a frequency set by the authorities. Emptying of septic tanks occur at a minimum one time each year.

The national emission inventory for wastewater handling includes an estimation of the emission of methane ($CH_4$) and nitrous oxide ($N_2O$) from wastewater treatment and discharge. $CH_4$ is produced during anaerobic conditions and treatment processes, while $N_2O$ is emitted during biological N removal processes; i.e. during nitrification and denitrification processes under anaerobic as well as aerobic conditions as well as from anaerobic ammonia oxidation (e.g. Adouani et al., 2010; Kampschreur et al., 2009).

A significant part of the Danish industries are connected to the collective sewer system in Denmark and mixed wastewater from households and industries constitutes the influent wastewater at centralised WWTPs. The contribution from the industry to the influent wastewater at the centralised WWTPs has increased from zero in 1987 to around 40 % in 2006 with the highest influent contribution occurring at the biggest and most advanced technological WWTPs in Denmark (Thomsen & Lyck, 2005; DME 2014; Nielsen et al., 2014). No separate reporting on the emissions from industrial and municipal wastewater treatment occurs.

Activity data on wastewater treatment at industrial WWTPs is scarce and for this reason, the direct $N_2O$ emissions from separate industries with internal wastewater treatment have so far only been included in the Danish inventory for category 5.D to the extent influent activity data are reported to the Danish Nature Agency. This report presents a first estimation of the direct $N_2O$ emissions from industrial wastewater treatment plants (Annex E).

Input parameters for calculation of indirect $N_2O$ emissions from separate industries originate from the yearly reported data on nitrogen in effluent wastewater. Such data are available at plant level and is reported yearly by the Danish Nature Agency and published by the Danish Ministry of Environment (DMEE, 1994a, b, 1995a, b; DME 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003a, 2004a, 2005, 2006, 2007, 2008, 2009a, 2010, 2011, 2012a, 2013, 2014).

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, 2014).

The IPCC 2006 guidelines provide a default methodology, which allocates different emission factors to different population groups according to their income and area of living. For each country default values for the distribution of different treatment pathways according to three categories: rural population, urban high-income population group, and urban low-income population group (IPCC, 2006, Chapter 5, Table 6.5). For each category, a specified distribution of treatment types (septic tanks, lagoons, anaerobic/anaerobic tanks etc.), default $B_o$ and *MCF* values exists (IPCC, 2006, Chapter 5, Table 6.2 and 6.3) for calculating pathway specific EF values. The EFs for the individual treatment technologies are 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).

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 emission factors. Still, at a conceptual level the country-specific methodology follows the principles of the IPCC guidelines.

The principle of equation 6.1 in the IPCC 2006 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 (93 %) 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 (7%) is comprised by domestic wastewater, produced within scattered settlements not connected to the collective sewer system. Such wastewater is modelled as being managed in 3) septic tanks accompanied by sludge collection used as ingestate (initial substrate) at anaerobic WWTPs. A flow chart of the treatment pathways in Denmark is visualised in Figure 1.1 in units of COD flows.

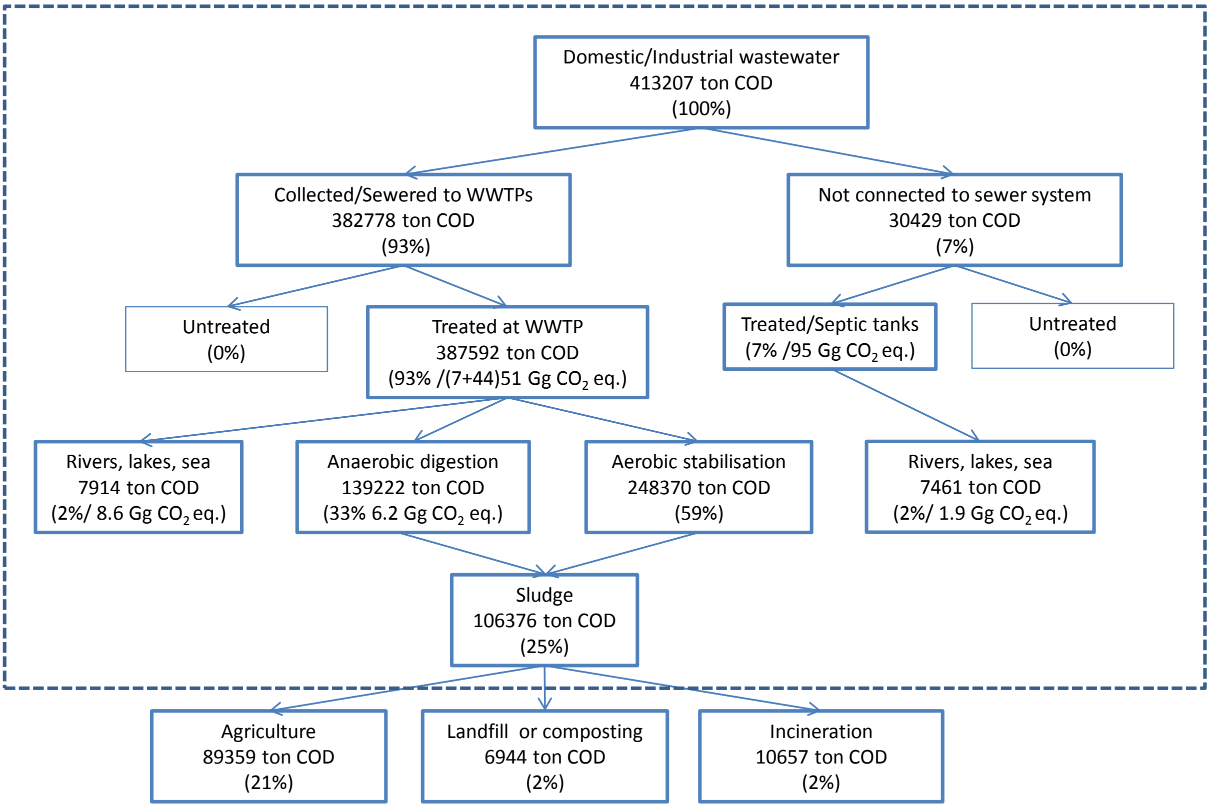


Figure 1.1 Overview of the COD flow through the treatment systems and discharge pathways in Denmark in 2013. Of the total COD (100 %) produced, 93 % is collected via the sewer system and transported to centralised WWTPs, while 7 % of the COD produced within scattered settlements not connected to the sewer system is modelled as septic tank systems. Of the 93 % COD treated at centralised WWTPs, 33 % enters WWTPs with anaerobic sludge digestion and 59 % enters WWTPs with aerobic sludge stabilisation. GHG emissions from aerobic mechanical and biological treatment processes occur prior to anaerobic digestion or aerobic sludge stabilisation at all WWTPs in Denmark. Of the 387592 Gg COD entering the Danish WWTPs, a GHG emission (primarily $N_20$) of 51 Gg $CO_2e$ results from the aerobic biological treatment step common to both WWTPs with anaerobic and aerobic sludge management strategies. The main source of methane emission occurs from anaerobic sludge digestion corresponding to 6.2 Gg $CO_2e$ (1.3 % of the recovered amount of methane). Approximately 25 % of the COD in the influent wastewater remains in the final sludge from anaerobic and aerobic stabilisation while 4 % of the total COD produced in DK is lost to the aquatic system (rivers, lakes and sea) resulting in indirect $N_2O$ emissions summing up to 10.5 Gg $CO_2e$.

Figure 1.1 shows the COD flow and corresponding points of emissions. IPCC, 2006 recognized $CH_4$ and $N_2O$ as the only GHG emissions from WWTP processes while $CO_2$ process emissions defined as biogenic carbon-neutral emissions are not reported (IPCC, 2006). Therefore, only methane and nitrous oxide emissions have been included in Figure 1.1. In the box "Treated at WWTP", the 51 (7 +44) Gg $CO_2e$ refers to methane and nitrous oxide emissions from sewer, mechanical and biological wastewater treatment processes. Methane emissions from anaerobic sludge digestion correspond to 6.2 Gg $CO_2e$. Methane emissions from the part of the population that are not connected to collective sewer system is modelled assuming septic tank systems only; i.e. representing an overestimation of the methane emission from scattered settlements in Denmark. Emissions from scattered settlements as well as emission from WWTP relate to nitrous oxide; i.e. corresponding to 1.9 and 8.8 Gg $CO_2e$ from scattered settlements and WWTPs, respectively. Emissions from the combustion of sludge and digester gas with energy recovery are reported under biomass in the energy sector. Chapter 3 provides a description of the COD mass balances including losses to air during biological treatment and sludge digestion.

For the majority of the Danish WWTPs the mechanical (primary) and biological treatment processes occurs at well managed and regulated centralised plants with minimal $CH_4$ emissions (DME, 2014). Table 1.1 presents the percent 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 MBNDC (Mechanical, Biological Nitrification, Denitrification and Chemical). Table 1.1 presents the environmental performance for the whole time series, quantified as the reduction efficiencies of organic matter, N and P in the effluent wastewater with reference to the influent wastewater at national level (DME, 1992, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003a, 2004a, 2005, 2007, 2008, 2009a, 2010, 2012a, 2012, 2013; DMEE, 1994a and 1994b, 1995b, 1999b).

Table 1.1 Degree of utilization of modern, centralized WWT plants[1] and associated reduction in suspended and soluble organic matter in the effluent wastewater, [%][2].

| Year | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 |
|---|---|---|---|---|---|---|
| Share of WWTPs of the type MBNDC | 10 | 30 | 50 | 50 | 60 | 69 |
| $BOD_{effluent}$ - percent reduction of influent | - | - | - | 58 | 61 | 87[3] |
| Total $N_{effluent}$ - percent reduction of influent | - | - | - | 41 | 43 | 56 |
| Total $P_{effluent}$ - percent reduction of influent | - | - | - | 74 | 75 | 80 |
| Year | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 |
| Share of WWTPs of the type MBNDC | 72 | 86 | 84 | 85 | 85 | 90 |
| $BOD_{effluent}$ - percent reduction of influent | 80 | 94 | 94 | 94 | 95 | 96 |
| Total $N_{effluent}$ - percent reduction of influent | 61 | 76 | 74 | 74 | 77 | 79 |
| Total $P_{effluent}$ - percent reduction of influent | 84 | 89 | 90 | 90 | 91 | 92 |
| Year | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 |
| Share of WWTPs of the type MBNDC | 86 | 90 | 90 | 90 | 90 | 90 |
| $BOD_{effluent}$ - percent reduction of influent | 96 | 96 | 93 | 95 | 96 | 96 |
| Total $N_{effluent}$ - percent reduction of influent | 77 | 81 | 80 | na | 82 | 78 |
| Total $P_{effluent}$ - percent reduction of influent | 91 | 93 | 96 | na | 93 | 93 |
| Year | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 |
| Share of WWTPs of the type MBNDC | 90 | 90 | 90 | 90 | 90 | 91 |
| $BOD_{effluent}$ - percent reduction of influent | 96 | 95 | 96 | 92 | 92 | 95 |
| Total $N_{effluent}$ - percent reduction of influent | 82 | 80 | 82 | 78 | 81 | 82 |
| Total $P_{effluent}$ - percent reduction of influent | 93 | 91 | 93 | 90 | 92 | 92 |

[1]Centralized WWTPs of the most advanced technology type MBNDC (mechanical, biological nitrification, denitrification and chemical).

[2]BOD, the Biological Oxygen Demand, is an indirect measure of the amount of organic matter (that can be oxidized biologically) in the wastewater. The BOD test procedure is based on the activities of bacteria and other aerobic microorganisms (microbes), which feed on organic matter in presence of oxygen (DME, 1998).

[3]The significant increase in the reduction efficiency is partly explained by to the varying, but also changing methodology for measuring BOD. Reported number are represented by a mixture of modified (i.e. allylthiourea is added to the sample inhibiting the biological oxygenation of nitrogen/nitrification) and unmodified (simultaneous oxygenation of nitrogen) BOD measurement (Andersen, 1983; DME, 1996; DS/EN ISO 1899-1:2003; DS/EN ISO 1899-2:2004; DEPA, 2002 and 2005).

The increase in treatment efficiency is reflected in the number of plants types having the most advanced treatment technologies installed, which was 0.5 % before the first Water Environment Action Plan in 1983 (Thomsen & Lyck, 2005). As shown in Table 1.1, the fraction of influent wastewater at the Danish WWTPs treated by advanced organic matter, nitrogen and phosphorus removal technologies has increased further from 10 % in 1990 to 91 % in 2013 (DME, 2014).

The technological development of the Danish WWTPs has been accompanied by a centralisation of the wastewater treatment at fewer and bigger plants. As such, 1,989 WWTPs above 30 person equivalent (PE) were running in 1980, but since 1998, 1,074 Danish WWTPs has been closed, resulting in 906 WWTPs remaining today. 90 % of the Danish wastewater is treated at the 300 biggest WWTPs (DME, 2014; Niero et al., 2014; Jensen et al., 2015; Thomsen et al., 2015).

The centralisation of wastewater treatment at WWTPs using advanced treatment technologies have resulted in an increase in the N, P (phosphorus) and organic matter reduction efficiencies. As such, 41 %, 74 % and 58 % of the N, P and organic matter in the influent wastewater was reduced in the effluent wastewater in 1993 and the efficiency was increased to 82 % N, 92 % P and 95 % organic matter in 2013 (Thomsen and Lyck, 2005; DME, 2014). The above-described technological development for improved quality of the effluent wastewater has influenced the level of process emissions to air in negative direction. As such, a reduction in the indirect $N_2O$ emissions, i.e. $N_2O$ emissions originating from the N content in the effluent wastewater, corresponding to 78 % in 2013 compared to 1990 results. This reduction are accompanied by an increase in the direct $N_2O$ and $CH_4$ emissions from the wastewater treatment processes of respectively a factor 2 and 3 as shown in Table 1.2.

Table 1.2 Nitrous oxide and methane emissions from WWTPs and percent change from 1990-2013.

| Year | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 | 2012 | 2013 | %-change |
|---|---|---|---|---|---|---|---|---|---|
| $N_2O_{direct}$ [Mg]* | 73 | 111 | 134 | 161 | 136 | 150 | 131 | 147 | 101 |
| $N_2O_{WWTP\ effluents}$ [Mg] | 265 | 140 | 73 | 60 | 63 | 62 | 60 | 57 | -78 |
| $CH_{4,WWTP}$ [Gg] | 11 | 15 | 23 | 23 | 24 | 26 | 31 | 30 | 182 |

*Excluding the direct $N_2O$ emissions from separate industries shown in Annex E.

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 2 presents the methodology for estimating the $CH_4$ and $N_2O$ emissions from Danish WWPTs and scattered settlements; including updated information on activity data and EF values. Sub-chapters 3.1 and 3.2 presents a verification of the activity data, input parameters and model approach for estimating $CH_4$ and $N_2O$ emissions from Danish WWPTs, respectively. Lastly, Chapter 4 presents planned improvements.

# 2 Methodology – Wastewater treatment and discharge

The methodology developed for estimating emission of methane and nitrous oxide from wastewater treatment and discharge follows the IPCC Guidelines (IPCC, 2006). This section includes methodological issues related to the $CH_4$ and $N_2O$ emission calculations, respectively.

## 2.1 National Methodology – Activity data

The Danish Nature Agency is responsible for monitoring and reporting of point sources within 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 public WWTPs in Denmark. For separate industrial wastewater, mainly data on effluent wastewater are reported (DMEE, 1989, 1990 1992, 1994a, b, 1995a, b; DME 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003a, 2004a, 2005, 2006, 2007, 2008, 2009a, 2010, 2011, 2012a, 2013, 2014). The Danish aquatic monitoring programme also includes measurements of emissions to the aquatic environment from aquaculture, rainwater conditioned effluents, and scattered settlements (Nature Agency, 2016). The Danish Nature Agency, reports yearly monitoring data at plant level and are responsible for data reported in a national water quality database **(**http://www.miljoeportal.dk/English**).**

Compared to other countries, Denmark is unique regarding the availability of monitoring data quantifying the input activity data at plant level. This implies that monitoring data on BOD as well as COD are available for all WWTPs in Denmark.

The Danish Energy Agency provides data on the energy production for all WWTP using anaerobic digestion as sludge management strategy.

## 2.2 National Methodology - Methane emission

Methane emissions from the Danish WWTPs are divided into contributions from 1) the sewer system, primary settling tank and aerobic biological N and P removal processes and 2) from anaerobic treatment processes in closed systems with biogas generation that are combusted for energy production. The methane emission from scattered settlements not connected to the collective sewer system in Denmark is modelled through 3) septic tanks using default parameters (IPCC, 2006).

The methane emissions from WWTPs are divided into a contribution from the sewer system, primary (mechanical) settling tank and aerobic biological N and P removal processes, $CH_{4,sewer+MB}$, and from anaerobic treatment processes in closed systems with biogas extraction for energy production, $CH_{4,AD}$ :

$$CH_{4,WWTP} = CH_{4,sewer+MB} + CH_{4,AD} \qquad \text{Eq. 1}$$

Emission factors for estimating the methane emissions are provided in units of biological or chemical oxygen demand (BOD or COD) in the influent wastewater in accordance with the IPCC guidelines (IPCC, 2006). 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 (including the recalcitrant fraction of organic pollutants), while BOD consumes an amount of $O_2$ corresponding to the biochemical degradable fraction of carbon.

In the National Inventory, the yearly reported BOD monitoring data on wastewater have been used for estimating the methane emissions throughout the time series in the reporting years 2006 to 2014 (Illerup et al., 2006-2007; Nielsen et al., 2008-2014). However, in the reporting year 2015, the more consistent COD data replaced BOD monitoring data.

The uncertainty in BOD data is higher than COD data. This is because different standard methodologies exist for measuring BOD (ISO 5815-1:2003; 5815-2:2003). Some BOD measurements include the biochemical oxidation of not only carbonaceous, but also nitrogenous compounds, making the BOD measures are inconsistent. This adds further to the uncertainty in the reported BOD data (DMEE, 1998). With C:N ratios in waste water 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.

A COD analysis oxygenates practically all organic material, while nitrogen compounds are not oxidised (Henze et al., 2010; DHI, 2001), which 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. The most important reason for changing the methodology to be based on COD data is a more robust measure, that are used by the WWTPs for process control adjustments, for which reason more process specific measurements are available such as the COD content in the final sludge (Section 3.1.2 and 3.17 and Thomsen et al., 2015).

### 2.2.1 $CH_4$ emission from wastewater treatment processes

The fugitive emissions from the sewer system, primary (and secondary) settler tanks (clarifiers) and aerobic biological treatment processes, $CH_{4,sewer+MB}$, are estimated as:

$$CH_{4,sewer+MB} = EF_{sewer+MB} \cdot TOW_{inlet} \qquad \text{Eq. 2}$$

$$\Downarrow$$

$$CH_{4,sewer+MB} = B_o \cdot MCF_{sewer+MB} \cdot TOW_{inlet}$$

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, 2006).

The fraction of $TOW$ that is unintentionally converted to $CH_4$ in sewers, primary clarifiers and aerobic biological treatment processes, $MCF_{sewer+MB}$, is set equal to 0.003 based on an expert knowledge on the state and technological management of the Danish sewer systems (Vollertsen, personal communication, September, 2012). The emission factor, $EF_{sewer+MB}$, for these processes equals 0.00075 kg $CH_4$ 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, 2006 guidelines reporting a default MCF for open and closed flowing sewer of 0.

Furthermore, Johansen (2013) 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 (EF) of 0.00042 $Nm^3$ $CH_4$ or 0.0003 kg $CH_4$ 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. 0.00075 kg $CH_4$ per kg COD in the inlet wastewater, represents a conservative estimate of methane from sewer, mechanical and biological treatment processes.

### 2.2.2 $CH_4$ emission from anaerobic sludge digestion

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. At present, most WWTPs combusts the produced biogas in a biogas-driven engine for the production of heat and electricity; however, emerging technologies such as upgrading of the biogas by $CO_2$ extraction (e.g. Frederica WWTP) or $CO_2$ conversion ([www.biofos.dk](http://www.biofos.dk)) allows for the production of bio-natural gas that may be sold and distributed in the natural gas grid (Thomsen et al., 2015).

The methane emission from an anaerobic sludge digestion may occur via venting and to a minor extent from storage of the digestate (Johansen, 2013). Equation 3, provides a theoretical equation for calculating the methane emission from anaerobic sludge digestion:

$$CH_{4,AD,net} = CH_{4,AD,gross} - (B_o \cdot S) - CH_{4,AD,energy} - CH_{4,AD,flaring} \quad \text{Eq. 3}$$

where $CH_{4,AD,gross}$ is the gross methane emission quantifying the total methane potential contained in the ingestate COD ($S_{ingestate}$), $B_o$ is the default maximum $CH_4$ producing capacity and $S$ is the COD in the final sludge; i.e. recalcitrant carbon. The unconverted theoretical $CH_4$ potential in the recalcitrant carbon contained in the final sludge, $S$, may be expressed as $MCF_s$, the methane correction factor of the final sludge, multiplied by the COD content in the ingestate, $S_{ingestate}$, where $MCF_s$ is equal to 1- $MCF_{AD}$. $CH_{4,\ energy}$ represents the amount of methane recovered for energy production and $CH_{4,\ flaring}$ quantifies the methane recovered and flared (cf. Chapter 3.1).

The gross methane emissions, $CH_{4,AD,gross}$, are calculated as:

$$CH_{4,AD,gross} = f_{AD} \cdot MCF_{AD} \cdot B_o \cdot TOW_{inlet} \quad \text{Eq. 4a}$$

In case of co-digestion of external carbon sources equation 4a is slightly modified as shown in equation 4b

$$CH_{4,AD,gross} = B_o \cdot MCF_{AD} \cdot [(f_{AD} \cdot TOW_{inlet}) + TOW_{external}] \quad \text{Eq. 4b}$$

where $f_{AD}$ is the fraction of the COD in the influent wastewater that are conserved in the ingestate is ranging from 0.3 in 1990 increasing to a maximum level of 0.6 from 1999 to 2013 (Jensen et al., 2015; Thomsen et al., 2015 and Chapter 3);

$MCF_{AD}$, the methane correction factor, adjust the default maximum $CH_4$ producing capacity or theoretical methane yield to the expected conversion under real operating conditions and is set equal to 0.8 (IPCC, 2006);

$TOW_{inlet}$ equals the influent organic degradable matter measured as the sum of chemical oxygen demand (COD) in the influent wastewater at WWTPs using anaerobic sludge digestion in a digester tank for the production of biogas.

$B_o$ is the default maximum $CH_4$ producing capacity, i.e. 0.25 kg $CH_4$ per kg COD (IPCC, 2006). By dividing $B_o$ with the density of methane, i.e. 0.72 kg $CH_4/m^3$, the theoretical methane yield of 0.35 $Nm^3$ $CH_4$ per kg COD is obtained; a value which, as expected, is strongly above the yield in real operating conditions upon reference to the influent amount of COD (Table 2.5).

The above described eq. 4a and 4b is in line with IPCC-guidelines, and this concept is used for verifying the country-specific methane emission factor (chapter 3). However, the error propagation, associated to equations 4a and 4b, are high, and the verification of the country-specific EF value is unavoidable, based on a derived difference between two large numbers including also uncertainties. The criteria for verification of the country-specific EF value may therefore at best consist in verifying that the value calculated according to Eq. 5 lies within the uncertainty range of the COD mass balance.

The net methane emission from anaerobic digestion in biogas tanks are at present estimated according to equation 5 for the whole time series:

$$CH_{4,AD,net} = EF_{AD} \cdot CH_{4,AD,recovred} \qquad \text{Eq. 5}$$

where the emission factor, $EF_{AD}$, has been set equal to 1.3 % of the methane content in the gross energy production at national level reported by the Danish Energy Agency; i.e. 0.013 (see Table 3. and Chapter 3 on verification).

At the present stage of verification of activity data, equation 5 is the most appropriate equation for estimating the net methane emission from anaerobic digestion of sludge; i.e. the net methane emission from anaerobic digestion equals the methane emissions due to venting associated to the biogas production and storage tanks (Hjort-Gregersen, 2013; Nielsen et al., 2015).

### 2.2.3 $CH_4$ emissions from septic tanks

For the part of the population not connected to the collective sewer system, simple decentralised wastewater handling is modelled as septic tanks. Only little knowledge is available about the frequency of collection and no measurements of the methane emissions from septic tanks and the pumping and management of septage, including its transportation to a wastewater treatment facility exist. Methane emission from septic tanks is calculated as:

$$CH_{4,st} = EF_{st} \cdot f_{nc} \cdot P \cdot DOC_{st} \qquad \text{Eq. 6}$$

where the emission factor is calculated from the default IPCC value quantifying the maximum methane producing capacity $B_o$ of 0.25 kg $CH_4$ per kg COD multiplied by the methane conversion factor for septic tanks, corresponding to the amount of suspended organic material that settles in the septic tank, equal to 0.5 (IPCC, 2006). Hence, an $EF_{st}$ value of 0.125 kg $CH_4$ per kg COD.

The fraction of the population, *P*, not connected to the collective sewer system, $f_{nc}$, is set equal to 10 % for the entire time series estimated from National statistics of scattered settlements in percent of the total number of households in Denmark (DME, 2014; Statistics Denmark).

Lastly, the default IPCC value of the per capita produced degradable organic matter, $DOC_{st}$, i.e. 22.63 kg BOD per person corresponding to 56.6 kg COD per person (IPCC, 2006), were used in place of default value of 18.25 kg BOD per 1000 persons per year according to the old IPCC guidelines (IPCC, 1996).

## 2.3 Activity data and Emission Factors – $CH_4$ emission

The "TOW, average" represents a key activity data set for deriving methane emissions from anaerobic and aerobic wastewater treatment processes (subchapter 2.1.1 and 2.1.2). Table 2.1 shows a first extract of a plant level data from a database especially developed with the purpose of performing plant level emission inventories for sector 5D wastewater treatment and discharge. For details regarding the calculation of "TOW, average" the reader is referred to Annex A. COD data, Table A 1.

Table 2.1 Total organic waste in the influent wastewater at Danish WWTPs measured in tonne COD.

| Year | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 | 2012 | 2013 |
|---|---|---|---|---|---|---|---|---|
| TOW, country data | 294,772 | 327,284 | 364,655 | 363,571 | 372,330 | 377,754 | 363,881 | 382,778 |
| TOW, plant level data | NA | NA | 350,689 | - | 369,873 | 371,713 | 349,876 | 386,151 |
| Fraction of the TOW entering WWTPs using anaerobic sludge digestion, % | 36 | 47 | 48 | 48 | 48 | 42 | 31 | 36 |
| Fraction of the TOW entering WWTPs using aerobic sludge stabilization, % | 64 | 53 | 52 | 52 | 52 | 58 | 69 | 64 |
| TOW entering WWTPs using anaerobic sludge digestion | 105,777 | 153,561 | 176,671 | 173,898 | 177,359 | 159,189 | 113,942 | 137,456 |
| TOW entering WWTPs using aerobic sludge stabilization | 188,995 | 173,723 | 187,984 | 189,672 | 194,971 | 218,565 | 249,939 | 245,322 |

*COD data calculated from modified BOD measurements multiplied by the COD/BOD conversion factor of 2.4. For a complete presentation of the dataset used for deriving the "TOW, average", which are the activity data set used in the emission inventory the reader is referred to Annex A, Table A1.1.

The activity data entitled "TOW, country level data" in Table 2.1 are based on reported BOD data converted into COD by multiplying with the default COD/BOD conversion factor of 2.4 (IPCC, 2006).

The "TOW, plant level data" are based on plant level COD monitoring data from the monitoring program published by the Danish Nature Agency (DME, 1992, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003a, 2004a, 2005, 2007, 2008, 2009a, 2010, 2012a, 2012, 2013, 2014; DMEE, 1994a and 1994b, 1995b, 1999b) and the Danish water quality database (www.miljoeportalen.dk). Data from the Danish water quality database consists of plant level unpublished monitoring data, which are part of the National Monitoring and Assessment Programme for the Aquatic and Terrestrial Environments.

The "TOW, plant level data" are furthermore part of a database designed specifically for the Danish emission inventories for the sector 5B Wastewater treatment and discharge, in which plant level IDs from the Danish monitoring program has been paired with plant level data from the Danish Energy Agency. Based on the present quality assurance of data, Table 2.1 shows that the plant level data closely resembles the country level data reported by the Danish Nature Agency. The plant level database allow for a differentiation between Danish WWTPs with, aerobic sludge stabilisation and anaerobic sludge digestion respectively (Table 2.2).

In this way, the total amount of organic matter in the influent wastewater, *TOW*, is used for estimating the unintentional methane emission from aerobic processes at both plant types. Aerobic processes comprise emissions from the sewer system, mechanical and aerobic biological treatment processes (see sub-chapter 2.1.12.2.1).

The fraction of the total TOW in Danish influent wastewater entering WWTPs using sludge digestion as sludge management strategy (Annex A, Table A 3) quantifies the key parameter $TOW_{influent,\ anaerobic}$ in sub-chapter 2.1.2 on methane emission from anaerobic sludge digestion.

### 2.3.1 Wastewater treatment processes

The methane emissions from sewer, mechanical and aerobic biological treatment are common treatment steps for respectively all WWTPs whether they apply anaerobic digestion or aerobic stabilization as sludge management strategy (Jensen et al., 2015; Thomsen et al., 2015). For this reason, the activity data used for calculating the methane emission from sewer, mechanical, and biological treatment processes is the total national COD in the influent wastewater. Table 2.2 shows the TOW and resulting methane emission from mechanical and biological wastewater treatment processes allocated according to the percent influent COD at WWTPs with anaerobic and aerobic sludge management strategies (Annex A, Table A.3).

Table 2.2 Amounts of TOW in the influent wastewater according to WWTP types (anaerobic sludge digestion and aerobic sludge stabilization), and $CH_4$ emissions from sewer system, mechanical and aerobic biological treatment steps.

| Year | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 | 2012 | 2013 |
|---|---|---|---|---|---|---|---|---|
| *TOW*, [tonne COD] | 294,772 | 327,284 | 364,655 | 363,571 | 372,330 | 377,754 | 363,881 | 382,778 |
| $TOW_{influent,\ anaerobic\ WWTP}$ [% COD] | 36 | 47 | 48 | 48 | 48 | 42 | 31 | 36 |
| $TOW_{influent,\ aerobic\ WWTP}$ [% COD] | 64 | 53 | 52 | 52 | 52 | 58 | 69 | 64 |
| $TOW_{influent,\ anaerobic\ WWTP}$ [tonne COD] | 105,777 | 153,561 | 176,671 | 173,898 | 177,359 | 159,189 | 113,942 | 137,456 |
| $TOW_{influent,\ aerobic\ WWTP}$ [tonne COD] | 188,995 | 173,723 | 187,984 | 189,672 | 194,971 | 218,565 | 249,939 | 245,322 |
| $CH_{4sewer+MB,\ anaerobic\ WWTP}$ [Gg $CH_4$] | 0.08 | 0.12 | 0.13 | 0.13 | 0.13 | 0.12 | 0.09 | 0.10 |
| $CH_{4sewer+MB,\ aerobic\ WWTP}$ [Gg $CH_4$] | 0.14 | 0.13 | 0.14 | 0.14 | 0.15 | 0.16 | 0.19 | 0.18 |
| $CH_{4sewer+MB,\ total}$ [Gg $CH_4$][1] | 0.22 | 0.25 | 0.27 | 0.27 | 0.28 | 0.28 | 0.27 | 0.29 |

[1] $EF_{sewer+MB} = B_o * MCF_{sewer+MB}$ and $MCF_{sewer+MB}$ = 0.003 and $B_o$ = 0.25 kg $CH_4$ per kg COD.

As mentioned in Chapter 2.1.1, the emission factor for mechanical and biological wastewater treatment processes are set equal to 0.00075 kg $CH_4$/kg COD in the influent wastewater with no further distinction between plant types as all WWTPs include an aerobic biological wastewater treatment step prior to aerobic sludge stabilization or anaerobic sludge digestion.

### 2.3.2 Anaerobic digestion

TOW data in the influent wastewater is a key parameter for calculating the methane emission from anaerobic digestion. Formerly, the fraction of sludge treated by anaerobic digestion was quantified by data on sludge statistics (Nielsen et al., 2013; Thomsen and Lyck, 2005). The sludge database, however, no longer exists (DMEE, 1999a and 2001; DME, 2003b, 2004b, 2009b and 2012b). For this reason, the methodological approach for quantifying the amount of sludge treated by anaerobic digestion is no longer based on sludge statistics, but on statistics on influent TOW data received at plant types including anaerobic digester tanks for biogas production (cf. Table 2.3).

At two-step plants, up to around 40 % of the COD in the influent wastewater, i.e. primary sludge from the primary clarifier tank, may be used as ingestate for the anaerobic digester tank (Figure 3.1 and Jensen et al., 2015; Thomsen et al., 2015).

Table 2.3 shows the development in TOW entering WWTPs with anaerobic sludge digestion, the fraction of COD conserved in the ingestate and the resulting gross methane production potential from WWTPs using anaerobic sludge digestion as sludge management strategy.

Table 2.3 Activity data and model parameters for WWTPs using anaerobic sludge digestion as sludge management strategy.

| Year | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 | 2012 | 2013 |
|---|---|---|---|---|---|---|---|---|
| $TOW_{influent,\ total}$ [tonne COD] | 294,772 | 327,284 | 364,655 | 363,571 | 372,330 | 377,754 | 363,881 | 382,778 |
| Fraction of TOW in influent at anaerobic WWTPs [%][1] | 36 | 47 | 48 | 48 | 48 | 42 | 31 | 36 |
| $TOW_{influent,\ anaerobic\ plants}$ [tonne COD][2] | 105,777 | 153,561 | 176,671 | 173,898 | 177,359 | 159,189 | 113,942 | 137,456 |
| $f_{AD}$[2] | 0.44 | 0.40 | 0.48 | 0.52 | 0.57 | 0.54 | 0.54 | 0.56 |
| $COD_{ingestate}$ [tonne COD][2] | 46,542 | 61,425 | 84,802 | 89,732 | 100,740 | 85,325 | 61,073 | 76,975 |
| $B_o*MCF*f_{AD}$ [tonne $CH_4$/ tonne COD][2] | 0.09 | 0.08 | 0.10 | 0.10 | 0.11 | 0.11 | 0.11 | 0.11 |
| $CH_{4AD,gross}$ [Gg $CH_4$][2] | 9.31 | 12.28 | 16.96 | 17.95 | 20.15 | 17.07 | 12.21 | 15.40 |

[1]Annex A, Table A 3.

[2] Equation 4a and Annex A, Table A 2.

For WWTPs with anaerobic sludge digestion it is assumed that they belong to the WWTPs, which have implemented advanced treatment technologies, i.e. MBNDC type WWTPs ranging from 10 % in 1990 to more the 90 % in 2013 (Table 2.1). The fraction of the influent TOW reaching the digester tank, $f_{AD}$, is based on intra-calibration according to knowledge about the reduction efficiency of COD in the effluent wastewater, the amount of recovered methane and final sludge amounts. The full time series of the percent distribution of COD calibrated against these known parameters are provided in Annex A, Table A 2.

In this year´s inventory, the methane emission from anaerobic digestion is still calculated according to equation 5, meaning that the recovered methane is calculated from the reported gross energy production (energy recovery and flaring) multiplied by an EF value of 0.013 assuming that 1.3 % of the gross energy production is lost as methane. For the moment, the EF is kept constant throughout the time series.

### 2.3.3 Scattered settlements

Activity data used for deriving methane emissions for the fraction of the population, not connected to the collective sewer system are shown in Table 2.4.

Table 2.4 Amount of TOW produced by households not connected to the collective sewer system.

| Year | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 | 2012 | 2013 |
|---|---|---|---|---|---|---|---|---|
| Population not connected to sewers, $P*f_{nc}$ | 513,541 | 521,572 | 533,002 | 541,141 | 553,474 | 556,063 | 558,052 | 560,263 |
| COD, septic tanks [tonne COD] | 27,891 | 28,328 | 28,948 | 29,390 | 30,060 | 30,201 | 30,309 | 30,429 |
| $CH_4$, septic tanks [Gg $CH_4$] | 3.49 | 3.54 | 3.62 | 3.67 | 3.76 | 3.78 | 3.79 | 3.80 |

It is assumed that half suspended organic matter settles in the septic tank. The MCF is therefore set equal to 0.5 throughout the time series and an emission factor of 0.125 $CH_4$ per kg COD is obtained according to the IPCC default parameters.

For scattered settlements, the fraction of the population not connected to the collective sewer system has been set equal to 10 %, $P*f_{nc}$, which is low compared to statistics on residential property types included in the category "scattered settlements" (e.g. DME, 2014), however, scattered housing includes allotments and summer houses that are not used all year. For further details, the reader is referred to Chapter 3 on verification and Annex B. , Table B 5.

## 2.4 National Methodology - Nitrous oxide emission

$N_2O$ formation and releases both during the treatment processes at the WWTPs and from discharged effluent wastewater are included. The emission of $N_2O$ from wastewater treatment and discharge is calculated as the sum of contributions from wastewater treatment processes at the WWTPs and from sewage effluents. The emission from effluent wastewater, i.e. indirect emissions, includes separate industrial discharges, rainwater-conditioned effluents, scattered settlements and aquaculture.

### 2.4.1 $N_2O$ emissions - Wastewater treatment processes

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 nitrous oxide emissions from wastewater treatment processes are calculated according to equation 7:

$$N_2O_{direct} = EF_{N_2O,direct} \cdot \left(m_{N,influent} + m_{N,reject}\right) \quad \text{Eq. 7}$$

where

$N_2O_{direct}$ refers to the process related emissions of $N_2O$

$EF_{N2O,direct}$ is set equal to 4.99 g $N_2O$ per kg N in the influent wastewater

$m_{N,influent}$ is the total amount of N in the influent wastewater monitored and reported by the Nature Agency (section 2.1)

$m_{N,reject}$ is the amount of N in the reject water originating from dewatering of biogasified sludge at WWTPs adding external carbon to ingestate, taking into account the technology design; e.g. whether or not the specific plant have implemented Anammox (an alternative N removal technology that removes N without microbial use of COD) on the reject water to remove the additional N content introduced via the additional biomass digested (Thomsen et al., 2015).

### 2.4.2 $N_2O$ emission from wastewater discharges

The indirect emission of $N_2O$ from wastewater treatment plants refers to emission from the effluent wastewater as are calculated according to equation 8:

$$N_2O_{indirect} = EF_{N_2O,indirect} \cdot m_{effluent} \cdot \left(M_{N_2O} / M_{N_2}\right) \qquad \text{Eq. 8}$$

where

$EF_{N2O,indirect}$ equals 0.005 kg $N_2O$-N/kg effluent N (IPCC, 2006)

$M_{N2O}/M_{N2}$ is the molecular mass ratio between $N_2O$ and $N_2$ that transforms the mass u in unit of N into unit of $N_2O$.

Besides effluent from wastewater treatment plants, additional contributions to indirect $N_2O$ emissions results from effluent from the separate industry, effluent from aquaculture, rainwater conditioned effluents and scattered settlements. The amount of N in the effluent wastewater is monitored by the National monitoring program of the aquatic environment and nature (section 2.1).

## 2.5 Activity data and Emission Factors – $N_2O$ emissions

### 2.5.1 Wastewater treatment processes

The content of N in the influent wastewater at the Danish WWTPs represents a key activity data set for calculating the direct $N_2O$ emissions from wastewater treatment.

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. 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 anaerobic conditions. Upon successive denitrification, free nitrogen is a gas that bubbles out of the wastewater. However, challenges in the design of alternating aerobic and anaerobic conditions in the biotank result in the emission of nitrous oxide (Kimochi et al., 1998; Tallec et al., 2006 and 2008).

The $N_2O$ emission depends on several factors, such as pH, temperature, $NO_3^-$, oxygen and COD content in a complex pattern not yet fully understood (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. (2006), reporting the $N_2O$ emissions to be positively related to oxygenation ($R^2 = 0.99$) during nitrification. Danish wastewater treatment plants have COD/N ratios in the influent wastewater in the range of 12-16 (Table 2.5).

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 %, 0.001-0.006 % and 1.1-3.8 %. This study does not report on the amount of inflowing N, whereas Adouani et al., 2009 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 (e.g. Kampschreur et al., 2009). A recent review of $N_2O$ emissions from wastewater treatment (Kampschreur et al., 2009) gives a thorough overview of existing studies showing a huge variation and uncertainty in the $N_2O$ emission ranging between 0 and 95 % at lab-scale and in the range of 0-14.5 % 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 physico-chemical operational condition, micro-organisms composition and activity exists (Sivret et al., 2008) and measurements on $N_2O$ emission in Denmark are scarce according to the knowledge of the authors (Thomsen et al., 2015). Nitrous oxide emission occur 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). The average of the two highest EF values from activated sludge processes was used to derive a national EF value of 0.32 % of the N content of the influent wastewater (Nielsen et al., 2014). The latter derived from an average of 0.6 and 0.035 % of the influent N multiplied by the ratio of the molecular weight of $N_2O$ to $N_2$ and corresponds to an EF value of 4.99 in units of g $N_2O$/kg N in the influent wastewater.

The above emission factor is in good agreement with a recent Dutch study (Daelman et al., 2013; Thomsen et al., 2015) that indicates a $N_2O$ emission factor of 28 g $N_2O$-N/kg of nitrogen in the influent wastewater. Danish studies show that the country specific emission factor, i.e. 24 g $N_2O$/PE in 2013 represents the higher end of measurements carried out at Danish wastewater treatment plants. Measurements performed at a high and low loaded WTTP in Denmark reveals an EF value in the range of 9 to 28 g $N_2O$/PE/ year (Thomsen et al., 2015). As such, the country specific EF value represents a conservative estimate of the direct $N_2O$ EF. The EF value in units of g $N_2O$/PE has increased from 14 g $N_2O$/PE in 1990 to 24 g $N_2O$/PE in 2013. This increase do not reflect an increase in the population alone, but to a higher degree an increase in the contribution from industries to the N load of the influent wastewater. For this reason, and due to the fact that we have monitoring data on the influent amount of N, we use the emission factor 4.99 g $N_2O$/kg N in the influent wastewater. As such the country specific emission factor is kept constant throughout the time series; the increase in the direct $N_2O$ emission is to be found in the increasing amount of N in the influent wastewater. Still the emission factor is conservative compared to the IPCC guidelines, which provides an emission factor of 3.2 g $N_2O$/PE, representing a significant underestimation of the direct $N_2O$ emission according to Danish state-of-art wastewater treatment technologies.

Table 2.5 shows, in addition to the activity data on the total influent amount of N, plant level data on the N content in the influent wastewater compared to national totals reported by the Danish Nature Agency revealing good agreement between the plant level database developed for future emission calculations and national data reported by the Danish Nature Agency.

Table 2.5 Total nitrogen content in the influent wastewater at Danish WWTPs, reported in units of tonne TN.

| Year | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 | 2012 | 2013 |
|---|---|---|---|---|---|---|---|---|
| $m_{N,influent,}$ country level, [tonne][1] | 14,679 | 22,340 | 26,952 | 32,288 | 27,357 | 30,049 | 26,316 | 29,557 |
| $m_{N,influent}$, plant level, [tonne[1] | - | - | 27,306 | - | 27,357 | 28,989 | 26,316 | 29,557 |
| $m_{N,influent,}$,anaerobic WWTPs, [tonne][2] | - | - | 14,779 | - | 12,855 | 11,829 | 7,416 | 10,317 |
| $m_{N,influent,}$,aerobic WWTPs, [tonne] [2] | - | - | 12,527 | - | 14,502 | 17,160 | 18,901 | 19,240 |
| $N_{influent}$ _anaerobic WWTPs, [%] | - | - | 54 | - | 47 | 41 | 28 | 35 |
| $N_{influent}$ _aerobic WWTPs, [%] | - | - | 46 | - | 53 | 59 | 72 | 65 |
| COD/N ratio, plant level, all | - | - | 13 | - | 14 | 12 | 13 | 13 |
| Contribution from industrial inlet [%] | 2.5 | 22.2 | 42.0 | 40.5 | 40.5 | 40.5 | 40.5 | 40.5 |
| Population-Estimates (1000) | 5,135 | 5,216 | 5,330 | 5,411 | 5,535 | 5,561 | 5,581 | 5,603 |

[1]DMEE, 1989, 1990 1992, 1994a, b, 1995a,b; DME 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003a, 2004a,2005, 2006, 2007, 2008, 2009a, 2010, 2011, 2012a, 2013, 2014.

[2]Selective extraction of plant level data on reported amounts of N in the influent wastewater for plants included in the Energy Producer Accounts (DEA, 2014).

At present, country level activity data has been used for calculation the nitrous oxide emissions from the Danish WWTPs as the present methodology do not differentiate between individual plant designs, e.g. with and without a biogas tank, struvite precipitation, etc. (Jensen et al., 2015; Thomsen et al., 2015). However, by combining plant level data from the energy producer accounts and the plant level data on nitrogen, it is possible to calculate the amount of N received at biogas producing plants, i.e. WWTPs having a biogas tank connected to the sludge line of the wastewater treatment plant (see Figure 3.1). Such data are presented in the third row of Table 2.5.

When calculating the nitrous oxide emission (see Chapter 2.3) it is assumed that approximately 90 % of the nitrous oxide emission originates from activated sludge processes; i.e. biological N and P removal processes performed by bacteria and microorganisms (Kampschreuer et al., 2009) occurring mainly prior to anaerobic digestion (Figure 3.1), aerobic stabilisation and additional treatment processes. For this reason, the methodology used for calculating the $N_2O$ emission is the same for both plant types and the activity data used is the total amount of nitrogen in the influent wastewater provided in the first two rows of Table 2.5. The amount of N in the influent wastewater has increased by approximately 100 % since 1990; the latter caused by an increase in number of industries coupled to the public sewer system and increased population size (Table 2.5 and Nielsen et al., 2014).

### 2.5.2 Separate Industries

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, 1990). In the period 1985-1990, industries have implemented wastewater treatment technologies and less polluting processes resulting in a reduction of 80 % of the total industrial effluent amount of COD (DME, 1990 and 1998; Annex D, Table D.2). The total nitrogen discharge from industrial sources was reduced by around 80 % through the period 1989-98, while the discharge of phosphorus was reduced by approximately 90 % (DME, 1998). According to the knowledge of the author, the general picture is that no methane emission is occurring from separate industries. At present, only one industry is reporting biogas production to the Danish Energy Agency, which is included in the calculated amount of methane emitted and recovered from WWTP with anaerobic sludge digestion. The direct $N_2O$ emissions from separate industries have not been included in the National Inventory due to missing data. A first attempt to include direct $N_2O$ emissions from separate industries is presented in Annex E.

### 2.5.3 Wastewater discharges

For the wastewater discharges, the default IPCC emission factor of 0.005 kg $N_2O$-N per kg effluent N is used (IPCC, 2006). Discharges of N contained in effluent wastewater are comprised by: Effluent N from wastewater treatment plants, the separate industry, aquaculture, rain water conditioned effluents and scattered settlements. Activity data used for calculating $N_2O$ emission from wastewater discharges of N to surface waters in the national inventory are presented in Table 2.6 (DME, 1992, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003a, 2004a, 2005, 2007, 2008, 2009a, 2010, 2012a, 2012, 2013, 2014; DMEE, 1994a and 1994b, 1995b, 1999b)

Table 2.6 N discharged with wastewater from different sources, [tonne N].

| Year | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 | 2012 | 2013 |
|---|---|---|---|---|---|---|---|---|
| Effluent from separate industry discharges | 2,574 | 2,471 | 897 | 441 | 338 | 312 | 221 | 271 |
| Rainwater conditioned effluent | 921 | 867 | 762 | 622 | 762 | 703 | 729 | 1045 |
| Effluent from scattered settlements | 1,280 | 1,141 | 979 | 919 | 902 | 859 | 825 | 796 |
| Effluent from aquaculture | 1,737 | 1,735 | 2,714 | 1,225 | 933 | 1019 | 973 | 634 |
| Effluent from WWTPs | 16,884 | 8,938 | 4,653 | 3,831 | 4,025 | 3,916 | 3,849 | 3,652 |
| Total effluent N | 23,396 | 15,152 | 10,005 | 7,038 | 6,960 | 6,809 | 6,597 | 6,399 |

As may be observed from Table 2.6, the content of N in effluent wastewater is reduced by 78 % from 1990 to 2013. Effluents from separate industries has decreased by 89 % from 1990 to 2013 and in the same time interval the effluent N form scattered housed has decreased by 38 %; the latter may be explained by a reduction in the number of settlements(Annex B, Table B 2) reported to be reduced by 7 % (DME, 2015). Another cause for the reduction may be assigned to an improved treatment of wastewater within the scattered settlements (DME, 2015). The only source showing an increasing trend is the amount of N discharged to surface water in rainwater conditioned effluents, which has increased by 13 % from 1990 to 2013.

# 3 Verification

## 3.1 $CH_4$ emissions

Until the reporting year 2009, the emission factor used to calculate the potential methane production from anaerobic wastewater treatment processes was based on activity data extracted from the Danish sludge database, which has been closed down (Bagge, personal communication, February, 2013). Sludge statistics on the fraction of final sludge produced from anaerobic digestion were used as correction factor to derive at an $EF_{AD}$ for the estimation of a gross methane conversion potential (Nielsen et al., 2009). The recovered (flared and used for energy production) amount of methane were estimated by summing up estimated amount of methane potential in different sludge disposal categories including sludge digested in a biogas reactor. The net methane emission was derived by subtraction the recovered amount of methane from the gross methane conversion potential.

Due to the low quality of data, including frequency of reporting, the activity data for the final disposal categories used for estimating the recovered amount of methane was underestimated, resulting in unrealistic high net methane emissions from wastewater treatment (Nielsen et al., 2009). For this reason, an inter-ministerial expert group recommended that the value of the theoretical emission factor for the fraction of sludge treated by anaerobic digestion only was defined. Based on the recommendation, the fractions of anaerobic and aerobic treated sludge were estimated, and used to derive an emission factor for the anaerobic digestion. Based on this change in methodology, the fugitive methane was at first estimated to be 10 % of the gross methane emissions (Nielsen et al., 2010).

From the reporting year 2011 until present, the methane recovery for anaerobic wastewater treatment with biogas production was set equal to 99 %; i.e. a reduction of the methane emission factor from 10 to 1 % of the biogas production (Nielsen et al., 2011). The UNFCCC review team were however, not satisfied with the approach of quantifying the methane emission factor; i.e. as (1- $MR_{AD}$); $MR_{AD}$, the methane recovery, being defined as the Danish biogas generation and combustion efficiency of 99 % (UNFCCC, 2013). For this reason a review of plant specific data were initiated with the purpose of identifying process emissions from the biogas production at wastewater treatment plants, and emissions reported as biogas loss by venting were presented in Nielsen et al. (2014). Data on biogas lost via venting is scarce but based on a review of environmental account data reported voluntary by the single WWTPs the value used presently is 1.3 % of the gross energy production as documented in Nielsen et al. (2014). The UNFCCC review team is still not satisfied with the transparency and completeness in the national activity data and derived emissions factor, recommended better documentation (UNFCCC, 2013, 2014). For this reason, this chapter presents an overview and comparison of different data sources with the aim of further verification of the selected EF value used in the Danish emission inventory.

### 3.1.1 Completeness in TOW data

From the reporting year 2015 and forward, the total organic waste (*TOW*) entering the Danish WWTPs is quantified in units of COD. A plant level COD database has been designed for use in future plant level emission modelling. Plant level COD data have been verified to sum up to the yearly national level reported COD data by the Danish Nature Agency as shown in Table 3.1.

Table 3.1 TOW data (DMEE, 1989, 1990 1992, 1994a, b, 1995a, b; DME 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014)[6].

| Unit of measure [tonne COD] | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 | 2012 | 2013 |
|---|---|---|---|---|---|---|---|---|
| *TOW*, country data[1] | - | - | 381,700 | 357,842 | 369,873 | 386,223 | 349,876 | 386,151 |
| *TOW*, plant level data[2] | - | - | 350,689 | - | 369,873 | 371,713 | 349,876 | 386,151 |
| *TOW*, default COD IPCC[3] | 278,914 | 283,276 | 289,484 | - | 300,603 | 302,009 | 303,089 | 304,290 |
| Contribution from industrial COD in the inlet [%] | 2.5 | 22.2 | 42.0 | 40.5 | 40.5 | 40.5 | 40.5 | 40.5 |
| *TOW*, default COD IPCC, corrected[4] | 285,887 | 346,163 | 411,067 | 293,904 | 422,304 | 424,279 | 425,797 | 427,527 |
| *TOW*, National Unit PE BOD value[5] | 303,657 | 308,405 | 315,164 | 412,893 | 327,269 | 328,800 | 329,976 | 331,283 |
| *TOW*, average | 294,772 | 327,284 | 364,655 | 319,976 | 372,330 | 377,754 | 363,881 | 382,778 |
| Percent standard deviation [%] | 4.4 | 10.1 | 15.4 | 23.8 | 15.0 | 15.0 | 15.0 | 15.2 |

[1]"TOW, country data" are based on reported BOD data converted into COD by multiplying with the default COD/BOD conversion factor of 2.4 (IPCC, 2006).

[2]"TOW, plant level data" are based on plant level COD monitoring data that were extracted from respectively reports from the Danish Nature Agency and the Danish water quality database (www.miljoeportalen.dk).

[3]"TOW, default COD IPCC" are the default IPPC PE value of 62 g BOD/person/day multiplied by the default COD/BOD conversion factor of 2.4 (IPCC, 2006) multiplied by the population number of Denmark.

[4]"TOW, default COD IPCC, corrected" are the above corrected for the contribution from industries connected to the collective sewer system in Denmark.

[5]"TOW, National Unit PE BOD value" are the national BOD value of 21.9 kg BOD per year (www.mst.dk) multiplied by a national COD/BOD conversion factor of 2.7 obtained as an average of the yearly reported BOD and COD monitoring data throughout the time series and multiplied by the population number of Denmark.

*Data for the whole time series provided in Annex 1, Table 1.1.1.

The "*TOW*, average" is used as the key activity data set for deriving methane emissions from wastewater treatment. "TOW, average" is the average of available data throughout the time series. The relative standard deviation is above the 10 % provided in the NIR for the majority of the cases (Nielsen et al., 2015). However, upon using the plant level data, the uncertainty is insignificant as may be observed from comparing the national level country data reported by the Danish Nature Agency and our extracted plant level data in the two first rows of Table 3.1.

The "*TOW*, plant level data" are part of a database, designed specifically for the emission inventories, in which plant level data from the Danish monitoring program are paired with plant level data from the Danish Energy Agency. Country level data are the sum of the yearly monitoring data for the Danish WWTPs, while the plant level data consists of data from the water quality database. These data have been going through a quality control process to be sure that our plant level data resembles the yearly reported national sum as reported by the Danish Nature Agency. A first version of the plant level data is presented in the Table 3.1 showing that the plant level data resembles the country level data reported by the Danish Nature Agency (Data for the whole time series are provided in Annex A, Table A 1).

The average TOW data was used to allocate COD in the influent wastewater treated at WWTP using, respectively, aerobic stabilization and anaerobic digestion as sludge management strategy (Table 3.11 and Annex A, Table A 3). The allocation was performed by identifying and coupling plant level data from the water quality database with plant level data on energy production from sludge-based biogas plant; i.e. the anaerobic digester tank at the Danish WWTPs.

Besides COD in the influent wastewater, data are also available on COD in the effluent wastewater and for primary, secondary and post digested sludge (Henze et al., 2010; Thomsen et al., 2015). Furthermore, COD data are measured and reported by the WWTPs themselves in the so-called Environmental Reports, which, in some cases, are published on a yearly basis as part of their continuous control, monitoring and optimization of their treatment technologies. The plant level environmental reports also include information about external carbon received as additional supply for biogas and fertilizer production at some WWTPs (cf. Chapter 3.1.3). As such, the plant level environmental reports represent a third data source in addition to the activity data reported by the Danish Nature Agency and the Danish Energy Agency.

### 3.1.2 COD mass balance – National level

An example of a COD mass balance for centralised Danish wastewater treatment plants treating the sludge by anaerobic digestion anno 2015 is visualised in Figure 3.1.

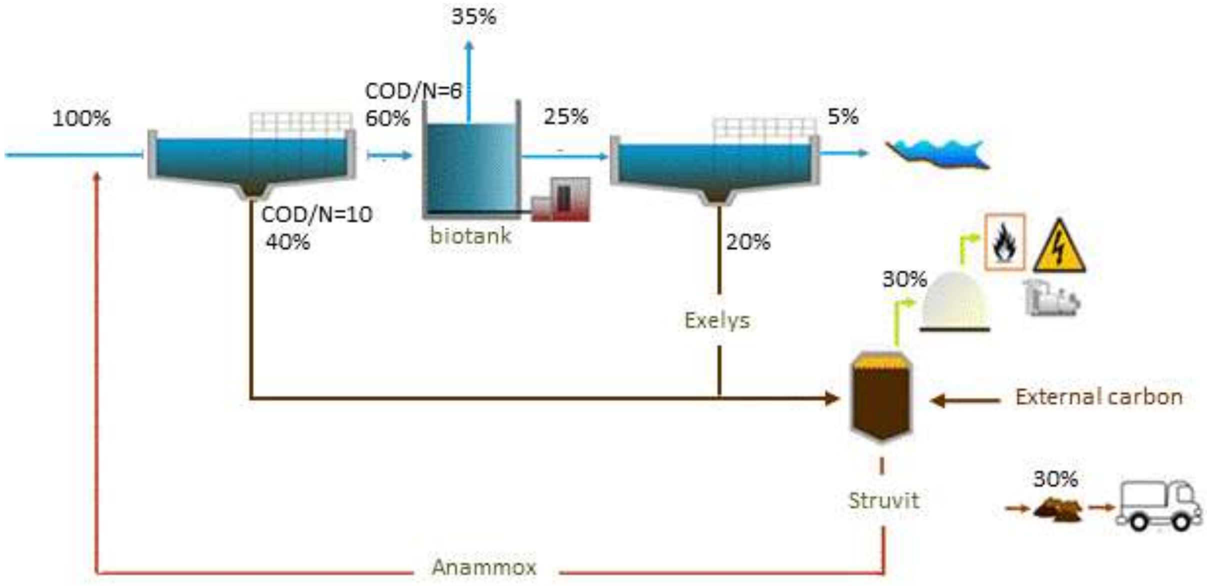


Figure 3.1 Visualization of the treatment steps and conversion processes that may be in play at Danish wastewater treatment plants. The most important for the present methodology report being the biotank, i.e. aerobic biological treatment, and brown the box in which anaerobic digestion takes place. Exelys is a sludge hydrolysis technology, which increases the methane conversion potential by increasing the biodegradable fraction of carbon in the ingestate, struvite precipitation as an example of a technology for N and P capture and reuse technology that reduces the N content in the reject water and thereby potentially the $N_2O$ emission. Anammox representing an alternative N removal technology that removes N without microbial use of COD. Struvite precipitation and Anammox implemented at the reject water line supports a favourable COD/N ratio needed for optimal condition for conventional biological N removal in the biotank. N removal from the reject water becomes more important upon the use of externally supplied biomass for codigestion with the sludge to increase the bioenergy production (Thomsen et al., 2015).

In accordance with the recommendation of the UNFCCC review team, a TOW budget for the whole time series was set up, in units of Chemical Oxygen Demand (COD), according to Eq. 9, which follows the principle of equation 6.1 in the IPCC guidelines (IPCC, 2006):

$$COD_{influent} + COD_{external\ carbon} - (COD_{effluent} + COD_{final\ sludge} + COD_{air\ emission,\ biotank} + COD_{recovered}) = COD_{vented} \quad \text{Eq. 9}$$

where

$COD_{influent}$ is the organic matter in the influent wastewater

$COD_{external\ carbon}$ is the external organic matter added to the digester tank

$COD_{effluent}$ is the organic matter in the effluent wastewater

$COD_{final\ sludge}$ is the organic matter in the final sludge

$COD_{air\ emission,\ biotank}$ is the amount of organic matter that are transformed to gas during the biological treatment processes

$COD_{recovered}$ is the organic matter transformed into biogas either converted into energy or flared

$COD_{vented}$ is the organic matter converted into biogas, but lost via venting

The mass balance visualised in Figure 3.1 is a reproduction from Petersen (2013), representing a two-step plant with anaerobic sludge digestion and advanced technologies as described in more detail in Thomsen et al., 2015. For the WWTP using aerobic stabilization a simplified version of equation 9 was adopted as shown below.

$$COD_{influent} - (COD_{effluent} + COD_{final\ sludge} + COD_{air\ emission,\ biotank}) = 0 \quad \text{Eq. 10}$$

The national level COD mass balances for the whole time series and for both WWTPs with anaerobic digestion and aerobic stabilization aligned according to reported data on effluent COD, energy statistics and final sludge amounts may be presented as shown in Table 3.2 (Data for the whole time series provided in Annex A, Table A 2).

Table 3.2 COD mass balance for Danish WWTPs, [tonne COD][*].

| Year | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 | 2012 | 2013 |
|---|---|---|---|---|---|---|---|---|
| COD mass balance for WWTPs with aerobic sludge treatment | | | | | | | | |
| Biotanks, $COD_{air\ emission}$ [%] | 30 | 45 | 60 | 60 | 60 | 60 | 60 | 60 |
| Effluent, $COD_{effluent}$ [%] | 52 | 7 | 5 | 5 | 4 | 8 | 8 | 5 |
| Final sludge, $COD_{sludge}$ [%] | 18 | 48 | 35 | 35 | 36 | 32 | 32 | 35 |
| Influent, $COD_{influent}$ [tonne] | 188,995 | 173,723 | 187,984 | 189,672 | 194,971 | 218,565 | 249,939 | 245,322 |
| Biotanks, $COD_{air\ emission}$ [tonne] | 56,698 | 78,175 | 112,791 | 113,803 | 116,983 | 131,139 | 149,963 | 147,193 |
| Effluent, $COD_{effluent}$ [tonne] | 97,360 | 11,835 | 9,399 | 10,432 | 7,799 | 17,485 | 19,995 | 12,266 |
| Final sludge, $COD_{sludge}$ [tonne] | 34,936 | 83,713 | 65,795 | 65,437 | 70,190 | 69,941 | 79,980 | 85,863 |
| Eq.10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| COD mass balance for WWTPs with anaerobic sludge treatment | | | | | | | | |
| Biotanks, $COD_{air\ emission}$ [%] | 20 | 30 | 35 | 30 | 25 | 25 | 25 | 25 |
| Effluent, $COD_{effluent}$ [%] | 25 | 20 | 5 | 5 | 4 | 8 | 8 | 5 |
| Digester tank, $COD_{ingestate}$ [%] | 44 | 40 | 48 | 52 | 57 | 54 | 54 | 56 |
| Final sludge, $COD_{sludge}$ [%] | 11 | 10 | 12 | 13 | 14 | 13 | 13 | 14 |
| Recovered, $COD_{recovered}$ [%] | 43 | 39 | 47 | 51 | 56 | 53 | 53 | 55 |
| Vented, $COD_{vented}$ [%] | 0.6 | 0.5 | 0.6 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |
| Influent, $COD_{influent}$ [tonne] | 105,777 | 153,561 | 176,671 | 173,898 | 177,359 | 159,189 | 113,942 | 137,456 |
| Biotanks, $COD_{air\ emission}$ [tonne] | 21,155 | 46,068 | 61,835 | 52,170 | 44,340 | 39,797 | 28,486 | 34,364 |
| Effluent, $COD_{effluent}$ [tonne] | 26,444 | 30,712 | 8,834 | 9,564 | 7,094 | 12,735 | 9,115 | 6,873 |
| Ingestate, $COD_{ingestate}$ [tonne] | 58,177 | 76,781 | 106,003 | 112,164 | 125,925 | 106,657 | 76,341 | 96,219 |
| Final sludge, $COD_{sludge}$ [tonne] | 11,635 | 15,356 | 21,201 | 22,433 | 25,185 | 21,331 | 15,268 | 19,244 |
| Recovered, $COD_{recovered}$ [tonne] | 45,937 | 60,626 | 83,700 | 88,565 | 99,430 | 84,216 | 60,279 | 75,974 |
| Vented, $COD_{vented}$ [tonne], Eq. 9 | 605 | 799 | 1,102 | 1,167 | 1,310 | 1,109 | 794 | 1,001 |
| Verification of final sludge amounts | | | | | | | | |
| COD in digestate [tonne COD/tonne DM] | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 |
| Inorganics in digestate [%] | 40 | 40 | 40 | 30 | 30 | 30 | 30 | 30 |
| COD in aerobic stabilized sludge [tonne COD/tonne DM] | 1.20 | 1.20 | 1.20 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Inorganics in aerobic stabilized sludge [%] | 50 | 50 | 50 | 40 | 40 | 40 | 40 | 40 |
| Estimated amount of digestate [tonne DM] | 24,241 | 31,992 | 44,168 | 40,059 | 44,973 | 38,092 | 27,265 | 34,364 |
| Estimated amount of aerobic stabilized sludge [tonne DM] * | 77,844 | 198,661 | 157,393 | 108,536 | 116,689 | 115,979 | 132,709 | 142,734 |
| Estimated amount of total final sludge [tonne DM]* | 102,085 | 230,653 | 201,561 | 148,595 | 161,663 | 154,070 | 159,974 | 177,098 |
| Reported total final sludge [tonne DM] | - | 187,430 | 163,422 | 76,084 | - | - | - | 116,998 |
| %RSD total final sludge | - | 15 | 15 | 46 | - | - | - | 29 |
| TOW in final sludge [tonne COD] | 44,070 | 98,132 | 86,781 | 87,554 | 95,199 | 90,918 | 94,894 | 104,884 |
| Inorganic content [%] | - | 48 | 47 | - | - | - | - | 10 |
| Reported amount of digestate [%] | - | 31 | 43 | 54 | - | - | - | 29 |
| Amount of digestate [tonne DM] | - | 58,103 | 69,945 | 41,085 | - | - | - | 34,329 |
| %RSD digestate | - | 40 | 31 | 2 | - | - | - | 0.07 |
| Verification of reduction efficiency | | | | | | | | |
| Reported reduction efficiencies [%] | 58 | 87 | 95 | 92 | 96 | 92 | 92 | 95 |
| Effluent COD, National level [tonne COD] | 123,804 | 42,547 | 18,233 | 30,220 | 14,893 | 30,220 | 29,110 | 19,139 |
| Verification of methane production | | | | | | | | |
| $CH_{4,AD,gross}$ [Gg], (Eq. 5) | 11.32 | 16.42 | 16.42 | 17.50 | 16.10 | 15.75 | 17.66 | 17.99 |
| $CH_{4,AD,gross}$ [Gg], (Eq. 4a) | 10.94 | 18.65 | 16.28 | 17.23 | 19.34 | 16.38 | 11.73 | 14.78 |
| $EF_{AD}$ [kg $CH_4$/kg COD] $=B_o*MCF_{AD}*f_{AD}$ (Eq.4a) | 0.07 | 0.09 | 0.09 | 0.10 | 0.11 | 0.10 | 0.10 | 0.11 |
| Estimated $EF_{AD}$ [%] | -3.4 | 11.9 | -0.9 | -1.6 | 16.8 | 3.9 | -50.6 | -21.7 |

*Estimated from equation 9 and 10.

### COD mass balances (Table 3.2, part 1 and 2)

COD mass balances for WWTPs using 1. aerobic and 2. anaerobic sludge treatment have been approached from plant level integration of plant level data received from the Danish Nature Agency and the Danish Energy Agency, and calibrated against by 3. reported final sludge amounts (chapter 3.1.7), 4. effluent wastewater reduction efficiencies (Table 1.1) and 5. the gross energy production, which includes flaring (Tafdrup, DEA, personal communication, august, 2014).

### Influent COD – $COD_{influent}$

The absolute amounts of COD in the influent wastewater, is known (Table 2.3) and allocated to respectively WWTPs with anaerobic digestion and aerobic stabilization according to plant level data on biogas producing WWTPs by the Danish Energy Agency (Table 2.4 and Annex A, Table A 3).

### Effluent COD - $COD_{effluent}$

The effluent COD is obtained from the reported reduction efficiencies of the influent COD provided in Table 1.1, which makes it possible to estimate the absolute amount of COD in the effluent wastewater at national level. Trade-offs in terms of a lower performance of the WWTPs starting (also) to implement anaerobic digester tanks in the early nineteens is anticipated, while WWTPs with aerobic sludge stabilisation is expected to perform better having reached a mature level of technology performance (Thomsen & Lyck, 205; Henze et al., 2014).

### Air emissions during the biological process tank - $COD_{air\ emission,\ biotank}$

The COD mineralised during biological wastewater treatment is set equal to 30 % in 1990 increasing to 60 % from 2000 and forward at WWTPs with aerobic stabilization (cf. Annex A, Table A 2). The argumentation for this is technological development of the biological treatment processes driven by quality requirement to the N content in the effluent wastewater (Henze et al., 2014).

For WWTPs designed for optimized biogas production, the COD loss during biological wastewater treatment was set equal to the trend for WWTPs without biogas production. The increase in COD reached a maximum of 35 % in the years 1996-2004, after which the COD loss decreased to a constant level of 25 % from 2008 and forward. From 2008-2013 an optimisation of the conservation of COD is presumed due to the development of 2-step WWTPs with the possibility for using primary in addition to the secondary sludge used in 1-step plants as ingestate as shown in Figure 3.1 (Kristensen & Jørgensen, 2008; Niero et al., 2014; Jensen et al., 2015; Thomsen et al., 2015).

### $COD_{recovered}$ and $COD_{vented}$

The above described trends were calibrated to respect that the amount of recovered and flared methane should be equal or greater than the reported amounts of recovered methane for energy production (cf. Table 3.8) for the anaerobic plants; i.e. for zero methane loss situation, the percent COD recovered equals $f_{AD}$ in equation 4a. Still, the sum of effluents, i.e. $COD_{effluent}$, from both plant types should equal the monitored and reported amount of effluent COD in Table 3.2.

### COD in the final sludge – $COD_{final\ sludge}$

For the WWTPs with aerobic sludge stabilisation the percent COD in the final sludge were calculated according to eq. 10, while for the WWTPs with anaerobic sludge digestion eq. 9 is applied adopting the IPCC methane correction factor $MCF_{AD}$ ingestate, meaning that the unconverted COD or recalcitrant amount of carbon in the final sludge, $MCF_s$, equals 1-$MCF_{AD}$ (1-0.8=0.2). In short, the percent COD in the digestate is calculated as percent COD in the influent minus the COD loss in the effluent and biological treatment step multiplied by the $MCF_s$ (Eq. 3).

Finally, the COD mass balance should respect the amounts of produced final sludge as presented in Table 3.10 and discussed below.

**Verification of sludge amounts (Table 3.2, part 3)**

Final sludge amounts produced by WWTPs using anaerobic digestion and aerobic stabilisation, respectively, is reported in the Danish sludge database held by the Danish EPA reported in unit of dry matter (DM) (Table 3.10).

Conversion of the final sludge amounts from units of units of COD into units of dry matter was performed using a value of 0.8 tonne COD/tonne DM sludge for anaerobic digested sludge. The conversion into dry matter, corrected to take into account an inorganic matter content of 40 % (Henze, 2010), reduced to 30 % from 2005 and forward based on increase in biological phosphorous removal replacing the use of chemical precipitation agents (Jensen et al., 2015).

For WWTPs producing aerobic stabilized sludge $CaCO_3$ may be added in amounts corresponding to 10-30 % of the dry matter (Henze et al., 2010). The total content of inorganics in aerobic stabilized final sludge was set equal to 50 % in the period 1990-2004 and reduced to 40 % from 2005 and forward as a not all aerobic stabilized sludge are being calcified (DMEE, 1999 and 2001; DME, 2003b, 2004b, 2009b and 2012b; DCCA, 2014).

In general, the organic matter content in sludge is around 60-70 % of the total dry matter content; the remaining 30-40 % of the dry matter is of inorganic origin. Of the 60-70 % organic dry matter, approximately 40 % represent organic degradable matter, while the residual non-degradable represents the recalcitrant carbon fraction remaining in the final sludge at plant with anaerobic sludge digestion (Eq. 3).

The nitrogen content represents the largest share of about 30 kg total N per tonne of dry matter, while the phosphorus (P) content is about 20 kg P per tonne of dry matter and the potassium content is approximately 2 kg per tonne dry matter. The content of metal salts varies greatly from one sludge producer to another according to the number of metal emitting industries in the catchment area of the individual WWTPs. The average metal contents in the final sludge are: 25 kg Fe (iron)/tonne of dry matter, 2 kg Zn (zinc)/tonne, 0.25 kg Cu (copper)/tonne, 0.4 kg Cd (cadmium)/ tonne and 40 g Ni (nickel)/ tonne dry matter (BAI, 2011; Henze, 2008; Jensen et al., 2015; Niero et al., 2014; Pizzol et al., 2015). Verification of the final sludge amounts, reflected in the percent relative standard deviation (%RSD total final sludge) ranging between 3 and 30 %, when comparing the estimated amount of total final sludge in dry matter with the reported amount of total final sludge in tonne DM.

The COD content in the final sludge is verified by deriving a measure of the inorganic content of the final total amount of sludge. This is obtained by 1 minus the sum of the calculated COD in final anaerobic digested and aerobic stabilised sludge (provided in Table 3.2 part 1 and 2) divided with the reported produced amount of total dry matter final sludge resulting (part 3). The result of this exercise is an estimated content of inorganics which is inside the range of parameters (30-50 %) used for transforming aerobic and anaerobic treated final sludge into units of tonne DM, with exception for 2007 and 2013 (cf. Annex A, Table A 2).

Finally, the amount of final sludge from WWTPs with anaerobic sludge treatment was verified by comparing the derived amount from the COD mass balance (part 2 in Table 3.2) transformed into units of dry matter, with the reported amount of final sludge from anaerobic treatment. The percent relative standard deviation (%RSD digestate) is ranging from 1 to 40 %, which is acceptable taken into account the uncertainty in the COD mass balance as well as reporting frequency in the national statistics.

#### Verification of reduction efficiency and methane production (Table 3.2, part 4 and 5)

Regarding verification of respecting the reduction efficiencies, the percent distribution of COD consumption during the biological treatment were calibrated to match the sum of effluent from the two plant types. Still, the amount of recovered and vented COD should equal the gross methane emission calculated according to equation 4a or at least correspond to the amount of recovered methane (Eq. 5) or the gross energy production reported by the Danish Energy Agency.

As may be observed from Table 3.2 it was not possible to obtain gross methane production data from the COD mass balance that exceeds the methane content in the biogas based energy production reported by the Danish Energy Agency. A likely reason for this is the tendency for increased use of external carbon as feedstock for the biogas production which is so far not reported, an therefore not accounted for in the national methodology. Data on the addition of external carbon at plant level is still not complete but may be obtained from plant level Environmental reports published by the WWTPs themselves (e.g. Billund Vand A/S, 2014; Chapter 3.1.3).

The above COD mass balance supports that the country-specific methane emission from anaerobic sludge treatment, i.e. venting, is conservative; the latter presuming an insignificant addition of external carbon to the ingestate at WWTPs using anaerobic sludge digestion in a national perspective.

### 3.1.3 COD mass balance – Plant level

This chapter presents a COD mass balance for two WWTPs using anaerobic sludge digestion as sludge management strategy.

WWTP1 is a big wastewater treatment plant, with an influent wastewater load of 205,833 PE in 2013, receiving no external carbon except for septic sludge. WWTP2 is a small plant with an influent wastewater treatment load of 10,137 PE in 2013 (DME, 2014) receiving 10 times as much ingestate TOW in terms of external carbon the ingestate compared to in the sludge from the WWTP if self. COD mass balances and associated methane budgets for the two plants are presented in the below sub-chapters.

### WWTP1

WWTP1 represents a plant receiving an insignificant amount of external carbon added to the digester tank. Table 3.3 presents data from the environmental report (ER) of WWTP1.

Table 3.3 Plant level COD mass balance, Eq. 9, based on reported data for WWTP1, tonne COD/year.

| Year | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 |
|---|---|---|---|---|---|---|
| $COD_{influent}$ [1] | 13,900 | 15,800 | 13,000 | 12,500 | 11,400 | 11,563 |
| $COD_{external\ carbon}$ [1] | - | - | - | - | 2,474 | 2,413 |
| $COD_{air\ emission,\ biotank}$ [2] | 4,048 | 3,616 | 3,013 | 2,012 | 3,958 | 4,135 |
| *% COD loss in the aerobic biotank* | 29 | 23 | 23 | 16 | 35 | 36 |
| $COD_{effluent}$ [1] | 720 | 790 | 769 | 757 | 586 | 564 |
| *% COD in effluent* | 5 | 5 | 6 | 6 | 5 | 5 |
| *DM in ingestate*[1] | 8,800 | 10,400 | 8,724 | 9,417 | 9,028 | 9,028 |
| *FeCl in ingestate*[1] | 1,190 | 911 | 1,068 | 1,318 | 1,303 | 1,303 |
| $COD_{ingestate}$ [3] | 9,132 | 11,387 | 9,187 | 9,719 | 9,270 | 9,270 |
| *%COD in the ingestate* ($f_{ad}$) | 66 | 72 | 71 | 78 | 60 | 59 |
| $Nm^3$ *biogas*[1] | 3,400,000 | 3,100,000 | 3,300,000 | 3,100,000 | 3,300,000 | 3,211,263 |
| $COD_{recovered}$ [4] (ER) | 6,365 | 5,803 | 6,178 | 5,803 | 6,178 | 6,011 |
| $MCF_{ad}$ | 0,70 | 0,51 | 0,67 | 0,60 | 0,81 | 0,78 |
| $COD_{recovered}$ (IPCC, 2006) | 7,306 | 9,109 | 7,350 | 7,775 | 7,416 | 7,416 |
| $MCF_{ad}$ | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 |
| $COD_{recovered}$ (DEA) | 5,983 | 5,325 | 5,242 | 4,886 | 5,615 | 5,302 |
| $MCF_{ad}$ | 0.66 | 0.47 | 0.57 | 0.50 | 0.61 | 0.57 |
| *Sludge_combustion* [tonne DM] | 5,200 | 5,570 | 5,496 | 5,874 | 7,914 | 5,105 |
| $COD_{final\ sludge}$ [5] ( ER) | 2,496 | 2,674 | 2,638 | 2,820 | 3,799 | 2,450 |
| *% COD in the sludge* ( ER) | 0.18 | 0.17 | 0.20 | 0.23 | 0.27 | 0.18 |
| $COD_{final\ sludge}$ [6] (Eq. 3) | 1,826 | 2,277 | 1,837 | 1,943 | 1,854 | 1,854 |
| *% COD in the sludge* (Eq. 3) | 0.13 | 0.14 | 0.14 | 0.16 | 0.13 | 0.13 |
| $COD_{vented}$ [7] | 271 | 2,917 | 403 | 1,108 | -646 | 815 |
| $COD_{vented}$ [8] | 941 | 3,313 | 1,203 | 1,984 | 1,298 | 1,412 |
| $COD_{vented}$ [9] | 1,323 | 3,792 | 2,139 | 2,901 | 1,861 | 2,121 |
| COD lost via venting, [% of recovered COD] | 4 | 50 | 7 | 19 | -10 | 4 |

[1]Reported in the Environmental Report.

[2]Calculated as $COD_{air\ emission,\ biotank} = COD_{influent} + COD_{external\ carbon} - COD_{effluent} - COD_{ingestate}$.

[3] Reported in units of dry matter. Transformed into units of COD by subtracting the amount of FeCl added for the chemical precipitation of phosphorous before multiplying by a factor of 1.2 tonne COD/tonne DM sludge (Henze et al., 2010).

[4]Calculated from the reported biogas production multiplied by a volume percent content of methane of 65 % and a density of 0.72 kg $CH_4$/ $Nm^3$ and lastly converted into unit of COD by dividing with the methane conversion factor of 0.25 kg $CH_4$/kg COD.

[5] Reported in units of dry matter. Transformed into units of COD by correction for the content of inorganic material, i.e. multiplying with 0.6, an multiplying by 0.8 tonne COD/tonne DM (Henze et al., 2010).

[6] Calculated according to Eq. 3: $COD_{final\ sludge}=(1- MCF_{AD})*S_{ingestate}$, using WWTP1 derived data to quantify $S_{ingestate}$ ($=COD_{ingestate}$).

[7] Calculated according to equation 9 basd on WWTP1 ER data.

[8] Calculated according to equation 9 basd on WWTP1 ER data, except or the $COD_{final\ sludge}$ which is based on Eq. 3.

[9] Calculated according to equation 9 basd on WWTP1 ER data, except or the $COD_{recovered}$ which were replaced by DEA data.

COD data in the influent and effluent wastewater as well as ingestate amount and final sludge for combustion (digstate) presented in Table 3.3 originates from the environmental report of WWTP1.

For reported received external carbon in terms of septic sludge in tonnes of dry matter, a COD content of 0.8 kg COD kg DM is assumed (Henze et al., 2010).

For the reported amount of the dry matter final sludge, it is assumed to contain 40 % inert mass and for the remaining organic dry matter fraction a COD content of 0.8 kg per kg DM is assumed.

The recovered amount of COD was derived from the reported amount of biogas production in tonne $CH_4$ using the maximum methane conversion potential of 0.25 kg $CH_4$ per kg COD.

The plant reports that around 24 % of the influent COD is lost during aerobic biological treatment processes, corresponding to the level presumed for the latest years in the national COD mass balance for WWTPs with anaerobic sludge treatment (Annex A, Table A 2). In 2012 and 2013 the COD lost during the aerobic biological treatment at WWTP1 is higher estimated based on the lower reported amount of ingestate sludge.

The calculated $f_{AD}$ value, quantifying the amount of COD conserved in the ingestate is highest in 2011 and may be influenced by missing data on external carbon in terms of septic sludge. The national level COD mass balance shows an average $f_{AD}$ value for the whole time series of 0.6 (Nielsen et al., 2014) while the average value for the reporting years 2008-2013 of WWTP1 is slightly lower; i.e. 0.54.

The percent COD remaining in the final sludge is higher for WWTP1 compared to the average national level of 12 % (cf. Table 3.2 and Annex A, Table A.2) as the WWTP1 derived COD value in the final sludge shows an value of 20 %.

By using the COD data in Table 3.3 as input parameters in equation 9, the methane lost via venting expressed in units of COD in percent of the recovered COD is ranging from 0 to 50 %.

The mass balance presented in Table 3.3 shows differences in COD recovered between data derived from the WWTP1 Environmental report, the energy statistics as well IPCC derived data. Especially, the methane correction factors ($MCF_{AD}$) derived from the ratio between the recovered COD and the COD in the ingestate, indicates that the performance of biogas production at WWTP1 is lower (0.51-0.81) compared to the default IPCC $MCF_{AD}$ of 0.8 (cf. Table 3.3).

Table 3.4 presents a resume of the COD mass balance in Table 3.3 using the DEA derived COD recovery (i.e. "$COD_{recovered}$ (DEA)") in place of the theoretical WWTP1 derived COD recovery data ("$COD_{recovered}^4$ (ER)" in Table 3.3).

Table 3.4 Plant level COD mass balance for WWTP1, [tonne COD/year].

| Year | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 |
|---|---|---|---|---|---|---|
| $COD_{influent}$ | 13,900 | 15,800 | 13,000 | 12,500 | 11,400 | 11,563 |
| $COD_{external\ carbon}$ | - | - | - | - | 2,474 | 2,413 |
| $COD_{effluent}$ | 720 | 790 | 769 | 757 | 586 | 564 |
| $COD_{ingestate}$ | 9,132 | 11,387 | 9,187 | 9,719 | 9,270 | 9,270 |
| $COD_{final\ sludge}$ | 2,496 | 2,674 | 2,638 | 2,820 | 3,799 | 2,450 |
| $COD_{air\ emission,\ biotank}$ | 4,048 | 3,616 | 3,013 | 2,012 | 3,958 | 4,135 |
| $COD_{recovered\ (ER)}$ | 6,365 | 5,803 | 6,178 | 5,803 | 6,178 | 6,011 |
| $COD_{vented}$ | 271 | 2.910 | 372 | 1.096 | -706 | 808 |
| Venting in percent of recovered COD [%] | 4 | 50 | 6 | 19 | -11 | 13 |

The COD lost by venting is calculated as the WWTP1 derived data on COD in the ingestate, $COD_{ingestate}$, and final sludge, $COD_{final}$; i.e as $COD_{ingestate}$ - $COD_{final}$ - $COD_{recovered}$ (DEA).

The methane potential lost via venting in percent of the recovered methane, expressed in units of COD, range between 0 to 50 %.

The mass balance for the methane conversion, recovery and loss calculated according to Equation 3 as recommended by the UNFCCC review team are represented in Table 3.5.

Table 3.5 COD in the influent wastewater and resulting methane budget according to equation 3 and 4, [tonne $CH_4$] for WWTP1.

| Data source | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 |
|---|---|---|---|---|---|---|
| $COD_{influent\ (ER)}$ [tonne] | 13,900 | 15,800 | 13,000 | 12,500 | 11,400 | 11,563 |
| $COD_{influent\ (DNA)}$ [tonne] | 13,352 | 17,424 | 9,930 | 12,947 | 11,899 | 11,252 |
| %RSD | 3 | 7 | 19 | 2 | 3 | 2 |
| $CH_{4,AD,gross\ (Eq.4a\ )}$ (NM)[1] | 1,602 | 2,091 | 1,192 | 1,554 | 1,428 | 1,350 |
| $CH_{4,AD,gross\ (Eq.4b)}$ (ER)[2] | 1,826 | 2,277 | 1,837 | 1,944 | 1,854 | 1,854 |
| $CH_{4,\ AD,\ net\ energy}$ + $CH_{4,AD,flaring}$ (DEA) | 1,496 | 1,331 | 1,310 | 1,221 | 1,404 | 1,325 |
| $B_o$*(1- $MCF_{AD}$)*$COD_{ingestate}$ [3] | 624 | 668 | 659 | 704 | 949 | 612 |
| $B_o$*(1- $MCF_{AD}$)*$COD_{ingestate}$ [3] | 457 | 569 | 459 | 486 | 464 | 464 |
| $CH_{4,\ AD,\ net}$[4] | -126 | 377 | 68 | 236 | -13 | 65 |
| Venting in percent of recovered $CH_4$ | -8% | 28% | 5% | 19% | -1% | 5% |

[1] Calculated according to equation 4a.
[2] Calculated according to Equation 4b.
[3] Calculated according to Equation 3; the part of the equation relation to the methane potential remaining in the final sludge.
[4] Calculated according to Equation 3.

Table 3. shows the plant level COD data reported in the Environmental Report (WWTP2 ER) and Danish Nature Agency (DNA) and reflects an uncertainty level, quantified as the percent relative standard deviation, in the range of 2-19 %.

Calculation of the gross emission is according to Equation 4a. For the National Methodology (NM), the default *MCF* (0.8) and $B_o$ (0.25 kg $CH_4$/kg COD) have been applied to the DNA reported data according to equation 4a, while for the "$CH_{4,AD,gross\ (Eq.4a\ and\ 4b)}$ (WWTP1 ER)", the $B_o$ was multiplied with the actual amount of COD conserved in the ingestate as reported in Table 3.4.

The methane recovered for energy production and flaring reported by the Danish Energy Agency (DEA) was selected for quantifying the last part of equation 3, i.e. "$CH_{4,\ AD,\ net\ energy}$ + $CH_{4,AD,flaring}$ ", while methane recovery data from the Environmental Report (ER) was excluded as these are reported as "calculated".

The methane potential contained in the final sludge, was obtained by multiplying the WWTP1 ER derived COD content in the final sludge (Table 3.3) by the $B_o$ value 0.25 tonne $CH_4$/tonne COD.

The reported data on the COD content in the ingestate were used to estimate the methane content in the final sludge; i.e. $B_o*S = B_o *(1- MCF_{AD})* COD_{ingestate}$.

The net emission, $CH_{4, AD, net}$, represents the amount of methane lost via venting and is calculated according to equation 3. The results on venting in percent of recovered methane indicates that the country-specific emission factor (eq. 5) may be overestimated as the results show an average value of 10.6 %; still acceptable, the uncertainty range of the input data taken into account.

### WWTP2

WWTP2 is a small plant with a wastewater influent load of 10,137 PE in 2013 (DME, 2014). The plant receives four types of external carbon (Thomsen et al., 2015):

1. Organic household waste (OHW) corresponding to 729 tonne COD and an estimated $B_o$ value of 0.28 kg $CH_4$/kg COD. The $B_o$ value were derived by multiplying a methane conversion potential of 0.5 $Nm^3$ $CH_4$/kg dry matter (DM) OHW with a COD content of 1.3 kg COD/kg DM OHW resulting in a $B_o$ value of 0.38 $Nm^3$ $CH_4$/kg COD corresponding to 0.28 kg $CH_4$/kg COD (DME, 2003).
2. Sludge from a neighbouring WWTPs with a dry matter content of approximately 20 % and a COD content of 1.1 kg COD/kg dm sludge corresponding to 1210 tonne COD. The default $B_o$ value of 0.25 kg $CH_4$/kg COD is used.
3. Industrial liquid waste with a high content of fats corresponding to 930 tonne COD and an estimated $B_o$ value of 0.22 kg $CH_4$/kg COD. The $B_o$ value were derived by multiplying a methane conversion potential of 0.73 $Nm^3$ $CH_4$/kg fat with a COD content of 2.4 kg COD/kg fat resulting in a $B_o$ value of 0.3 $Nm^3$ $CH_4$/kg COD corresponding to 0.22 kg $CH_4$/kg COD.
4. Liquid waste from an airport with a high ethanol/glycol content corresponding to 516 tonne COD and an estimated $B_o$ value of 0.13 kg $CH_4$/kg COD. The $B_o$ value were derived by multiplying a methane conversion potential of 0.38 $Nm^3$ $CH_4$/kg EtOH with a COD content of 2.15 kg COD/kg EtOH resulting in a $B_o$ value of 0.18 $Nm^3$ $CH_4$/kg COD corresponding to 0.13 kg $CH_4$/kg COD.

The COD mass balance for WWTP2 for the year 2013 is presented in Table 3.6.

Table 3.6 COD mass balance using input data received from WWTP2 (WWTP2 ER) and data reported by, respectively, the Danish Nature Agency (DNA) and Energy Agency (DEA), [tonne COD].

| | WWTP2 ER | DNA, DEA | % difference |
|---|---|---|---|
| $COD_{influent}$ | 632 | 565 | 11 |
| $COD_{external\ carbon}$ | 3,385 | *3,385** | - |
| $COD_{effluent}$ | 69 | 31.6 | 54 |
| $COD_{ingestate}$ | 3,773 | 3,723 | |
| $COD_{final\ sludge}$ | 425 | *753** | -77% |
| $COD_{air\ emission,\ biotank}$ | 221 | 198 | 11 |
| $COD_{recovered}$ | 3,018[1] | 2,979[1] | 1 |
| $COD_{vented}$ | 315[2] | 39[3] | 88 |
| % COD lost via venting | 10% | 1.3% | |

*WWTP2 ER data on external sludge were used in the DNA, DEA column to estimate the final sludge and the amount of recovered COD.
[1]Calculated according to equation 4b.
[2]Calculated according to equation 9.
[3]Calculated according to equation 5.

Plant level data for WWTP2 shows that the reduction efficiency of COD, i.e. the concentration in the effluent wastewater, is 54 % higher (double) than the national COD reduction efficiency of 95 % (cf. Annex A. COD data, Table A 2).

The COD entering the digester tank is set equal to the sum of 60 % of the COD in the influent wastewater (Figure 3.1) and the external carbon. For the "WWTP2 ER" column an additional smaller contribution of 9 tonnes COD from reject water (Thomsen et al., 2015) is added. Such contribution is judged insignificant and not taken into account in the "DNA, DEA" column.

Both the influent and effluent COD data reported in the national monitoring program is smaller compared to the data reported in the plant specific Environmental Reports. One explanation may be that the plant level environmental reports are based on a higher number of samples compared to the 12 samples included in the National Monitoring Program (Rindel, personal communication, august, 2014).

The COD in the final sludge (column 2 (WWTP2 ER)) is based on the reporting of 4200 tonnes final sludge for agricultural application, with a dry matter content of 20 %. Of the 20 % dry matter content, 40 % consist of inert carbon and inorganic material (i.e. the concentration of Pb (lead), Cd (cadmium), Cu (copper), Hg (mercery), Ni (nickel), Zn (zinc), TN (total nitrogen) and TP (total phosphorus) being respectively 32, 2, 172, 1, 34, 883, 92, 47 ppm total dry matter).

Another approach was to use the measured organic matter content by loss on ignition (504 tonnes), which was corrected for 40 % contribution from inorganic. Both numbers were converted into units of COD using the plant specific number on the COD content of 874 mg COD/kg TS resulting in final sludge values of respectively 293.6 and 264.3 tonnes COD. The average value, 279 tonnes COD, was used adding the contribution from external carbon for which it was assumed that a fraction of 0.2 of the OHW and the external sludge remains in the final sludge resulting in a total value of 425 tonnes COD as reported in Table 3.6. This value is 77 % lower than the number obtained using equation 3, i.e. which assumes a fraction of 0.2 (1-($f_{AD} \cdot MCF_{AD}$)) as explained in Chapter 2. The reason is that the $MCF_{AD}$ is set equal to 1 for the industrial liquids.

The loss of COD during the aerobic biological treatment were set equal to 35 % (Eq. 9) in both columns "WWTP2 ER" and "DNA, DEA" column (Annex A, Table A 2 and Figure 3.1).

For the purpose of verification of the recovered amount of COD calculated based on knowledge of the amount and characteristics of the types of external carbon added to the ingestate, a back-calculation from the reported gross energy production (DEA, 2014) from biogas were performed according to equation 11:

$$COD_{recovered} = (E/H)/(MCF \cdot B_o/d) \qquad \text{Eq. 11}$$

where $E$ is the reported gross energy production, in the case of WWTP2 equal to 7303 , multiplied by the conversion factor 0.0036 GJ/kWh

$H$ is the calorific value of methane equal to 0.035 GJ/Nm$^3$; corresponding to 0.023 GJ/Nm$^3$ biogas with a methane content of 65 % (DEA, 2014)

*MCF* is the methane conversion factor 0.8

$B_o$ is the maximum methane producing capacity of 0.25 kg $CH_4$/kg COD

*d* is the density of methane equal to 0.72 kg/$Nm^3$

In the case of WWTP2 a value of 2979 tonnes recovered COD is obtained which is a bit lower than the reported 3018 tonnes recovered COD in Table 3.6. This may partly be explained by differences in $MCF*B_o$ values for the industrial liquids compared to the default values applied in equation 11. In fact, Table 3.7 shows that it is crucial to include information about amounts and characteristics of external carbon added to the ingestate if the national methodology is to be based on the COD mass balance.

In Table 3.6, the amount of COD vented was set equal to 1.3 % of the recovered COD, assuming a linear proportional relationship between the COD mass balance and $CH_4$ conversion potentials. From Table 3.6 one may tend to conclude that a more conservative estimate of the amount of methane lost by venting is 10 % of the recovered COD used for energy production and flared.

The methane budget associated with the COD mass balance of WWTP2 in Table 3.6 is provided in Table 3.7.

Table 3.7 COD in the influent wastewater and resulting methane budget according to equation 3 and 4, [tonne $CH_4$] for WWTP2 for the year 2013.

| Data source | WWTP2 ER | DNA, DEA | % difference |
|---|---|---|---|
| $CH_{4,AD,gross}$ | 665[1] | 745[2] | -12 |
| $CH_{4,\ AD,\ net\ energy} + CH_{4,AD,flaring}$ | 541[3] | 596[3] | -10 |
| $MCFs*B_o*S$ [2] | 116[4] | 188 | -62 |
| $CH_{4,\ AD,\ net}$ | 8[4] | 8[5] | 2 |
| Venting in percent of recovered $CH_4$ | 1 | 1.3 | 11 |

[1]Calculated according to Eq. 4b.

[2]Calculated according to Eq. 4a.

[3]Calculated as by multiplying with $B_o$ *MCF.

[4]Calculated according to Eq. 3.

[5]Calculated according to Eq. 5.

Activity data for calculating the gross emission, i.e. the maximum methane potential in the ingestate, according to equation 4b, are based on the influent TOW as shown in Table 3.6.

As described in the methodology Chapters 2.1 and 2.2, activity data used in the National Methodology are the influent TOW at the wastewater treatment plants. These are used for calculating the gross emission according to equation 4a, while the methane emission via venting is calculated according to equation 5; i.e. at present calculated as 1.3 % of the recovered $CH_4$.

Table 3.7 represents one case study of the plant level COD mass balance and the associated $CH_4$ conversion potentials and loss. The amount of recovered methane in the "WWTP2 ER" column is calculated according to equation 11 excluding "$MCF*B_o$" in the equation.

Table 3.7 suggests that the national $EF_{AD}$ value of 0.013 applied to the gross energy production (Equation 5) is a good estimate of methane loss via venting.

### 3.1.4 $CH_4$ recovery and venting – plant level data

Plant level data on biogas produced and consumed at the plant together with information on the amount of biogas vented and flared reported in the Environmental Reports (ER) published by the WWTPs compared to biogas production data reported by the Danish Energy Agency (DEA) are presented in Table 3.88.

Table 3.8 Plant level for WWTPs that includes reporting on flaring and venting in environmental reports (ER) reports compared to data on biogas production from the energy producer accounts (DEA).

| Plant | Unit | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|
| WWTP1 | | | | | | | |
| Biogas produced, ER | $Nm^3$ | - | 6,330,381 | 5,942,571 | 5,792,838 | 6,695,142 | 7,154,932 |
| Biogas consumed, ER | $Nm^3$ | - | 6,045,766 | 5,282,995 | 5,297,866 | 5,748,674 | 6,251,319 |
| Flaring, ER | $Nm^3$ | - | 284,615 | 659,576 | 494,972 | 946,468 | 903,613 |
| $CH_4$ produced, ER | Tonne | - | 2,963 | 2,781 | 2,711 | 3,133 | 3,349 |
| $CH_4$ flared, ER | Tonne | - | 133 | 309 | 232 | 443 | 423 |
| $CH_4$ flared, ER | % | - | 4.5 | 11.1 | 8.5 | 14.1 | 12.6 |
| Biogas produced, DEA | GJ | 101,606 | 113,940 | 106,966 | 104,271 | 91,295 | 143,780 |
| Biogas produced, ER | GJ | - | 145,599 | 136,679 | 133,235 | 153,988 | 164,563 |
| $CH_4$ produced, DEA | Tonne | 2,067 | 2,318 | 2,177 | 2,122 | 1,858 | 2,926 |
| Percent difference | % | | 22 | 22 | 22 | 41 | 13 |
| WWTP2 | | | | | | | |
| Biogas produced, ER | $Nm^3$ | - | 2,690,037 | 1,665,416 | 2,123,357 | 1,997,333 | 1,918,325 |
| Biogas consumed, ER | $Nm^3$ | - | 2,632,287 | 1,607,666 | 1,816,022 | 1,903,183 | 1,681,375 |
| Flaring, ER | $Nm^3$ | - | 57,750 | 57,750 | 307,335 | 94,150 | 236,950 |
| $CH_4$ produced, ER | Tonne | - | 1,259 | 779 | 994 | 935 | 898 |
| $CH_4$ flared, ER | Tonne | - | 27 | 27 | 144 | 44 | 111 |
| $CH_4$ flared, ER | % | - | 2.1 | 3.5 | 14.5 | 4.7 | 12.4 |
| Biogas produced, DEA | GJ | | 45,765 | na | 31,475 | - | 11,042 |
| Biogas produced, ER | GJ | - | 61,871 | 38,305 | 48,837 | 45,939 | 44,121 |
| $CH_4$ produced, DEA | Tonne | - | 931 | na | 640 | - | 225 |
| Percent difference | % | - | 26 | na | 36 | - | 75 |
| WWTP3[1] | | - | - | - | - | - | - |
| Venting, accidental | $Nm^3$ | - | - | - | | 12,100 | 10,700 |
| Venting total | - | - | - | - | | - | 142,667 |
| Venting | -% | - | - | - | , | -, | 1.6 |
| WWTP4 | | | | | | | |
| Biogas produced, ER | $Nm^3$ | 3,300,000 | 3,400,000 | 3,100,000 | 3,300,000 | 3,100,000 | 3,300,000 |
| Biogas consumed, ER | $Nm^3$ | 3,200,000 | 3,300,000 | 3,000,000 | 3,200,000 | 2,900,000 | 3,300,000 |
| Flaring, ER | $Nm^3$ | 140,000 | 140,000 | 54,000 | 170,000 | 36,000 | 10,000 |
| $CH_4$ produced, ER | Tonne | 1,544.4 | 1,591.2 | 1,450.8 | 1,544.4 | 1,450.8 | 1,544.4 |
| $CH_4$ flared, ER | Tonne | 65.52 | 65.52 | 25.27 | 79.56 | 16.85 | 4.68 |
| $CH_4$ flared, ER | % | 4.2 | 4.1 | 1.7 | 5.2 | 1.2 | 0.3 |
| Biogas produced, DEA | GJ | 66,123 | 72,709 | 64,713 | 63,701 | 59,373 | 68,235 |
| Biogas produced, ER | GJ | 75,900 | 78,200 | 71,300 | 75,900 | 71,300 | 75,900 |
| $CH_4$ produced, DEA | Tonne | 1,345 | 1,479 | 1,317 | 1,296 | 1,208 | 1,388 |
| Percent difference | % | 12.9 | 7.0 | 9.2 | 16.1 | 16.7 | 10.1 |
| Venting, accidental, ER | Tonne $CO_2$-eq./tonne | | 0.001 | 0.003 | 0.022 | 0.052 | 0.020 |
| Venting, accidental | Tonne $CH_4$ | 0.00 | 0.48 | 1.43 | 10.50 | 24.82 | 9.55 |
| Venting, accidental | % | 0.0 | 0.03 | 0.1 | 0.7 | 1.7 | 0.6 |
| WWTP5 | | | | | | | |
| Biogas produced, ER | $Nm^3$ | 3,074,000 | 2,160,000 | 1,879,000 | 1,890,000 | 1,692,000 | 1,820,000 |
| Biogas consumed, ER | $Nm^3$ | - | - | - | - | - | - |
| Flaring, ER | $Nm^3$ | - | - | - | - | - | - |
| $CH_4$ produced, ER | Tonne | 1,439 | 1,011 | 879 | 885 | 792 | 852 |
| $CH_4$ flared, ER | Tonne | - | - | - | - | - | - |
| $CH_4$ flared, ER | % | - | - | - | - | - | - |
| Biogas produced, DEA | GJ | 52,811 | 36,758 | 30,047 | 28,092 | 37,333 | 41,438 |
| Biogas produced, ER | GJ | 70,702 | 49,680 | 43,217 | 43,470 | 38,916 | 41,860 |
| $CH_4$ produced, DEA | Tonne | 1,075 | 748 | 611 | 572 | 760 | 843 |
| Percent difference | % | 25.3 | 26.0 | 30.5 | 35.4 | 4.1 | 1.0 |

[1] There have been nine cases of leakage of biogas from the digesters in 2012 corresponding to approximately 10,700 $m^3$ biogas. The accidents represent 5-10 % of the total biogas loss via ventilation etc.

The plant level data presented in Table 3.8 include biogas production data reported in the Environmental Reports (ER), which are reported as calculated data in most cases, while the biogas production data reported to the Danish Energy Agency are measured. The data presented supports a general trend of the calculated biogas production data being above the monitored energy and derived biogas production data reported by the Danish Energy Agency. The difference may to some extent reflect the methane emission via venting or other unintentional causes to some extent reported in the plant level Environmental Reports.

The amount of reported data on venting and flaring are scarce. Flaring is included in the gross energy production data reported by the Danish Energy Agency. In the emission inventory for the reporting year 2015, a value of 1.3 % of the produced biogas were applied (Equation 5) to calculate the amount of methane lost by venting, while a value of 10 % of the gross methane production were reported as recovered and flared. The values are in agreement with the above shown values, where the average percentage of the produced biogas flared is 7 % ± 5 % with a maximum value of 14.5 %, while the maximum reported value on venting is 1.7 %, the average value is 0.7 % ± 0.7 %.

Regarding venting, the data presented are mainly reported as accidental emissions from operational failures at the plant. In one occasion, the accidental emission is reported to be 5-10 % of the total biogas emission due to ventilation. In general, diffuse methane emissions from anaerobic digestion are difficult to determine. The information of such emissions are scarce, but in a report from the Danish EPA on treatment technologies in the fish industry, the total fugitive methane emission from anaerobic digestion is estimated to vary between 0-10 % of the gas production by full digestion (DEPA, 2000) and numbers in the lower end of this range have been documented for Danish WWTPs.

The UNFCCC have asked for further documentation of the size of the methane emission factor from anaerobic digestion of sludge in terms of a verification of the mass balance as provided in the IPCC guidelines (Chapter 5, page 6.11, equation 6.1 in IPCC, 2006). The mass balance is to verify the methane emissions factor from anaerobic treatment processes, at present quantified as 1.3 % of the methane content in the gross energy produced as shown in Nielsen et al., 2014.

The data presented in Table 3.8 on available data on methane emissions caused by venting, indicate that the methane emission, due to loss of biogas via venting, is in agreement with the national emission inventory.

### 3.1.5 Biogas production and Gross Energy parameters

The default maximum $CH_4$ producing capacity ($B_o$) represents the theoretical methane production given the condition of 100 % efficient conversion of the COD in the ingestate and no emission loss during conversion of biomass into biogas. However, losses do occur as described in the former chapters.

The minor part of the methane emission originating from the biogas driven engine, i.e. emissions originating from energy production, is included in the energy sector, while only the emission from wastewater treatment and anaerobic sludge digestion are included in sector 5.D Wastewater treatment and discharge. Methane emissions may potentially occur from gas engine generator unit, in the form of fugitive emissions from digester tank and after the degassed residue left biogas plant to be applied to agricultural land. For gas engine generator units biogas emissions are in the order of 1-7 % of the produced gas depending on engine type. The methane emission from biogas driven engines are included in the energy sector. However, for the purpose of clarification, the emission factor for biogas to energy conversion at wastewater plant has been investigated and reported in two reports on emissions from decentralised CHP (combustion heat plant) plant based on monitoring data from 2002 and 2006, respectively (Nielsen et al., 2002; Nielsen et al., 2009). Furthermore, monitoring data reported by the Danish Gas Technological Centre in 2009 verify that the content of methane in the uncombusted hydrocarbons, UHC, contained in the gas emission from biogas driven engines at wastewater treatment plants consists of more than 98 % methane (DGC, 2009). The UHC emission factor for gas engines running on biogas originating from manure, landfills and from anaerobic digested sludge at wastewater treatment plants are reported in Nielsen et al. (2003; 2009). For gas engines running on biogas from anaerobic digested sludge, an EF is reported to be 276 g UHC per GJ resulting in a methane emission factor of 270 g $CH_4$ per GJ. Methane emission from incomplete combustion of the biogas in biogas driven engines are not included in this sector as it belongs to the gross to net energy budget.

The above described methane loss during combustion in a biogas driven engine or boiler including the biogas to energy conversion efficiency calculation, which belongs to the energy sector; i.e. the gross energy numbers reported presented in this report, do not include biogas or energy losses during conversion of the biogas into heat and electricity. As such, loss of biogas via venting influences the Danish biogas generation and recovery efficiency, but is not associated to the energy conversion or combustion efficiency as discussed in the introductory part of Chapter 3.1.

In Sector 5.D the gross energy production numbers are used to verify or calculate the amount of recovered methane, which are input parameters in Equation 3. Gross energy production numbers, derived from the energy statistics reported, by the Danish Energy Agency, as well as the Environmental report at plant level, includes flaring, but not venting.

In conclusion, sector 5.D includes methane emissions from wastewater treatment process of wastewater and sludge to final product; i.e. wastewater effluents, final sludge and biogas production.

Methane emission during conversion of biogas to electricity and heat is included in the energy sector (Nielsen et al., 2014). Table 3.9 provides key parameters used for transforming reported gross energy production in PJ into tonne $CH_4$.

Table 3.9 Key parameters for gross energy production and component content in biogas.

| Parameter | Unit | Biogas from AD | Methane |
|---|---|---|---|
| Calorific value, lower | $GJ/Nm^3$ | 0.023 | 0.035 |
| | $kWh/Nm^3$ | 6.5 | 10 |
| | GJ/kWh | 0.0036 | 0.0036 |
| | GJ/tonne | 20.2 | 31.1 |
| Density | $kg/Nm^3$ | 1.2 | 0.67[1]/0.72[2] |
| Methane | vol-% | 65 | 100 |
| Carbon dioxide | vol-% | 35.00 | |

[1]NTP - Normal Temperature and Pressure - is defined as 20°C (293.15 K, 68°F) and 1 atm (101.325 $kN/m^2$, 101.325 kPa, 14.7 psia, 0 psig, 30 in Hg, 760 torr).

[2]STP - Standard Temperature and Pressure - is defined as 0°C (273.15 K, 32°F) and 1 atm (101.325 $kN/m^2$, 101.325 kPa, 14.7 psia, 0 psig, 30 in Hg, 760 torr).

At national level, the gross biogas production calculated based on the COD in the influent wastewater is for the majority of the years higher than the gross energy production derived value based on the Danish Energy statistics. In the national model, the density of methane at normal temperature and pressure were applied.

### 3.1.6 Sludge production

In the former inventories, national sludge statistics were used to derive the fraction of the influent TOW that was treated by anaerobic digestion. However, the sludge database, which was based on voluntary reporting, has been closed down and is now only partly included in the new waste reporting system (Nielsen et al., 2014). In the absence of high quality statistics on sludge data according to sludge management strategies at the Danish wastewater treatment plants, an integration of data from the Danish Energy agency on WWTPs producing biogas with WWTP resource flow data from the Danish Nature Agency have been performed for the time period 1998-2013 as shown in Annex A, Table A 2. An estimation of the amount of TOW in the influent wastewater treated at WTTPs, with anaerobic and anaerobic sludge management technologies, was derived from integration of plant level data on energy production and measured COD data in the influent wastewater. Final sludge amounts from the two types of plants were verified by a comparison with reported sludge data reported in national statistics as shown in Table 3.10.

10.

Table 3.10 Estimated aerobic stabilized, anaerobic digested and total dry weight final sludge compared to reported final sludge amounts in units of tonne dry matter.

| Year | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 |
|---|---|---|---|---|---|---|
| Final sludge, aerobic treatment [tonne COD] | 35,642 | 41,459 | 38,027 | 36,406 | 41,290 | 85,558 |
| Final sludge, digested [tonne COD] | 11,871 | 11,522 | 11,395 | 9,775 | 12,021 | 15,695 |
| Final sludge, total [tonne COD] | 47,513 | 52,981 | 49,422 | 46,181 | 53,311 | 101,252 |
| Final sludge, digested, national statistics [tonne COD] | - | - | - | - | - | 27,890 |
| %RSD | - | - | - | - | - | 40 |
| Final sludge, national statistics [tonne COD] | - | - | - | - | - | 103,087 |
| %RSD | - | - | - | - | - | 1 |
| TOW in aerobic stabilized sludge [tonne DM] | 85,542 | 99,501 | 91,264 | 87,374 | 99,097 | 205,338 |
| TOW in digested sludge [tonne DM] | 24,730 | 24,005 | 23,739 | 20,365 | 25,044 | 32,697 |
| TOW in total amount of final sludge [tonne DM] | 110,272 | 123,506 | 115,003 | 107,739 | 124,140 | 238,035 |
| Final sludge, national statistics [tonne DM]* | - | - | - | - | - | 187,430 |
| %RSD | - | - | - | - | - | 17 |
| Year | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 |
| Final sludge, aerobic treatment [tonne COD] | 65,685 | 51,719 | 59,290 | 58,317 | 66,567 | 59,080 |
| Final sludge, digested [tonne COD] | 14,568 | 18,522 | 21,985 | 22,733 | 21,449 | 24,563 |
| Final sludge, total [tonne COD] | 80,253 | 70,242 | 81,275 | 81,050 | 88,017 | 83,643 |
| Final sludge, digested, national statistics [tonne COD] | 24,525 | 23,247 | - | - | 20,144 | 20,344 |
| %RSD | 36 | 16 | - | - | 4 | 13 |
| Final sludge, national statistics [tonne COD] | 90,652 | 85,925 | 87,659 | 88,298 | 89,882 | 90,353 |
| %RSD | 9 | 14 | 5 | 6 | 1 | 5 |
| TOW in aerobic stabilized sludge [tonne DM] | 157,645 | 124,127 | 142,297 | 139,962 | 159,761 | 141,792 |
| TOW in digested sludge [tonne DM] | 30,349 | 38,588 | 45,802 | 47,360 | 44,686 | 51,173 |
| TOW in total amount of final sludge [tonne DM] | 187,994 | 162,715 | 188,099 | 187,322 | 204,447 | 192,965 |
| Final sludge, national statistics [tonne DM]* | 164,821 | 156,227 | 159,379 | 160,542 | 163,422 | 164,278 |
| %RSD | 9 | 3 | 12 | 11 | 16 | 11 |
| Year | 2002 | 2003 | 2004 | 2005* | 2006* | 2007 |
| Final sludge, aerobic treatment [tonne COD] | 64,598 | 58,625 | 57,925 | 66,469 | 71,894 | 76,601 |
| Final sludge, digested [tonne COD] | 21,972 | 24,567 | 21,034 | 22,787 | 21,436 | 21,162 |
| Final sludge, total [tonne COD] | 86,570 | 83,192 | 78,959 | 89,256 | 93,330 | 97,762 |
| Final sludge, digested, national statistics [tonne COD] | 19,110 | - | - | 16,105 | - | 23,534 |
| %RSD | 10 | - | - | 24 | - | 8 |
| Final sludge, national statistics [tonne COD] | 81098 | - | 77486 | 49,454 | 49,561 | 78,046 |
| %RSD | 5 | - | 1 | 41 | 43 | 16 |
| TOW in aerobic stabilized sludge [tonne DM] | 129,195 | 117,250 | 115,849 | 110,782 | 119,823 | 127,668 |
| TOW in digested sludge [tonne DM] | 45,775 | 51,180 | 43,822 | 40,691 | 38,279 | 37,789 |
| TOW in total amount of final sludge [tonne DM] | 174,971 | 168,430 | 159,671 | 151,472 | 158,102 | 165,456 |
| Final sludge, national statistics [tonne DM]* | 147,451 | - | 140,884 | 76,084 | 76,247 | 120,070 |
| %RSD | 12 | - | 9 | 47 | 49 | 22 |
| Year | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 |
| Final sludge, aerobic treatment [tonne COD] | 74,496 | 67,095 | 71,019 | 70,759 | 80,955 | 86,862 |
| Final sludge, digested [tonne COD] | 18,220 | 23,960 | 25,483 | 21,581 | 15,454 | 19,468 |
| Final sludge, total [tonne COD] | 92,716 | 91,055 | 96,501 | 92,340 | 96,410 | 106,329 |

| Continued | | | | | | |
|---|---|---|---|---|---|---|
| Final sludge, digested, national statistics [tonne COD] | - | - | - | - | - | 13,457 |
| %RSD | - | - | - | - | - | 26 |
| Final sludge, national statistics [tonne COD] | - | - | - | - | - | 76,049 |
| %RSD | - | - | - | - | - | 23 |
| TOW in aerobic stabilized sludge [tonne DM] | 124,159 | 111,825 | 118,365 | 117,932 | 134,925 | 144,770 |
| TOW in digested sludge [tonne DM] | 32,536 | 42,785 | 45,504 | 38,537 | 27,597 | 34,764 |
| TOW in total amount of final sludge [tonne DM] | 156,695 | 154,610 | 163,869 | 156,469 | 162,523 | 179,533 |
| Final sludge, national statistics [tonne DM]* | - | - | - | - | - | 116,998 |
| %RSD | - | - | - | - | - | 30 |

*DMEE, 1999 and 2001; DME, 2003b, 2004b, 2009b and 2012b - for the years 2005 and 2006 a very low reporting frequency was obtained and the sludge amounts are incorrect; underestimated (DME, 2009b).
** DCCA, 2014.

A comparison between final sludge amounts estimated from the COD mass balance (Table 3.2) with the national sludge statistics shows a maximum percent difference of 32 %.There is a general tendency for the plant level methodology to underestimate the final sludge amounts. This may on the one hand indicate that the national level MCF is set to high, which would also explain the overestimation of the gross methane production. On the other hand, Chapter 3.1.1 has verified that the missing external carbon added to the ingestate is for sure one reason for the underestimated final sludge amounts at national level (see Table 3.7). Furthermore, Chapter 3.1.1 indicates that the national level emission factor quantifying the methane lost via venting may be underestimated (cf. Table 3. and Table 3.7). The percent difference between the COD in the final sludge derived from the COD mass balance and the old sludge statistics is within the level of reported uncertainties on TOW.

Table 3.10 verifies that the COD data and associated mass balance derived as shown in Table 3.2 and Annex 2, Table A2 are able to quantify the COD remaining in the final sludge.

The fraction of sludge treated by anaerobic digestion, formerly estimated from national statistics on final sludge amounts (Nielsen et al., 2014), have from the reporting year 2015 been replaced by COD data (Table 2.1). In future inventories calculated amounts of COD treated by anaerobic digestion will be calculated from plant level knowledge on the COD content in the influent wastewater at plants registered in the Energy Producer Account database; the results of plant level data on COD from plants producing energy is shown in Annex A. COD data

### 3.1.7 Population living in the scattered settlements

As only 90 % of the population are documented to be connected to the collective sewer system, a third treatment pathway is modelled by septic tanks. A visualization of the treatment systems and discharge pathways is shown in Figure 1.1.

The fraction of the population not connected to the collective sewer system is derived from reported data on scattered settlements by the Danish Nature Agency. An estimate of the number of people living in a permanent habitation not connected to the sewer system may be obtained by multiplying the number of permanent habitation with a PE number of 2.5 persons per permanent habitation. The results of comparing the number of people living in permanent habitation with the population number of Denmark are shown in Table 3.11.

Table 3.11 Fraction of the population not connected to the collective sewer system.

| Year | 2002 | 2004 | 2006 | 2008 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|
| Persons not connected to sewer system | 579,705 | 600,043 | 522,413 | 518,080 | 536,158 | 514,685 | 518,290 |
| Population - estimate | 5,368 354 | 5,397 640 | 5,427 459 | 5,475 791 | 5,534 738 | 5,560 628 | 5,580 516 |
| $f_{nc}$ [%] | 10.80 | 11.12 | 9.63 | 9.46 | 9.69 | 9.26 | 9.29 |

Table 3.11 shows one of several approaches for estimating the fraction of the population not connected to the sewer system. Using a unit value of 2.5 PE for the property type permanent habitation as defined by the Danish Nature Agency (see Annex B. , Table B 1), a percent estimate of the fraction of the population not connected to the collective sewer system were derived.

Instead when calculating the fraction of the population from the reported number of permanent habitation within the scattered settlements in percent of the total number of permanent habitation in Denmark, the percent of the population not connected to the sewer system is 13.6 to 14.1 in the time range 2010-2012 (see Annex B. , Table B 5).

The numbers provided in Table 3.11 may be underestimated as only one of the four residential property types is included in the estimate (see Annex B. , Table B 5). Until the results of mapping the extension of the collective sewer system is released by the Danish EPA, a constant value of 10 % is considered verified as a best estimate (Villumsen, personal communication, June, 2014).

### 3.1.8 Scattered settlements - $CH_4$ emission from septic tanks

Wastewater solutions in the scattered settlements are modelled by the default septic tank system (see Chapter 2). Different simple technologies for wastewater handling in scattered settlements exist and collection of the settled COD occurs at minimum one time per year. In the default methodology, it is assumed that 50 % of the TOW settles resulting in an emission factor of 0.125 kg $CH_4$ per kg COD.

The calculated amount of produced TOW and methane emissions per property type and in total for the years 2002, 2004, 2006, 2008 and 2010-2013, is presented in Table 3.12. In the grey shaded rows of Table 3.12, a comparison with the estimated TOW and $CH_4$ emission using the National Methodology, is presented.

Table 3.12 TOW and $CH_4$ emissions produced per property type and in total from scattered house compared to the National Methodology.

| Residential Properties | Year | Permanent habitation | Summer house | Allotment | Other | Total |
|---|---|---|---|---|---|---|
| $COD_{inflow}$* | 2013 | 28,008 | 2,894 | 291 | 1,184 | 32,378 |
| $COD_{effluent}$** | 2013 | 6,970 | 104 | 91 | 296 | 7,461 |
| $COD_{inflow}$-$COD_{effluent}$ | 2013 | 21,038 | 2,790 | 200 | 888 | 24,917 |
| $CH_{4,\ septic\ tanks}$ | 2013 | 2,630 | 349 | 25 | 111 | 3,115 |
| $COD_{inflow}$ | 2013 | | | | | 31,697 |
| Percent difference [%] | 2013 | | | | | -2 |
| $CH_{4,\ septic\ tanks}$ | 2013 | | | | | 3,962 |
| Percent difference [%] | 2013 | | | | | 21 |
| $COD_{inflow}$* | 2012 | 28,376 | 2,949 | 227 | 1,210 | 32,762 |
| $COD_{effluent}$** | 2012 | 7,325 | 109 | 55 | 303 | 7,793 |
| $COD_{inflow}$-$COD_{effluent}$ | 2012 | 21,051 | 2,840 | 172 | 908 | 24,970 |
| $CH_{4,\ septic\ tanks}$ | 2012 | 2,631 | 355 | 22 | 113 | 3,121 |
| $COD_{inflow}$ | 2012 | | | | | 31,572 |
| Percent difference [%] | 2012 | | | | | -4 |
| $CH_{4,\ septic\ tanks}$ | 2012 | | | | | 3,946 |
| Percent difference [%] | 2012 | | | | | 21 |
| $COD_{inflow}$* | 2011 | 28,179 | 3,128 | 227 | 1,280 | 32,814 |
| $COD_{effluent}$** | 2011 | 7,563 | 218 | 58 | 320 | 8,158 |
| $COD_{inflow}$-$COD_{effluent}$ | 2011 | 20,617 | 2,911 | 169 | 960 | 24,657 |
| $CH_{4,\ septic\ tanks}$ | 2011 | 2,577 | 364 | 21 | 120 | 3,082 |
| $COD_{inflow}$ | 2011 | | | | | 31,459 |
| Percent difference [%] | 2011 | | | | | -4 |
| $CH_{4,\ septic\ tanks}$ | 2011 | | | | | 3,932 |
| Percent difference [%] | 2011 | | | | | 22 |
| $COD_{inflow}$* | 2010 | 28,376 | 2,949 | 227 | 1,210 | 32,762 |
| $COD_{effluent}$** | 2010 | 3,025 | 87 | 23 | 128 | 3,263 |
| $COD_{inflow}$-$COD_{effluent}$ | 2010 | 25,351 | 2,862 | 204 | 1,082 | 29,499 |
| $CH_{4,\ septic\ tanks}$ | 2010 | 3,169 | 358 | 26 | 135 | 3,687 |
| $COD_{inflow}$ | 2010 | | | | | 31,313 |
| Percent difference [%] | 2010 | | | | | -4 |
| $CH_{4,\ septic\ tanks}$ | 2010 | | | | | 3,914 |
| Percent difference [%] | 2010 | | | | | 6 |
| $COD_{inflow}$* | 2008 | 28,365 | 2,755 | 291 | 550 | 31,960 |
| $COD_{effluent}$** | 2008 | 8,005 | 95 | 5 | 138 | 8,243 |
| $COD_{inflow}$-$COD_{effluent}$ | 2008 | 20,360 | 2,660 | 286 | 413 | 23,718 |
| $CH_{4,\ septic\ tanks}$ | 2008 | 2,545 | 332 | 36 | 52 | 2,965 |
| $COD_{inflow}$ | 2008 | | | | | 30,979 |
| Percent difference [%] | 2008 | | | | | -3 |
| $CH_{4,\ septic\ tanks}$ | 2008 | | | | | 3,872 |
| Percent difference [%] | 2008 | | | | | 23 |
| $COD_{inflow}$* | 2006 | 28,365 | 2,755 | 291 | 550 | 31,960 |
| $COD_{effluent}$** | 2006 | 8,005 | 95 | 5 | 138 | 8,243 |
| $COD_{inflow}$-$COD_{effluent}$ | 2006 | 20,360 | 2,660 | 286 | 413 | 23,718 |
| $CH_{4,\ septic\ tanks}$ | 2006 | 2,545 | 332 | 36 | 52 | 2,965 |

| Continued | | | | | | |
|---|---|---|---|---|---|---|
| $COD_{inflow}$ | 2006 | | | | | 30,706 |
| Percent difference [%] | 2006 | | | | | -4 |
| $CH_{4, septic\ tanks}$ | 2006 | | | | | 3,838 |
| Percent difference [%] | 2006 | | | | | 23 |
| $COD_{inflow}$* | 2004 | 28,602 | 2,744 | 284 | 590 | 32,220 |
| $COD_{effluent}$** | 2004 | 7,410 | 105 | 5 | 148 | 8,745 |
| $COD_{inflow}$-$COD_{effluent}$ | 2004 | 21,192 | 2,639 | 279 | 443 | 23,475 |
| $CH_{4, septic\ tanks}$ | 2004 | 2,649 | 330 | 35 | 55 | 2,934 |
| $COD_{inflow}$ | 2004 | | | | | 30,537 |
| Percent difference [%] | 2004 | | | | | -5 |
| $CH_{4, septic\ tanks}$ | 2004 | | | | | 3,817 |
| Percent difference [%] | 2004 | | | | | 23 |
| $COD_{inflow}$* | 2002 | 31,739 | 3,035 | 300 | 530 | 35,604 |
| $COD_{effluent}$** | 2002 | 9,218 | 150 | 3 | 133 | 9,500 |
| $COD_{inflow}$-$COD_{effluent}$ | 2002 | 22,521 | 2,885 | 298 | 398 | 26,104 |
| $CH_{4, septic\ tanks}$ | 2002 | 2,815 | 361 | 37 | 50 | 3,263 |
| $COD_{inflow}$ | 2002 | | | | | 30,371 |
| Percent difference [%] | 2002 | | | | | -15 |
| $CH_{4, septic\ tanks}$ | 2002 | | | | | 3,796 |
| Percent difference [%] | 2002 | | | | | 14 |
| $COD_{inflow}$* | 1997 | 31,739 | 3,035 | 300 | 530 | 35,604 |
| $COD_{effluent}$** | 1997 | 9,218 | 150 | 3 | 133 | 9,500 |
| $COD_{inflow}$-$COD_{effluent}$ | 1997 | 22,521 | 2,885 | 298 | 398 | 26,104 |
| $CH_{4, septic\ tanks}$ | 1997 | 2,815 | 361 | 37 | 50 | 3,263 |
| $COD_{inflow}$ | 1997 | | | | | 29,844 |
| Percent difference [%] | 1997 | | | | | -16 |
| $CH_{4, septic\ tanks}$ | 1997 | | | | | 3,730 |
| Percent difference [%] | 1997 | | | | | 13 |

*The content of BOD, N, P in the influent wastewater have been calculated using the Danish PE unit numbers, which are 21.9 kg organic matter in BOD/PE/year, 4.4 kg N/PE/year, 1.0 kg P/PE/year and 50 $m^3$ wastewater/year, and are presented in Annex B, Table B 2. The person equivalents (PE) per permanent habitation is set to 2.5 PE, 2 PE for summer houses and allotments for 3 months per year (DME, 2003) and for the property type "other" a back-calculation from reported effluent amounts of BOD in Annex B, Table B 1 was performed. Reduction efficiencies calculated from the reported effluent and calculated influent data are reported in Annex B. , Table B 3.

**Effluent data reported according to residential property types within the scattered settlements by the Danish Nature Agency are presented in Annex B. , Table B 1. Property types comprises permanent habitation, summer houses, allotments and other, which includes a typical household wastewater load such as schools, institutions, office buildings, restaurants etc.

The comparison between the total TOW produced within the scattered settlements, i.e. using the Danish PE unit values for BOD, and estimates from the National Methodology, i.e. allocation of 10 % of the total TOW in the influent wastewater to scattered settlements, show a percent difference in the $COD_{inflow}$, between -2 and -16 %. This level of uncertainty are within the range of uncertainty reported for TOW used in the National Inventory Report (Nielsen et al., 2014) and verifies the correctness of the National Methodology for estimating methane emissions from scattered settlements.

The methane emission calculated according to property type is lower than the number calculated by the National Methodology; the percent difference is between 6 and 23 %. The reason is that the effluent COD was subtracted before multiplying with the MCF value of 0.5 and the $B_o$. This implies that 50 % of the COD remaining, instead of 50 % of the input COD to the collection/septic tank, is used in the calculation of the methane emission. Precipitation tanks may be extended with infiltration, sand filters and micro WWTPs, which may result in a higher degree of suspended organic matter in the outlet and i.e. a reduced COD available for precipitation, while only collective tanks has no effluents.

The National Methodology provides a sufficiently accurate estimate of the methane emission from scattered settlements and the approach is verified by the effluent amount of COD less than 50 % of the inlet COD assuming to be precipitation and anaerobic digested (see Annex B. , Table B 3).

## 3.2 $N_2O$ emissions

### 3.2.1 Direct $N_2O$ emissions

The emission factor for nitrous oxide in PE units has been rising due to increasing amounts of industrial wastewater to the public sewer system. The share of industrial wastewater led to the public sewer system compared to the total wastewater treated increased from 2.5 % in 1990 to 40.5 % in 2004 and onwards. This has led to increased inputs of nitrogen to the Danish wastewater treatment plants, with resulting higher nitrous oxide emissions.

The Danish EF value is higher than the default IPCC EF value of 3.2 g $N_2O$ per person. The development in the Danish EF value is presented in Table 3.13.

Table 3.13 Population number, influent N and time trend for the Danish EF value in units of g $N_2O$/person/year.

| Year | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|
| Population number | 5,135,409 | 5,215,718 | 5,330,020 | 5,411,405 | 5,534,738 | 5,560,628 | 5,580,516 |
| $TN_{influent}$, country data | 14,679 | 22,340 | 26,952 | 32,288 | 27,357 | 30,049 | 26,316 |
| *EF* [g $N_2O$ per person] | 15.8 | 23.7 | 28.0 | 33.1 | 27.4 | 30.0 | 26.1 |
| $EF_{default\ IPPC}$, % underestimated | 80 | 87 | 89 | 90 | 88 | 89 | 88 |

As may be observed from Table 3.3, the Danish EF value in units of g $N_2O$ per person is fluctuating with an increasing tendency. From 1990 to 2013 the increase is 70 % in units of g $N_2O$ per person. As such, use of the default IPCC value would result in an underestimation the Danish $N_2O$ emissions by 80 % in 1990 and 88 % in 2013. The increase in the Danish EF value when expressed in units g $N_2O$ per person is partly to be explained by the increase in the contribution from industries to the influent wastewater content of N.

Measurements done at Danish wastewater treatment plants shows values for the $N_2O$ emission factor between 9 and 28 g $N_2O$ per PE per year at respectively low (Ejby Mølle) and high (Marselisborg) loaded plants (Andreasen, 2013). The Danish emission factor used for estimating the direct $N_2O$ emissions, i.e. 4.99 g $N_2O$ per kg N in the influent wastewater, corresponding to 26-30 g $N_2O$/person is in the higher end of the reported measurements.

### 3.2.2 Indirect $N_2O$ emissions

The activity data used for calculating the indirect nitrous oxide emissions are the total N content in the effluent wastewater presented in Chapter 2.4.

For activity data on N in the effluent wastewater from WWTPs, plant data have been extracted, but is not yet verified against the national level data reported by the Danish Nature Agency; i.e. as was done for the N and COD in influent wastewater (Table 2.1 and Table 2.8). Additionally, no efforts was done to verify the N content in the effluents from scattered settlements (Annex B. , Table B 1), neither regarding the contribution from rainwater conditioned effluents, aquaculture or separate industries.

# 4 Planned Improvements

For next year's emission inventory it is considered to use equation 3 to derive a percent COD lost as venting at national level. In addition, it is important is to setup plant level COD mass balances for WWTPs with biogas production.

Plant level mass balance is also required for nitrogen as external carbon in the ingestate influences the $N_2O$ emission. Lastly, a review and documentation for the country specific $N_2O$ EF based on changes in N removal technologies implemented at the WWT plants is needed (Thomsen et al., 2015).

Lastly, direct $N_2O$ emissions from separate industries, as presented in Annex E, will also be included in future GHG inventories for sub-category *5.D Wastewater treatment and Discharge*.

# References


Adouani, N., Lendormi, T., Limousy, L., Sire, O., 2010: Effect of the carbon source on $N_2O$ emissions during biological denitrification. Resources, Conservation and Recycling 54(5), 299-302. doi:10.1016/j.resconrec.2009.07.011.

Andersen, J.M., 1983: Sammenligning mellem modificeret og umodificeret BOD og betydning af forskelle for udlederkrav (English title: Comparrison of modified and unmodified BOD and the influence of differences on the regulatory effluent criteria), 15, 50-58. News from the reference laboratory on chemical water analysis, Danish EPA.

Andreasen, P., 2013. Monitorering og minimering af lattergasemission fra renseanlæg. Rapportering til VTUF om opnåede resultater og målopfyldelse.

Billund Vand A/S, 2014: Miljøredegørelse 2013 for Billund Energi og Grindsted renseanlæg. Available at:
http://www.billundvand.dk/files/files/2014-1_Billund_Vand_redeg%C3%B8relse.pdf

Bagge, L., personal communication, The National Sludge Database, 18-2-2013. Miljøstyrelsen - Jord & Affald, phone: 7254 4156, e-mail: bagge@mst.dk

BAI, 2011: Spildevand- Slambehandling. Undervisningsministeriet.

Chiu, Y.-C. & Chung, M.-S., 2003: Determination of optimal COD=nitrate ratio for biological denitrification. International Biodeterioration & Biodegradation 51:43 – 49.

Daelman, M.R.J., van Voorthuizen, E.M., van Dongen, L.G.J.M., Volcke, E.I.P. & van Loosdrecht, M.C.M., 2013: Methane and nitrous oxide emissions from municipal wastewater treatment – results from a long-term study. Water Sci Technol., in press. Available at:
http://users.ugent.be/~evolcke/pdf/2013_Daelman_WST_CH4_N2O_Longtermstudy.pdf (05-05-2016).

DCCA (Danish Competition and Consumer Authority), (In Danish: Konkurrence og forbrugerstyrelsen, Forsyningssekretariatet), 2014: version 2. Determination of individual efficiency requirements of price caps for 2015 ( In Danish: Results-oriented benchmarking for 2015. Fastsættelse af individuelle effektiviseringskrav i prislofterne for 2015). Available at:
http://www.kfst.dk/Vandtilsyn/Benchmarking/Benchmarking-2015

DGC, 2009: Gasmotoranlæg, MAN, renseanlæg. Målerapport 731-28-7. Available at:
http://www.energinet.dk/DA/KLIMA-OG-MILJOE/Emissionskortlægning/Sider/Maalerapporter-fra-emissionskortlaegningsprojektet.aspx

DEA (Danish Energy Agency), 2014: Danish Energy Production Account (unpublished).

DEPA, 2014: Organiske restprodukter - vurdering af potentiale og behandlet mængde Organiske restprodukter - vurdering af potentiale og behandlet mængde. Miljøprojekt nr. 1529. ISBN nr. 978-87-93026-83-4. Available at: http://www2.mst.dk/Udgiv/publikationer/2014/01/978-87-93026-83-4.pdf

DEPA, 2010: Anvendelse af affald til jordbrugsformål. Vejledning fra Miljøstyrelsen Nr. 1 2010. Available at: http://www.landbrugsinfo.dk/Regelinfo/Kommenteringer/Filer/pl_ri_11_054_b1.pdf (28/02-2014).

DEPA, 2005: Betydning af erstatning af DS metoder med EN metoder - Bestemmelse af biokemisk oxygenforbrug (BOD) Miljøstyrelsens Referencelaboratorium. Available at: http://www.reference-lab.dk/media/7799829/bod.pdf

DEPA, 2002: Miljøstyrelsens Referencelaboratorium Metodeafprøvning BOD5 i afløbsvand fra renseanlæg Interlaboratorieundersøgelse 2002.

DEPA, 2000: Livscyklus-Screening af renseteknologier indenfor fiskeindustrien. Arbejdsrapport fra Miljøstyrelsen nr. 18. Available at: http://www2.mst.dk/common/Udgivramme/Frame.asp?http://www2.mst.dk/udgiv/Publikationer/2000/87-7944-240-4/html/default.htm

DEPA, 1990: Danmarks udledning af industrielt spildevand. Miljøprojekt 153. Available at: http://www2.mst.dk/Udgiv/publikationer/1990/87-503-8610-7/pdf/87-503-8610-7.pdf

DHI, 2001: Regulering af belastningsparametre fra industrier i Lynettefællesskabets opland. Teknisk og miljømæssig udredning. Available at: http://www.spildevandsinfo.dk/lynette/itf5.50/knw/wit/ltfknowledge.nsf/WebLTFEmbedView/807E2E6AA50EDF5CC1256F000032AE70/$FILE/50858%20notat.pdf

DME (Danish Ministry of Environment), 1990: Danmarks udledning af industrielt spildevand. Available at: http://www2.mst.dk/Udgiv/publikationer/1990/87-503-8610-7/pdf/87-503-8610-7.pdf

DME (Danish Ministry of Environment), 1992: Forfældning af spildevand ved kvælstoffjernelse (English title: Precipitation of wastewater with N removal). Available at: http://www2.mst.dk/Udgiv/publikationer/1992/87-7810-052-6/pdf/87-7810-052-6.pdf

DME (Ministry of Environment), DEPA (Danish Environmental Agency), 1996: Punktkilder 1995 (English title: "Point sources 1995"). Available at: http://mst.dk/service/publikationer/publikationsarkiv/1997/jan/punktkilder-1995/

DME (Ministry of Environment), DEPA (Danish Environmental Agency), 1997: Punktkilder 1996 (English title: "Point sources 1996"). Available at: http://mst.dk/service/publikationer/publikationsarkiv/1998/feb/punktkilder-1996/

DME (Ministry of Environment), DEPA (Danish Environmental Agency), 1998: Punktkilder 1997 (English title: ”Point sources 1997”). Available at: http://mst.dk/service/publikationer/publikationsarkiv/1998/dec/punktkilder-1997/

DME (Ministry of Environment), DEPA (Danish Environmental Agency), 1999. Punktkilder 1998 (English title: ”Point sources 1998”). Available at: http://mst.dk/service/publikationer/publikationsarkiv/2000/jan/punktkilder-1998/

DME (Ministry of Environment), DEPA (Danish Environmental Agency), 2000: Punktkilder 1999 (English title: ”Point sources 1999”). Available at: http://mst.dk/90264

DME (Ministry of Environment), DEPA (Danish Environmental Agency), 2001: Punktkilder 2000 (English title: ”Point sources 2000”). Available at: http://mst.dk/service/publikationer/publikationsarkiv/2001/dec/punktkilder-2000/

DME (Ministry of Environment), DEPA (Danish Environmental Agency), 2002: Punktkilder 2001 (English title: ”Point sources 2001”). Available at: http://mst.dk/service/publikationer/publikationsarkiv/2002/dec/punktkilder-2001/

DME (Ministry of Environment), DEPA (Danish Environmental Agency), 2003a: Punktkilder 2002 (English title: ”Point sources 2002”). Available at: http://mst.dk/service/publikationer/publikationsarkiv/2003/dec/punktkilder-2002/

DME (Ministry of Environment and Energy), DEPA (Danish Environmental Agency), 2003b Spildevandsslam fra kommunale og private renseanlæg i 2000 og 2001 (English title: “Sewage sludge from municipal and private wastewater treatment plants in 2000 and 2001”). Available at: http://mst.dk/service/publikationer/publikationsarkiv/2003/okt/spildevandsslam-fra-kommunale-og-private-renseanlaeg-i-2000-og-2001/

DME (Ministry of Environment), DEPA (Danish Environmental Agency), 2004a: Punktkilder 2003 (English title: ”Point sources 2003”). Available at: http://mst.dk/service/publikationer/publikationsarkiv/2004/dec/punktkilder-2003/

DME (Ministry of Environment and Energy), DEPA (Danish Environmental Agency), 2004b: Spildevandsslam fra kommunale og private renseanlæg i 2002 (English title: “Sewage sludge from municipal and private wastewater treatment plants in 2002”). Available at: http://mst.dk/service/publikationer/publikationsarkiv/2004/mar/spildevandsslam-fra-kommunale-og-private-renseanlaeg-i-2002/

DME (Ministry of Environment), DEPA (Danish Environmental Agency) 2005: Punktkilder 2004 (English title: ”Point sources 2004”). Available at: http://mst.dk/service/publikationer/publikationsarkiv/2005/nov/punktkilder-2004/

DME (Ministry of Environment), DEPA (Danish Environmental Agency), 2007: Punktkilder 2006 (English title: ”Point sources 2006”). Available at: http://naturstyrelsen.dk/publikationer/2008/okt/punktkilder-2006-det-nationale-program-for-overvaagning-af-vandmiljoeet-fagdatacenterrapport/

DME (Ministry of Environment), URA (Urban and Rural Agency), 2008: Punktkilder 2007 (English title: ”Point sources 2007”). Available at: http://naturstyrelsen.dk/media/nst/70839/Punktkilderendelig.pdf

DME (Ministry of Environment), URA (Urban and Rural Agency), 2009a: Punktkilder 2008 (English title: ”Point sources 2008”). Available at: http://naturstyrelsen.dk/publikationer/2010/feb/punktkilderapport-2008/

DME (Ministry of Environment and Energy), DEPA (Danish Environmental Agency), 2009b: Spildevandsslam fra kommunale og private renseanlæg i 2005 (English title: “Sewage sludge from municipal and private wastewater treatment plants in 2005”). Available at: http://mst.dk/service/publikationer/publikationsarkiv/2009/maj/spildevandsslam-fra-kommunale-og-private-renseanlaeg-i-2005/

DME (Ministry of Environment), NA (Nature Agency), 2010: Punktkilder 2009 (English title: ”Point sources 2009”). Available at: http://naturstyrelsen.dk/publikationer/2011/jan/punktkilder-2009/

DME (Ministry of Environment), NA (Nature Agency), 2011: Punktkilder 2010 (English title: ”Point sources 2010”). Available at: http://naturstyrelsen.dk/publikationer/2011/dec/punktkilderapport-2010/

DME (Ministry of Environment), NA (Nature Agency), 2012a: Punktkilder 2011 (English title: ”Point sources 2011”). Available at: http://naturstyrelsen.dk/publikationer/2012/dec/punktkilder-2011/

DME (Ministry of Environment and Energy), DEPA (Danish Environmental Agency), 2012b: Spildevandsslam fra kommunale og private renseanlæg i 2005 (English title: “Sewage sludge from municipal and private wastewater treatment plants in 2008 and 2009”). Unpublished.

DME (Ministry of Environment), NA (Nature Agency), 2013: Punktkilder 2012 (English title: ”Point sources 2012”). Available at: http://naturstyrelsen.dk/media/nst/89739/Punktkilderapport2012.pdf

DME (Ministry of Environment), NA (Nature Agency), 2014. Punktkilder 2013 (English title: ”Point sources 2013”). Available at: http://naturstyrelsen.dk/publikationer/2015/feb/punktkilder-2013/

DMEE (Danish Ministry of Environment and Energy), Danish Environmental Protection Agency (DEPA), 1989: Spildevandsslam fra kommunale og private renseanlæg i 1987 ( English title: Wastewater from municipal and private wastewater treatment plants in 1987). Available at: http://www2.mst.dk/Udgiv/publikationer/1989/87-503-7944-5/pdf/87-503-7944-5.pdf

DMEE (Ministry of Environment and Energy), DEPA (Danish Environmental Agency), 1994a: Vandmiljø – 1994 (English title: Water Environment – 1994). Available at: http://www2.mst.dk/Udgiv/publikationer/1994/87-7810-273-1/pdf/87-7810-273-1.pdf

DMEE (Ministry of Environment and Energy), DEPA (Danish Environmental Agency) 1994b: Punktkilder 1993 (English title: "Point sources 1993"). Available at: http://mst.dk/service/publikationer/publikationsarkiv/1995/jan/punktkilder-1993/

DMEE (Ministry of Environment and Energy), DEPA (Danish Environmental Agency), 1995a: Spildevandstilladelser og renere teknologi. Available at: http://www2.mst.dk/Udgiv/publikationer/1995/87-7810-390-8/pdf/87-7810-390-8.pdf

DMEE (Ministry of Environment and Energy), DEPA (Danish Environmental Agency), 1995b: Punktkilder 1994 (English title: "Point sources 1994"). Available at: http://mst.dk/service/publikationer/publikationsarkiv/1996/jan/punktkilder-1994/

DMEE (Ministry of Environment and Energy), DEPA (Danish Environmental Agency), 1999a: Spildevandsslam fra kommunale og private renseanlæg i 1997 (English title: "Sewage sludge from municipal and private wastewater treatment plants in 1997"). Available at: http://mst.dk/service/publikationer/publikationsarkiv/1999/maj/spildevandsslam-fra-kommunale-og-private-renseanlaeg-i-1997/

DMEE (Ministry of Environment and Energy), DEPA (Danish Environmental Agency), 1999b: Vandmiljø-9. Status for vandmiljøets tilstand i Danmark. Available at: http://www2.mst.dk/udgiv/Publikationer/1999/87-7909-531-3/pdf/87-7909-530-5.pdf

DMEE (Ministry of Environment and Energy), DEPA (Danish Environmental Agency), 2001: Spildevandsslam fra kommunale og private renseanlæg i 1999 (English title: "Sewage sludge from municipal and private wastewater treatment plants in 1999"). Available at: http://mst.dk/service/publikationer/publikationsarkiv/2001/feb/spildevandsslam-fra-kommunale-og-private-renseanlaeg-i-1999/

DS/EN ISO 1899-1:2003: Vandundersøgelse. Biokemisk oxygenforbrug over n døgn, (BODn) Del 1: Fortyndingsmetode med podning og tilsætning af N-allylthiourinstof (English title: Water quality – Determination of biochemical oxygen demand after n days (BODn) – Part 1: Dilution and seeding method with allylthiourea addition) (EN 1899-1:1998). Available at: https://webshop.ds.dk/Files/Files/Products/52500_attachPV.pdf

DS/EN ISO 1899-2:2004: Water quality – Determination of biochemical oxygen demand after n days (BODn) – Part 2: Method for undiluted samples. Available at: https://webshop.ds.dk/Files/Files/Products/54648_attachPV.pdf

Hanaki, K., Hong, Z. & Matsuo, T. 1992: Production of nitrous oxide gas during denitrification of wastewater. Wat. Sci. Technol. 26:1027-1036.

Henze, M., Sørensen, P.E. & Petersen, G., 2014: Spildevandsrensning i Danmark 1969-2014. Vand & Jord 21. årgang nr. 4, december 2014. Available at: http://www.kruger.dk/krugeras/ressources/documents/3/39561,VJ-4_14_s160_167.pdf

Henze, M., Petersen, G., Kristensen, G.H. & Höök, B., 2010: Drift af Renseanlæg. Teknik, 3. udgave, Kommuneforlaget A/S. 978-87-7848-977-7-pdf

Henze. M., 2008: Biological Wastewater Treatment: Principles Modelling and Design. Edited by M. Henze, M.C.M. van Loosdrecht, G.A. Ekama and D. Brdjanovic. ISBN: 9781843391883. Published by IWA Publishing, London, UK. Available at: http://ocw.unesco-ihe.org/pluginfile.php/462/mod_resource/content/1/Urban_Drainage_and_Sewerage/5_Wet_Weather_and_Dry_Weather_Flow_Characterisation/DWF_characterization/Notes/Wastewater%20characterization.pdf

Hjort-Gregersen, K., 2013: Methane emission from Danish biogas plants. Economic Impact of Identified Methane Leakages. AgroTech, Project: ForskEl 2013-1-12093. Available at: http://www.agrotech.dk/sites/agrotech.dk/files/public/economic_impact_of_identified_methane_leakages.pdf (05-05-2016).

Illerup, J.B.; Lyck, E.; Nielsen, O.-K.; Mikkelsen, M.H.; Hoffmann, L.; Gyldenkærne, S.; Nielsen, M.; Sørensen, P.B.; Vesterdal, L.; Fauser, P.; Thomsen, M.; Winther, M., 2006: Denmark 's National Inventory Report 2006. Submitted under the United Nations Framework Convention on Climate Change, 1990-2004. National Environmental Research Institute, 2006. 555 s. (NERI Technical Report, Vol. 589).

Illerup, J.B., Lyck, E., Nielsen, O.-K., Mikkelsen, M.H., Hoffmann, L., Gyldenkærne, S., Vesterdal, L., 2007: Denmark's National Inventory Report 2007. Emission Inventories - Submitted under the United Nations Framework Convention on Climate Change, 1990-2005. Danmarks Miljøundersøgelser, Aarhus Universitet. (NERI Technical Report, Vol. 632).

ISO 5815-1, 2003: Water quality -- Determination of biochemical oxygen demand after n days (BODn) -- Part 1: Dilution and seeding method with allylthiourea addition.

ISO 5815-2, 2003: Water quality -- Determination of biochemical oxygen demand after n days (BODn) -- Part 2: Method for undiluted samples

IPCC, 2006: 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Available at: http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_6_Ch6_Wastewater.pdf

IPCC, 1996: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. Available at: http://www.ipcc-nggip.iges.or.jp/public/gl/invs5e.html

Itokawa, H.,Hanaki, K. & Matsuo, T., 2001: Nitrous oxide production in high-loading biological nitrogen removal process under low cod/n ratio condition. Wat. Res. 35:657-664.

Jensen, M.D., Tychsen, P., Thomsen, M., Martinsen, L. & Hasler, B., 2015: Bæredygtig udnyttelse af fosfor fra spildevand. En operativ vejledning til de danske vandselskaber. Danish Environmental Protection Agency, Ministry of Environment, Environmental Project no. 1661. Available at: http://mst.dk/service/publikationer/publikationsarkiv/2015/mar/baeredygtig-udnyttelse-af-fosfor-fra-spildevand

Johansen, R., 2013: Intelligent Carbon and Energy Utilization. Available at: http://www.envidan.dk/Publikationer/Artikler.aspx

Kampschreur,_M.J., van der Star, W.R.L., Wielders, H.A., Mulder, J.W., Jetten, M.S.N. & van Loosdrecht, M.C.M., 2008: Dynamics of nitric oxide and nitrous oxide emission during full-scale reject water treatment. Water Research, 42:812-826

Kampschreur, M.J., Temmink, H., Kleerebezem, R., Jetten, M.S.M. and van Loosdrecht, M.C.M., 2009: Nitrous oxide emission during wastewater treatment.Water Research, 43:4093-4103

Kimochi, Y., Inamori, Y., Mizuochi, M., Xu, K.-Q. & Matsumura, M., 1998: Nitrogen removal and $N_2O$ emission in a full-scale domestic wastewater treatment plant with intermittent aeration. Journal of Fermentation and Bioengineering, 86: 202-206.

Kristensen, G.H. & Jørgensen, P.E., 2008: Renseteknologi – oversigt over ny miljøteknologi indenfor spildevandshåndtering (English title: Wastewater treatment tenologies – overview of novel environmental technology within the wastewater sector). A report from the Ministry of Environment. Available at: http://www2.blst.dk/udgiv/Publikationer/2008/978-87-92256-39-3/pdf/978-87-92256-40-9.pdf

Nature Agency (2016). The National Programme for monitoring of the aquatic environment and the nature (in Danish). Available at: http://naturstyrelsen.dk/media/194550/novana2016-programbeskrivelse.pdf

Nielsen, M. & Illerup, J.B., 2003: Emissionsfaktorer og emissionsopgørelse for decentral kraftvarme: Eltra PSO projekt 3141. Kortlægning af emissioner fra decentrale kraftvarmeværker. Delrapport 6. Available at: http://www2.dmu.dk/1_viden/2_Publikationer/3_fagrapporter/rapporter/FR442.pdf

Nielsen, O.-K., Lyck, E., Mikkelsen, M.H., Hoffmann, L., Gyldenkærne, S., Winther, M., Nielsen, M., Fauser, P., Thomsen, M., Plejdrup, M.S., Illerup, J.B., Sørensen, P.B. & Vesterdal, L., 2008: Denmark's National Inventory Report 2008: Emission Inventories 1990-2006 - Submitted under the United Nations Framework onvention on Climate Change. National Environmental Research Institute, Aarhus University. NERI Technical Report, no. 667.

Nielsen, O.-K., Lyck, E., Mikkelsen, M.H., Hoffmann, L., Gyldenkærne, S., Winther, M., Nielsen, M., Fauser, P., Thomsen, M., Plejdrup, M.S., Albrektsen, R., Hjelgaard, K., Vesterdal, L., Møller, I.S. & Baunbæk, L. 2009: Denmark's National Inventory Report 2009. Emission Inventories 1990-2007 - Submitted under the United Nations Framework Convention on Climate Change. National Environmental Research Institute, Aarhus University. 826 pp. – NERI Technical Report No 724. Available at: http://www.dmu.dk/Pub/FR724.pdf

Nielsen, O.-K., Lyck, E., Mikkelsen, M.H., Hoffmann, L., Gyldenkærne, S., Winther, M., Nielsen, M., Fauser, P., Thomsen, M., Plejdrup, M.S., Albrektsen, R., Hjelgaard, K., Johannsen, V.K., Vesterdal, L., Rasmussen, E., Arfaoui, K. & Baunbæk, L., 2010: Denmark's National Inventory Report 2010. Emission Inventories 1990-2008 - Submitted under the United Nations Framework Convention on Climate Change and the Kyoto Protocol. National Environmental Research Institute, Aarhus University, Denmark. 1178 pp. – NERI Technical Report No 784. Available at: http://www.dmu.dk/Pub/FR784.pdf

Nielsen, M., Nielsen, O.-K. & Thomsen, M., 2010: Emissions from decentralised CHP plants 2007 - Energinet.dk Environmental project no. 07/1882. Project report 5 – Emission factors and emission inventory for decentralised CHP production. National Environmental Research Institute, Aarhus University. 113 pp. – NERI Technical report No. 786. Available at: http://www.dmu.dk/Pub/FR786.pdf.

Nielsen, O.-K., Mikkelsen, M.H., Hoffmann, L., Gyldenkærne, S., Winther, M., Nielsen, M., Fauser, P., Thomsen, M., Plejdrup, M.S., Albrektsen, R., Hjelgaard, K., Bruun, H.G., Johannsen, V.K., Nord-Larsen, T., Bastrup-Birk, A., Vesterdal, L., Stupak, I., Rasmussen, E., Arfaoui, K., Baunbæk, L. & Hansen, M.G. 2011: Denmark's National Inventory Report 2011. Emission Inventories 1990-2009 - Submitted under the United Nations Framework Convention on Climate Change and the Kyoto Protocol. National Environmental Research Institute, Aarhus University. NERI Technical Report, no. 827.

Nielsen, O.-K., Mikkelsen, M.H., Hoffmann, L., Gyldenkærne, S., Winther, M., Nielsen, M., Fauser, P., Thomsen, M., Plejdrup, M.S., Albrektsen, R., Hjelgaard, K., Bruun, H.G., Johannsen, V.K., Nord-Larsen, T., Bastrup-Birk, A., Vesterdal, L., Møller, I.S., Rasmussen, E., Arfaoui, K., Baunbæk, L. & Hansen, M.G. 2012: Denmark's National Inventory Report 2012. Emission Inventories 1990-2010 - Submitted under the United Nations Framework Convention on Climate Change and the Kyoto Protocol. Aarhus University, DCE - Danish Centre for Environment and Energy. Scientific Report from DCE – Danish Centre for Environment and Energy, no. 19.

Nielsen, O.-K., Plejdrup, M.S., Winther, M., Nielsen, M., Gyldenkærne, S., Mikkelsen, M.H., Albrektsen, R., Thomsen, M., Hjelgaard, K., Hoffmann, L., Fauser, P., Bruun, H.G., Johannsen, V.K., Nord-Larsen, T., Vesterdal, L., Stupak, I., Caspersen, O.H., Rasmussen, E., Petersen, S.B., Baunbæk, L. & Hansen, M.G. 2013: Denmark's National Inventory Report 2013. Emission Inventories 1990-2011 - Submitted under the United Nations Framework Convention on Climate Change and the Kyoto Protocol. Aarhus Universitet, DCE - Nationalt Center for Miljø og Energi. Scientific Report from DCE - Danish Centre for Environment and Energy, no. 56.

Nielsen, O.-K., Plejdrup, M.S., Winther, M., Nielsen, M., Gyldenkærne, S., Mikkelsen, M.H., Albrektsen, R., Thomsen, M., Hjelgaard, K., Hoffmann, L., Fauser, P., Bruun, H.G., Johannsen, V.K., Nord-Larsen, T., Vesterdal, L., Møller, I.S., Caspersen, O.H., Rasmussen, E., Petersen, S.B., Baunbæk, L. & Hansen, M.G. 2014: Denmark's National Inventory Report 2014. Emission Inventories 1990-2012 - Submitted under the United Nations Framework Convention on Climate Change and the Kyoto Protocol. Aarhus University, DCE – Danish Centre for Environment and Energy, 1214pp. Scientific Report from DCE – Danish Centre for Environment and Energy. Available at: http://dce2.au.dk/pub/SR101.pdf

Nielsen, O.-K., Plejdrup, M.S., Winther, M., Nielsen, M., Gyldenkærne, S., Mikkelsen, M.H., Albrektsen, R., Thomsen, M., Hjelgaard, K., Fauser, P., Bruun, H.G., Johannsen, V.K., Nord-Larsen, T., Vesterdal, L., Møller, I.S., Caspersen, O.H., Rasmussen, E., Petersen, S.B., Baunbæk, L. & Hansen, M.G. 2015: Denmark's National Inventory Report 2015. Emission Inventories1990-2013 – Submitted under the United Nations Framework Convention on Climate Change and the Kyoto Protocol. vol. 171, Aarhus University, DCE – Danish Centre for Environment and Energy.

Niero, M., Pizzol, M., Bruun, H.G. & Thomsen, M., 2014: Comparative life cycle assessment of wastewater treatment in Denmark including sensitivity and uncertainty analysis. Journal of Cleaner Production, 68, 25–35.

Park, K.Y., Inamori, Y., Mizuochi, M. & Ahn, K.H., 2000: Emission and control of nitrous oxide from a biological wastewater treatment system with intermittent aeration, Journal of Bioscience and Bioengineering 90: 247–252.

Petersen, G. 2013: Døgnkursus nov. 2013: "Intelligent kulstof og energi udnyttelse på renseanlæg". Available at: http://www.envidan.dk/Publikationer/Pr%C3%A6sentationer.aspx

Sharma, A.K., Guildal, T., Jacobsen, B.N., Rindel, K., Gustavsson, D., Nyberg, U., la Cour Jansen, J., Lindblom, E., Jeppsson, U., Petersen, J., Thomsen, H.A. & Önnerth, T., 2008: V Behandlingskapacitet og Optimering af Drift af Afløbssystemer og Renseanlæg I Øresundsregionen. - Resumé rapport. EU project, INTERREG IIIA: "OpDrift".

Sivret, E.C., Peirson, W.L. & Stuetz, R.M., 2008: Nitrous Oxide Monitoring for Nitrifying Activated Sludge Aeration Control: A Simulation Study. Biotechnology and Bioengineering, 110:109-118

Tafdrup, Søren, personal communication, Gross energy production, August 2014, Consultant, Danish Energy Agency, phone: +45 +3392 6771, e-mail: st@ens.dk.

Tallec, G., Garnier, J., Billen, G. & Gousailles, M., 2008: Nitrous oxide emissions from denitrifying activated sludge of urban wastewater treatment plants, under anoxia and low oxygenation.Bioresource Technology, 99:2200-2209.

Thomsen, M., With Ottosen, T. & Nyrup Drejer, L., 2015: Analyse af potentialer for ressourceudnyttelse i vand- og spilde-vandsforsyningen. Naturstyrelsen, Miljøministeriet, 2015. 85 s. Available at: http://ecoinnovation.dk/media/130961/analyse-af-potentialer-for-ressourceudnyttelse-i-vand-og-spildevandsforsyningen.pdf

Thomsen, M. & Lyck, E. 2005: Emission of $CH_4$ and $N_2O$ from Wastewater Treatment Plants (6B). National Environmental Research Institute, Denmark. 46 pp. – Research Notes from NERI no. 208. Available at: http://www2.dmu.dk/1_viden/2_Publikationer/3_arbrapporter/rapporter/AR208.pdf

Van Niel, E.W.J., Arts, P.A.M., Wesselink, B.J., Robertson, L.A. & Kuenen, J.G., 1993: Competition between heterotrophic and autotrophic nitrifiers for ammonia in chemostat cultures. FEMS Microbiology Ecology 102(2), 109-118.

Villumsen, C. R., personal communication, Extension of the sewer system in Denmark, 02-09-2014. Special consultant, Climate Adaption, Water sector and groundwater, Danish EPA, e-mail: carvi@nst.dk.

Vollertsen, J., personal communication, $MCF_{sewer+MB.}$ 16-09-2012. Aalborg University, Section of Water and Soil, Department of Civil Engineering, Mobile: +45 2895 9195, E-mail: jv@civil.aau.dk

UNFCCC, 2013: Report of the individual review of the annual submission of Denmark submitted in 2012. Available at: http://unfccc.int/resource/docs/2013/arr/dnk.pdf

UNFCCC, 2014: Report of the individual review of the annual submission of Denmark submitted in 2013. Available at: https://unfccc.int/documentation/documents/advanced_search/items/6911.php?priref=600008002

# Annex A. COD data

Table A 1 TOW in the influent wastewater measures in units of tonne COD.

| Unit of measure [tonne COD] | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 |
|---|---|---|---|---|---|---|
| TOW, country data | - | - | - | - | - | - |
| TOW, plant level data | - | - | - | - | - | - |
| TOW, default COD IPCC | 290,536 | 291,161 | 292,047 | 293,093 | 294,000 | 295,079 |
| Contribution from industrial inlet [%] | 2.5 | 2.5 | 2.5 | 5.,0 | 13.6 | 22.2 |
| TOW, default COD IPCC, adding Danish industrial influent loads | 297,799 | 298,441 | 299,348 | 307,748 | 333,984 | 360,587 |
| TOW, PE BOD value and COD/BOD CF of 2.5 (IPCC, 2000) | 303,657 | 304,311 | 305,237 | 306,330 | 307,277 | 308,405 |
| TOW, average | 300,728 | 301,376 | 302,292 | 307,039 | 320,631 | 334,496 |
| | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 |
| TOW, country data | - | - | - | 371,250 | 381,700 | 364,177 |
| TOW, plant level data | - | - | 258,586 | 347,385 | 350,689 | 363,687 |
| TOW, default COD IPCC | 297,077 | 298,440 | 299,557 | 300,616 | 301,546 | 302,632 |
| Contribution from industrial inlet [%] | 30.8 | 39.4 | 48.0 | 41.0 | 42.0 | 38.0 |
| TOW, default COD IPCC, adding Danish industrial influent loads | 388,577 | 416,025 | 443,344 | 423,868 | 428,195 | 417,632 |
| TOW, PE BOD value and COD/BOD CF of 2.5 (IPCC, 2000) | 310,493 | 311,918 | 313,085 | 314,192 | 315,164 | 316,299 |
| TOW, average | 349,535 | 363,972 | 378,214 | 369,770 | 375,020 | 366,036 |
| | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 |
| TOW, country data | 350,798 | 360,630 | 339,637 | 357,842 | 334,007 | 368,355 |
| TOW, plant level data | 350,798 | 360,630 | 339,637 | - | - | 369,006 |
| TOW, default COD IPCC | 303,715 | 304,572 | 305,371 | 306,150 | 307,058 | 308,169 |
| Contribution from industrial inlet [%] | 38.0 | 37.0 | 40.5 | 40.5 | 40.5 | 40.5 |
| TOW, default COD IPCC, corrected | 419,126 | 417,264 | 429,003 | 430,097 | 431,373 | 432,933 |
| TOW, National Unit PE BOD value | 317,431 | 318,327 | 319,162 | 319,976 | 320,926 | 322,086 |
| TOW, average | 362,452 | 365,407 | 362,601 | 369,305 | 362,102 | 374,458 |
| | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 |
| TOW, country data | 290,988 | 345,295 | 369,873 | 386,223 | 349,876 | 386,151 |
| TOW, plant level data | 290,988 | 342,131 | 369,873 | 371,713 | 349,876 | 386,151 |
| TOW, default COD IPCC | 309,793 | 311,810 | 313,128 | 314,593 | 315,718 | 316,969 |
| Contribution from industrial inlet [%] | 40.5 | 40.5 | 40.5 | 40.5 | 40.5 | 40.5 |
| TOW, default COD IPCC, corrected | 435,215 | 438,049 | 439,900 | 441,958 | 443,538 | 445,341 |
| TOW, National Unit PE BOD value | 323,784 | 325,892 | 327,269 | 328,800 | 329,976 | 331,283 |
| TOW, average | 349,995 | 369,745 | 379,014 | 380,823 | 374,463 | 387,592 |

"TOW, country data" are based on reported BOD data converted into COD by multiplying with the default COD/BOD conversion factor of 2.5 (IPCC, 2006).
"TOW, plant level data" are based on plant level COD monitoring data that were extracted from respectively reports from the Danish Nature Agency (DMEE, 1989, 1990 1992, 1994a, b, 1995a,b; DME 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003, 2004,2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014) and the Danish water quality database (www.miljoeportalen.dk).
"TOW, default COD IPCC" are the default IPCC PE value of 62 g BOD/person/day multiplied by the default COD/BOD conversion factor of 2.5 (IPCC, 2006) multiplied by the population number of Denmark.
"TOW, default COD IPCC, corrected" are the above corrected for the contribution from industries connected to the collective sewer system in Denmark.
"TOW, National Unit PE BOD value" are the national BOD value of 21.9 kg BOD per year multiplied by a national COD/BOD conversion factor of 2.7 and multiplied by the population number of Denmark.
The "TOW, average" is used as the key activity data set for deriving methane emissions from wastewater treatment. For the years 1990-1998 an average of the TOW data based on the "TOW, default COD IPCC, adding Danish industrial influent loads" and the "TOW, National PE for BOD using IPCC 2000 COD/BOD CF of 2.7". For the years 1999-2013 "TOW, country data" were included in the calculation of an average best TOW value; except for the years 2011 and 2013 where the plant level COD data were used instead of the country level data.
The "TOW, plant level data" are part of a database designed specifically for the emission inventories, in which plant level IDs from the Danish monitoring program has been paired with plant level data from the Danish Energy Agency. These data are presently going through a quality control process. Results presented in the table above showing that the plant level data resamples the country level data reported by the Danish Nature Agency (DMEE, 1989, 1990 1992, 1994a, b, 1995a, b; DME 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014) and the Danish water quality database (www.miljoeportalen.dk).

Table A 2 COD mass balance in percent of the COD in the influent wastewater fitted to reported data on effluent reduction efficiencies (bold), final sludge amounts (bold) and gross energy production data (bold) reported by the Danish EPA and the Danish Energy Agency.

| Year | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 |
|---|---|---|---|---|---|---|
| WWTPs with aerobic sludge treatment | | | | | | |
| Biotanks, $COD_{air\ emission}$ [%] | 30 | 30 | 30 | 35 | 35 | 45 |
| Effluent, $COD_{effluent}$ [%] | 52 | 48 | 51 | 48 | 44 | 7 |
| Final sludge, $COD_{sludge}$ [%] | 18 | 22 | 19 | 17 | 21 | 48 |
| Influent, $COD_{influent}$ [tonne] | 192,814 | 188,411 | 198,703 | 209,287 | 200,420 | 177,551 |
| Biotanks, $COD_{air\ emission}$ [tonne] | 57,844 | 56,523 | 59,611 | 73,250 | 70,147 | 79,898 |
| Effluent, $COD_{effluent}$ [tonne] | 99,327 | 90,429 | 101,066 | 99,631 | 88,983 | 12,095 |
| Final sludge, $COD_{sludge}$ [tonne] | 35,642 | 41,459 | 38,027 | 36,406 | 41,290 | 85,558 |
| WWTPs with anaerobic sludge treatment | | | | | | |
| Biotanks, $COD_{air\ emission}$ [%] | 20 | 17 | 20 | 20 | 20 | 30 |
| Effluent, $COD_{effluent}$ [%] | 25 | 32 | 25 | 30 | 30 | 20 |
| Digestor tank, $COD_{ingestate}$ [%] | 44 | 41 | 44 | 40 | 40 | 40 |
| Final sludge, $COD_{sludge}$ [%] | 11 | 10 | 11 | 10 | 10 | 10 |
| Recovered, $COD_{recovered}$ [%] | 43 | 40 | 43 | 39 | 39 | 39 |
| Vented, $COD_{vented}$ [%] | 0.57 | 0.53 | 0.57 | 0.52 | 0.52 | 0.52 |
| Influent, $COD_{influent}$ [tonne] | 107,914 | 112,965 | 103,589 | 97,752 | 120,211 | 156,945 |
| Biotanks, $COD_{air\ emission}$ [tonne] | 21,583 | 19,204 | 20,718 | 19,550 | 24,042 | 47,084 |
| Effluent, $COD_{effluent}$ [tonne] | 26,979 | 36,149 | 25,897 | 29,326 | 36,063 | 31,389 |
| Ingestate, $COD_{ingestate}$ [tonne] | 59,353 | 57,612 | 56,974 | 48,876 | 60,105 | 78,473 |
| Final sludge, $COD_{sludge}$ [tonne] | 11,871 | 11,522 | 11,395 | 9,775 | 12,021 | 15,695 |
| Recovered, $COD_{recovered}$ [tonne] | 46,865 | 45,490 | 44,987 | 38,592 | 47,459 | 61,962 |
| Vented, $COD_{vented}$ [tonne] | 617 | 599 | 593 | 508 | 625 | 816 |
| Verification of final sludge amounts | | | | | | |
| COD in digestate [tonne COD/tonne DM] | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 |
| Inorganics in digestate [%] | 40 | 40 | 40 | 40 | 40 | 40 |
| COD in aerobic stab. sludge [tonne COD/tonne DM] | 1.20 | 1.20 | 1.20 | 1.20 | 1.20 | 1.20 |
| Inorganics in aerobic stab. sludge [%] | 50 | 50 | 50 | 50 | 50 | 50 |
| Estimated amount of digestate [tonne DM] | 24,730 | 24,005 | 23,739 | 20,365 | 25,044 | 32,697 |
| Estimated amount of aerobic stabilised sludge [tonne DM] | 85,542 | 99,501 | 91,264 | 87,374 | 99,097 | 205,338 |
| Estimated amount of total final sludge [tonne DM] | 110,272 | 123,506 | 115,003 | 107,739 | 124,140 | 238,035 |
| Reported amount of total final sludge [tonne DM] | - | - | - | - | - | 187,430 |
| %RSD | - | - | - | - | - | 17 |
| TOW in total amount of final sludge [tonne COD] | 47,513 | 52,981 | 49,422 | 46,181 | 53,311 | 101,252[2] |
| Inorganic content [%] | - | - | - | - | - | 46 |
| Reported amount of digestate [%] | - | - | - | - | - | 31 |
| Amount of digestate [tonne DM] | - | - | - | - | - | 58,103 |
| %RSD | - | - | - | - | - | 40 |
| Verification of reduction efficiency | | | | | | |
| Reported reduction efficiencies [%] | 58 | 58 | 58 | 58 | 61 | 87[2] |
| Effluent COD, National level [tonne] | 126,306 | 126,578 | 126,963 | 128,956 | 125,046 | 43,484 |
| Verification of methane production | | | | | | |
| $CH_{4,AD,gross}$ [Gg], (Eq. 5) | 8.8 | 9.2 | 8.4 | 7.8 | 9.2 | 11.5 |

| *Continued* | | | | | | |
|---|---|---|---|---|---|---|
| $CH_{4,AD,gross}$ [Gg], (Eq. 4a) | 9.5 | 9.2 | 9.1 | 7.8 | 9.6 | 12.6 |
| $EF_{AD}$ [kg $CH_4$/kg COD] =$B_o*MCF_{AD}*f_{AD}$ (Eq.4a) | 0.09 | 0.08 | 0.09 | 0.08 | 0.08 | 0.08 |
| Estimated $EF_{AD}$ [%] | 7.7 | 0.6 | 8.1 | 0.5 | 4.7 | 8.7 |
| Year | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 |
| WWTPs with aerobic sludge treatment | | | | | | |
| Biotanks, $COD_{air\ emission}$ [%] | 45 | 45 | 55 | 60 | 60 | 60 |
| Effluent, $COD_{effluent}$ [%] | 20 | 22 | 6 | 6 | 5 | 4 |
| Final sludge, $COD_{sludge}$ [%] | 35 | 33 | 39 | 34 | 35 | 36 |
| Influent, $COD_{influent}$ [tonne] | 187,672 | 158,169 | 152,027 | 171,522 | 190,192 | 164,111 |
| Biotanks, $COD_{air\ emission}$ [tonne] | 84,453 | 71,176 | 83,615 | 102,913 | 114,115 | 98,467 |
| Effluent, $COD_{effluent}$ [tonne] | 37,534 | 35,273 | 9,122 | 10,291 | 9,510 | 6,564 |
| Final sludge, $COD_{sludge}$ [tonne] | 65,685 | 51,719 | 59,290 | 58,317 | 66,567 | 59,080 |
| WWTPs with anaerobic sludge treatment | | | | | | |
| Biotanks, $COD_{air\ emission}$ [%] | 35 | 35 | 35 | 35 | 35 | 35 |
| Effluent, $COD_{effluent}$ [%] | 20 | 20 | 6 | 6 | 5 | 4 |
| Digestor tank, $COD_{ingestate}$ [%] | 36 | 36 | 47 | 47 | 48 | 49 |
| Final sludge, $COD_{sludge}$ [%] | 9 | 9 | 12 | 12 | 12 | 12 |
| Recovered, $COD_{recovered}$ [%] | 36 | 36 | 47 | 47 | 47 | 48 |
| Vented, $COD_{vented}$ [%] | 0.47 | 0.47 | 0.61 | 0.61 | 0.62 | 0.63 |
| Influent, $COD_{influent}$ [tonne] | 161,862 | 205,803 | 186,311 | 192,652 | 178,746 | 201,338 |
| Biotanks, $COD_{air\ emission}$ [tonne] | 56,651 | 72,031 | 65,209 | 67,428 | 62,561 | 70,468 |
| Effluent, $COD_{effluent}$ [tonne] | 32,372 | 41,161 | 11,179 | 11,559 | 8,937 | 8,054 |
| Ingestate, $COD_{ingestate}$ [tonne] | 72,838 | 92,611 | 109,924 | 113,664 | 107,247 | 122,816 |
| Final sludge, $COD_{sludge}$ [tonne] | 14,567 | 18,522 | 21,985 | 22,733 | 21,449 | 24,563 |
| Recovered, $COD_{recovered}$ [tonne] | 57,512 | 73,126 | 86,796 | 89,749 | 84,682 | 96,975 |
| Vented, $COD_{vented}$ [tonne] | 758 | 963 | 1,143 | 1,182 | 1,115 | 1,277 |
| Verification of final sludge amounts | | | | | | |
| COD in digestate [tonne COD/tonne DM] | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 |
| Inorganics in digestate [%] | 40 | 40 | 40 | 40 | 40 | 40 |
| COD in aerobic stab. sludge [tonne COD/tonne DM] | 1.20 | 1.20 | 1.20 | 1.20 | 1.20 | 1.20 |
| Inorganics in aerobic stab. sludge [%] | 50 | 50 | 50 | 50 | 50 | 50 |
| Estimated amount of digestate [tonne DM] | 30,349 | 38,588 | 45,802 | 47,360 | 44,686 | 51,173 |
| Estimated amount of aerobic stabilised sludge [tonne DM] | 157,645 | 124,127 | 142,297 | 139,962 | 159,761 | 141,792 |
| Estimated amount of total final sludge [tonne DM] | 187,994 | 162,715 | 188,099 | 187,322 | 204,447 | 192,965 |
| Reported amount of total final sludge [tonne DM] | 164,821 | 156,227 | 159,379 | 160,542 | 163,422 | 164,278 |
| %RSD | 9 | 3 | 12 | 11 | 16 | 11 |
| TOW in total amount of final sludge [tonne COD] | 80,253 | 70,242 | 81,275 | 81,050 | 88,017 | 83,643 |
| Inorganic content [%] | 51 | 55 | 49 | 50 | 46 | 49 |
| Reported amount of digestate [%] | 31 | 31 | - | - | 43 | 43 |
| Amount of digestate [tonne DM] | 51,095 | 48,430 | - | - | 69,945 | 70,640 |
| %RSD | 36 | 16 | - | - | 31 | 23 |
| Verification of reduction efficiency | | | | | | |
| Reported reduction efficiencies [%] | 80 | 79 | 94 | 94 | 95 | 96 |
| Effluent COD, National level [tonne] | 69,906 | 76,434 | 20,300 | 21,850 | 18,447 | 14,618 |

| Continued | | | | | | |
|---|---|---|---|---|---|---|
| Verification of methane production | | | | | | |
| $CH_{4,AD,gross}$ [Gg], (Eq. 5) | 11.3 | 13.8 | 13.5 | 14.8 | 16.4 | 16.4 |
| $CH_{4,AD,gross}$ [Gg], (Eq. 4a) | 11.7 | 14.8 | 17.6 | 18.2 | 17.2 | 19.7 |
| $EF_{AD}$ [kg $CH_4$/kg COD] =$B_o*MCF_{AD}*f_{AD}$ (Eq.4a) | 0.07 | 0.07 | 0.09 | 0.09 | 0.10 | 0.10 |
| Estimated $EF_{AD}$ [%] | 2.9 | 6.8 | 23.5 | 18.6 | 4.3 | 16.4 |
| Year | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 |
| WWTPs with aerobic sludge treatment | | | | | | |
| Biotanks, $COD_{air\ emission}$ [%] | 60 | 60 | 60 | 60 | 60 | 60 |
| Effluent, $COD_{effluent}$ [%] | 4 | 4 | 7 | 5 | 4 | 4 |
| Final sludge, $COD_{sludge}$ [%] | 36 | 36 | 33 | 35 | 36 | 36 |
| Influent, $COD_{influent}$ [tonne] | 179,438 | 162,847 | 175,529 | 192,664 | 199,705 | 212,780 |
| Biotanks, $COD_{air\ emission}$ [tonne] | 107,663 | 97,708 | 105,318 | 115,598 | 119,823 | 127,668 |
| Effluent, $COD_{effluent}$ [tonne] | 7,178 | 6,514 | 12,287 | 10,597 | 7,988 | 8,511 |
| Final sludge, $COD_{sludge}$ [tonne] | 64,598 | 58,625 | 57,925 | 66,469 | 71,894 | 76,601 |
| WWTPs with anaerobic sludge treatment | | | | | | |
| Biotanks, $COD_{air\ emission}$ [%] | 35 | 35 | 35 | 30 | 30 | 30 |
| Effluent, $COD_{effluent}$ [%] | 4 | 4 | 7 | 5 | 4 | 4 |
| Digestor tank, $COD_{ingestate}$ [%] | 49 | 49 | 46 | 52 | 53 | 53 |
| Final sludge, $COD_{sludge}$ [%] | 12 | 12 | 12 | 13 | 13 | 13 |
| Recovered, $COD_{recovered}$ [%] | 48 | 48 | 46 | 51 | 52 | 52 |
| Vented, $COD_{vented}$ [%] | 0.63 | 0.63 | 0.60 | 0.67 | 0.69 | 0.69 |
| Influent, $COD_{influent}$ [tonne] | 180,100 | 201,365 | 181,331 | 176,641 | 162,397 | 160,315 |
| Biotanks, $COD_{air\ emission}$ [tonne] | 63,035 | 70,478 | 63,466 | 52,992 | 48,719 | 48,095 |
| Effluent, $COD_{effluent}$ [tonne] | 7,204 | 8,055 | 12,693 | 9,715 | 6,496 | 6,413 |
| Ingestate, $COD_{ingestate}$ [tonne] | 109,861 | 122,833 | 105,172 | 113,934 | 107,182 | 105,808 |
| Final sludge, $COD_{sludge}$ [tonne] | 21,972 | 24,567 | 21,034 | 22,787 | 21,436 | 21,162 |
| Recovered, $COD_{recovered}$ [tonne] | 86,746 | 96,989 | 83,044 | 89,962 | 84,631 | 83,546 |
| Vented, $COD_{vented}$ [tonne] | 1,143 | 1,277 | 1,094 | 1,185 | 1,115 | 1,100 |
| Verification of final sludge amounts | | | | | | |
| COD in digestate [tonne COD/tonne DM] | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 |
| Inorganics in digestate [%] | 40 | 40 | 40 | 30 | 30 | 30 |
| COD in aerobic stab. sludge [tonne COD/tonne DM] | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Inorganics in aerobic stab. sludge [%] | 50 | 50 | 50 | 40 | 40 | 40 |
| Estimated amount of digestate [tonne DM] | 45,775 | 51,180 | 43,822 | 40,691 | 38,279 | 37,789 |
| Estimated amount of aerobic stabilised sludge [tonne DM] | 129,195 | 117,250 | 115,849 | 110,782 | 119,823 | 127,668 |
| Estimated amount of total final sludge [tonne DM] | 174,971 | 168,430 | 159,671 | 151,472 | 158,102 | 165,456 |
| Reported amount of total final sludge [tonne DM] | 147,451 | - | 140,884 | 76,084 | 76,247 | 120,070 |
| %RSD | 12 | - | 9 | 47 | 49 | 22 |
| TOW in total amount of final sludge [tonne COD] | 86,570 | 83,192 | 78,959 | 89,256 | 93,330 | 97,762 |
| Inorganic content [%] | 41 | - | 44 | - | - | 19 |
| Reported amount of digestate [%] | 45 | - | - | 54 | - | 50 |
| Amount of digestate [tonne DM] | 66,353 | - | - | 41,085 | - | 60,035 |
| %RSD | 26 | - | - | 1 | - | 32 |
| Verification of reduction efficiency | | | | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| *Continued* | | | | | | |
| Reported reduction efficiencies [%] | 96 | 96 | 93 | 95 | 96 | 96 |
| Effluent COD, National level [tonne] | 14,382 | 14,569 | 24,980 | 20,312 | 14,484 | 14,924 |
| Verification of methane production | | | | | | |
| $CH_{4,AD,gross}$ [Gg], (Eq. 5) | 16.6 | 16.6 | 15.9 | 17.5 | 16.8 | 16.6 |
| $CH_{4,AD,gross}$ [Gg], (Eq. 4a) | 17.6 | 19.7 | 16.8 | 18.2 | 17.1 | 16.9 |
| $EF_{AD}$ [kg $CH_4$/kg COD] $=B_o*MCF_{AD}*f_{AD}$ (Eq.4a) | 0.10 | 0.10 | 0.09 | 0.10 | 0.11 | 0.11 |
| Estimated $EF_{AD}$ [%] | 5.5 | 15.4 | 5.4 | 4.0 | 1.8 | 2.1 |
| Year | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 |
| WWTPs with aerobic sludge treatment | | | | | | |
| Biotanks, $COD_{air\ emission}$ [%] | 60 | 60 | 60 | 60 | 60 | 60 |
| Effluent, $COD_{effluent}$ [%] | 4 | 5 | 4 | 8 | 8 | 5 |
| Final sludge, $COD_{sludge}$ [%] | 36 | 35 | 36 | 32 | 32 | 35 |
| Influent, $COD_{influent}$ [tonne] | 206,932 | 191,700 | 197,275 | 221,122 | 252,985 | 248,177 |
| Biotanks, $COD_{air\ emission}$ [tonne] | 124,159 | 115,020 | 118,365 | 132,673 | 151,791 | 148,906 |
| Effluent, $COD_{effluent}$ [tonne] | 8,277 | 9,585 | 7,891 | 17,690 | 20,239 | 12,409 |
| Final sludge, $COD_{sludge}$ [tonne] | 74,496 | 67,095 | 71,019 | 70,759 | 80,955 | 86,862 |
| WWTPs with anaerobic sludge treatment | | | | | | |
| Biotanks, $COD_{air\ emission}$ [%] | 25 | 25 | 25 | 25 | 25 | 25 |
| Effluent, $COD_{effluent}$ [%] | 4 | 5 | 4 | 8 | 8 | 5 |
| Digestor tank, $COD_{ingestate}$ [%] | 57 | 56 | 57 | 54 | 54 | 56 |
| Final sludge, $COD_{sludge}$ [%] | 14 | 14 | 14 | 13 | 13 | 14 |
| Recovered, $COD_{recovered}$ [%] | 56 | 55 | 56 | 53 | 53 | 55 |
| Vented, $COD_{vented}$ [%][1] | 0.74 | 0.73 | 0.74 | 0.70 | 0.70 | 0.73 |
| Influent, $COD_{influent}$ [tonne] | 128,311 | 171,142 | 179,454 | 161,052 | 115,331 | 139,055 |
| Biotanks, $COD_{air\ emission}$ [tonne] | 32,078 | 42,785 | 44,864 | 40,263 | 28,833 | 34,764 |
| Effluent, $COD_{effluent}$ [tonne] | 5,132 | 8,557 | 7,178 | 12,884 | 9,227 | 6,953 |
| Ingestate, $COD_{ingestate}$ [tonne] | 91,101 | 119,799 | 127,413 | 107,905 | 77,272 | 97,338 |
| Final sludge, $COD_{sludge}$ [tonne] | 18,220 | 23,960 | 25,483 | 21,581 | 15,454 | 19,468 |
| Recovered, $COD_{recovered}$ [tonne] | 71,933 | 94,593 | 100,605 | 85,201 | 61,014 | 76,858 |
| Vented, $COD_{vented}$ [tonne] | 947 | 1,246 | 1,325 | 1,122 | 804 | 1,012 |
| Verification of final sludge amounts | | | | | | |
| COD in digestate [tonne COD/tonne DM] | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 |
| Inorganics in digestate [%] | 30 | 30 | 30 | 30 | 30 | 30 |
| COD in aerobic stab. sludge [tonne COD/tonne DM] | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Inorganics in aerobic stab. sludge [%] | 40 | 40 | 40 | 40 | 40 | 40 |
| Estimated amount of digestate [tonne DM][3] | 32,536 | 42,785 | 45,504 | 38,537 | 27,597 | 34,764 |
| Estimated amount of aerobic stabilised sludge [tonne DM][4] | 124,159 | 111,825 | 118,365 | 117,932 | 134,925 | 144,770 |
| Estimated amount of total final sludge [tonne DM][5] | 156,695 | 154,610 | 163,869 | 156,469 | 162,523 | 179,533 |
| Reported amount of total final sludge [tonne DM] | - | - | - | - | - | 116,998 |
| %RSD[6] | - | - | - | - | - | 30 |
| TOW in total amount of final sludge [tonne COD][7] | 92,716 | 91,055 | 96,501 | 92,340 | 96,410 | 106,329 |
| Inorganic content [%] | - | - | - | - | - | 9.12 |
| Reported amount of digestate [%][5] | - | - | - | - | - | 29 |
| Amount of digestate [tonne DM] | - | - | - | - | - | 34329 |

| *Continued* | | | | | | |
|---|---|---|---|---|---|---|
| %RSD[6] | - | - | - | - | - | 0.89 |
| Verification of reduction efficiency | | | | | | |
| Reported reduction efficiencies [%] | 96 | 95 | 96 | 92 | 92 | 95 |
| Effluent COD, National level [tonne] | 13,410 | 18,142 | 15,069 | 30,574 | 29,465 | 19,362 |
| Verification of methane production | | | | | | |
| $CH_{4,AD,gross}$ [Gg], (Eq. 5)[8] | 16.2 | 16.1 | 16.1 | 15.7 | 17.2 | 18.5 |
| $CH_{4,AD,gross}$ [Gg], (Eq. 4a) | 14.6 | 19.2 | 20.4 | 17.3 | 12.4 | 15.6 |
| $EF_{AD}$ [kg $CH_4$/kg COD] $=B_o*MCF_{AD}*f_{AD}$ (Eq.4a)[1] | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 |
| Estimated $EF_{AD}$ [%][1] | -10.9 | 16.2 | 21.0 | 8.8 | -39.2 | -19.1 |

[1]Venting is provided in percent COD of the influent COD, while the methane emission via venting provided in equation 5 is expressed as a percent of the produced methane.
[2]The increase in the final sludge amount in 1995 is explained by the increase in the industrial contribution to the COD in the influent wastewater and the sharp increase in the reduction efficiency.
[3]The amount of dry matter digested sludge was derived from the COD content in the final sludge assuming a COD content of 0.8 kg COD/ kg DM. Furthermore, a content of 40 % inorganic material was assumed from 1990-2004, which were reduced to 30 % in 2005 to 2013 reflecting an increased focus on replacing chemical precipitation with biological removal of phosphorous from the wastewater.
[4]To convert the COD in the final aerobic stabilized sludge into units of dry matter a COD content of 1 kg COD/kg DM sludge and an inorganic content of 50 % to account for the addition of 10-30 % $CaCO_3$. The content of inorganics in the final sludge was reduced from 50 to 40 % from 2005 and forward as explained above.
[5]DMEE, 1999 and 2001; DME, 2003b, 2004b, 2009b and 2012b; DCCA, 2014. For the years 2005 and 2006 a very low reporting frequency was obtained and the sludge amounts are incorrect; underestimated (DME, 2009b).
[6]Percent difference between the estimated and reported dry matter final sludge.
[7]TOW is total amount of final sludge. It is calculated from the estimated percent distribution of COD and the COD content in the influent wastewater water.
[8]The $CH_{4,AD,gross}$ in equation 5 is derived from reported gross energy production data reported by the Danish Energy Agency, which includes flaring (Tafdrup, 2014).

Table A 3 Influent wastewater TOW data grouped according to WWTPs applying respectively sludge stabilization (aerobic sludge treatment) and digestion (anaerobic sludge treatment) as sludge management strategy, [tonne COD].

| Year* | Total influent TOW | Influent TOW, aerobic [tonne COD] | Influent TOW, anaerobic [tonne COD] | $F_{As}$ [%] | $F_{AD}$ [%] |
|---|---|---|---|---|---|
| 1998 | 258,586 | 116,191 | 142,394 | 44.9 | 55.1 |
| 1999 | 347,385 | 163,615 | 183,770 | 47.1 | 52.9 |
| 2000 | 350,689 | 180,785 | 169,905 | 51.6 | 48.4 |
| 2001 | 363,687 | 163,320 | 200,367 | 44.9 | 55.1 |
| 2002 | 350,798 | 175,076 | 175,722 | 49.9 | 50.1 |
| 2003 | 360,630 | 161,246 | 199,384 | 44.7 | 55.3 |
| 2004 | 339,637 | 167,058 | 172,579 | 49.2 | 50.8 |
| 2005 | 24,396 | 13,455 | 10,941 | 55.2 | 44.8 |
| 2006 | - | - | - | - | - |
| 2007 | 369,006 | 210,448 | 158,558 | 57.0 | 43.0 |
| 2008 | 290,988 | 179,615 | 111,373 | 61.7 | 38.3 |
| 2009 | 342,131 | 180,758 | 161,373 | 52.8 | 47.2 |
| 2010 | 369,873 | 193,685 | 176,189 | 52.4 | 47.6 |
| 2011 | 371,713 | 215,069 | 156,643 | 57.9 | 42.1 |
| 2012 | 349,876 | 240,319 | 109,557 | 68.7 | 31.3 |
| 2013 | 386,151 | 247,446 | 138,704 | 64.1 | 35.9 |

*Data from the year 2005 at plant level are not complete from the report series point sources. However, data at national level has been extracted directly from the Danish water quality database (Annex 1, Table 1.1). Likewise, plant level data from the reports from 1994-1997 are incomplete (DMEE, 1989, 1990 1992, 1994a, b, 1995a,b; DME 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003, 2004,2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014).

# Annex B. Scattered settlements

The Danish Nature Agency are responsible for the reporting of the effluent load of nutrients and organic matter to surface waters from scattered settlements, i.e. households not connected to the collective sewer system. The category scattered settlements includes an estimation of all wastewater solutions of a load less than 30 PE. The effluent loads from scattered housed are estimated based on theoretic PE unit numbers combined with the information recorded in the Buildings and Housing Registry (BBR). The person equivalents (PE) per property per permanent habitation is set to 2.5 and unit numbers are 21.9 kg organic matter in BOD/PE/year, 4.4 kg N/PE/year, 1.0 kg P/PE/year and 50 $m^3$ wastewater/year (DME, 2003).

Table B 1 Effluent from scattered settlements and number of settlements not connected to the collective sewer system according to type.

| Residential Properties | Year | Permanent habitation[1] | Summer house[2] | Allot-ment[2] | Other | Total |
|---|---|---|---|---|---|---|
| $BOD_{effluent}$ [tonne] | 2013 | 2,788 | 42 | 36 | 118 | 2,984 |
| $TN_{effluent}$ [tonne] | 2013 | 744 | 11 | 9 | 32 | 796 |
| $TP_{effluent}$ [tonne] | 2013 | 166 | 2 | 2 | 7 | 178 |
| $Wastewater_{effluent}$ [1000$m^3$] | 2013 | 9,516 | 137 | 118 | 405 | 10,176 |
| Number of residential property | 2013 | 204,627 | 105,728 | 10,635 | 1304 | 322,294 |
| $BOD_{effluent}$ [tonne] | 2012 | 2,930 | 44 | 22 | 121 | 3,117 |
| $TN_{effluent}$ [tonne] | 2012 | 776 | 11 | 6 | 32 | 825 |
| $TP_{effluent}$ [tonne] | 2012 | 174 | 3 | 1 | 7 | 185 |
| $Wastewater_{effluent}$ [1000$m^3$] | 2012 | 9,896 | 142 | 73 | 410 | 10,521 |
| Number of residential property | 2012 | 207,316 | 107,716 | 8,293 | 1293 | 324,618 |
| $BOD_{effluent}$ [tonne] | 2011 | 3,025 | 87 | 23 | 128 | 3,263 |
| $TN_{effluent}$ [tonne] | 2011 | 797 | 23 | 6 | 34 | 860 |
| $TP_{effluent}$ [tonne] | 2011 | 179 | 5 | 1 | 8 | 193 |
| $Wastewater_{effluent}$ [1000$m^3$] | 2011 | 10,145 | 286 | 74 | 427 | 10,932 |
| Number of residential property | 2011 | 205,874 | 114,279 | 8,278 | 1321 | 329,752 |
| $BOD_{effluent}$ [tonne] | 2010 | 3,270 | 45 | 23 | 132 | 3,470 |
| $TN_{effluent}$ [tonne] | 2010 | 851 | 12 | 6 | 34 | 903 |
| $TP_{effluent}$ [tonne] | 2010 | 192 | 3 | 1 | 8 | 204 |
| $Wastewater_{effluent}$ [1000$m^3$] | 2010 | 10,779 | 147 | 74 | 434 | 11,434 |
| Number of residential property | 2010 | 214,463 | 110,733 | 8,078 | 1305 | 334,579 |
| $BOD_{effluent}$ [tonne] | 2009 | - | - | - | - | 3,519 |
| $TN_{effluent}$ [tonne] | 2009 | - | - | - | - | 939 |
| $TP_{effluent}$ [tonne] | 2009 | - | - | - | - | 214 |
| $Wastewater_{effluent}$ [1000$m^3$] | 2009 | - | - | - | - | 11,944 |
| Number of residential property | 2009 | - | - | - | - | - |
| $BOD_{effluent}$ [tonne] | 2008 | 3,202 | 38 | 2 | 55 | 3,297 |
| $TN_{effluent}$ [tonne] | 2008 | 837 | 9 | 0 | 15 | 862 |
| $TP_{effluent}$ [tonne] | 2008 | 189 | 2 | 0 | 3 | 194 |
| $Wastewater_{effluent}$ [1000$m^3$] | 2008 | 10,798 | 129 | 5 | 205 | 11,138 |
| Number of residential property | 2008 | 207,232 | 100,630 | 10,617 | 1036 | 319,515 |

| *Continued* | | | | | | |
|---|---|---|---|---|---|---|
| $BOD_{effluent}$ [tonne] | 2006 | 2,964 | 42 | 2 | 59 | 3,498 |
| $TN_{effluent}$ [tonne] | 2006 | 770 | 10 | 0 | 16 | 907 |
| $TP_{effluent}$ [tonne] | 2006 | 174 | 2 | 0 | 4 | 206 |
| $Wastewater_{effluent}$ [1000m$^3$] | 2006 | 9,983 | 144 | 5 | 219 | 11,780 |
| Number of residential property | 2006 | 208,965 | 100,237 | 10,373 | 1171 | 320,746 |
| $BOD_{effluent}$ [tonne] | 2004 | 3,516 | 42 | 2 | 55 | 3,614 |
| $TN_{effluent}$ [tonne] | 2004 | 905 | 10 | 0 | 15 | 931 |
| $TP_{effluent}$ [tonne] | 2004 | 205 | 2 | 0 | 3 | 211 |
| $Wastewater_{effluent}$ [1000m$^3$] | 2004 | 11,693 | 143 | 5 | 206 | 12,046 |
| Number of residential property | 2004 | 240,017 | 98,106 | 10,578 | 1036 | 349,737 |
| $BOD_{effluent}$ [tonne] | 2003 | 3,630 | 47 | 2 | 54 | 3,732 |
| $TN_{effluent}$ [tonne] | 2003 | 931 | 11 | 1 | 15 | 957 |
| $TP_{effluent}$ [tonne] | 2003 | 207 | 3 | 1 | 3 | 218 |
| $Wastewater_{effluent}$ [1000m$^3$] | 2003 | 12,004 | 161 | 5 | 199 | 12,369 |
| Number of residential property | 2003 | - | - | - | - | - |
| $BOD_{effluent}$ [tonne] | 2002 | 3,687 | 60 | 1 | 53 | 3,800 |
| $TN_{effluent}$ [tonne] | 2002 | 941 | 14 | 1 | 14 | 3,800 |
| $TP_{effluent}$ [tonne] | 2002 | 214 | 3 | 1 | 3 | 221 |
| $Wastewater_{effluent}$ [1000m$^3$] | 2002 | 12,098 | 198 | 4 | 191 | 12,491 |
| Number of residential property | 2002 | 231,882 | 110,861 | 10,970 | 1015 | 354,728 |
| $BOD_{effluent}$ [tonne] | 1997 | 4,208 | 68 | 8 | 12 | 4,295 |
| $TN_{effluent}$ [tonne] | 1997 | 1,104 | 14 | 1 | 3 | 1,123 |
| $TP_{effluent}$ [tonne] | 1997 | 252 | 5 | 0 | 1 | 257 |
| $Wastewater_{effluent}$ [1000m$^3$] | 1997 | - | - | - | - | - |
| Number of residential property | 1997 | 232,100 | 104,972 | 11,528 | | 348,600 |

[1]The category "Other" includes settlements with an atypical household Wastewater load such as schools, institutions, office buildings, restaurants etc.

[2]For summer houses and allotment a load value of 20 PE/property with a load period of 3 months a year. For scattered settlements, the load is set equal to 25 PE/property throughout the year.

Table B 2 Inflow from scattered settlements and number of settlements not connected to the collective sewer system according to type.

| Residential Properties | Year | Permanent habitation | Summer house | Allotment | Other | Total |
|---|---|---|---|---|---|---|
| $BOD_{inflow}$ [tonne] | 2013 | 11,203 | 1,158 | 116 | 474 | 12,951 |
| $TN_{inflow}$ [tonne] | 2013 | 2,251 | 930 | 94 | 127 | 3,402 |
| $TP_{inflow}$ [tonne] | 2013 | 512 | 53 | 5 | 28 | 598 |
| $Wastewater_{inflow}$ [1000m$^3$] | 2013 | 25,578 | 2,643 | 266 | 1,620 | 30,107 |
| Number of residential property | 2013 | 204,627 | 105,728 | 10,635 | 1,304 | 322,294 |
| $BOD_{inflow}$ [tonne] | 2012 | 11,351 | 1,179 | 91 | 484 | 13,105 |
| $TN_{inflow}$ [tonne] | 2012 | 2,280 | 948 | 73 | 128 | 3,429 |
| $TP_{inflow}$ [tonne] | 2012 | 518 | 54 | 4 | 29 | 605 |
| $Wastewater_{inflow}$ [1000m$^3$] | 2012 | 25,915 | 2,693 | 207 | 1,640 | 30,455 |
| Number of residential property | 2012 | 207,316 | 107,716 | 8,293 | 1,293 | 324,618 |
| $BOD_{inflow}$ [tonne] | 2011 | 11,272 | 1,251 | 91 | 512 | 13,126 |
| $TN_{inflow}$ [tonne] | 2011 | 2,265 | 1,006 | 73 | 136 | 3,479 |
| $TP_{inflow}$ [tonne] | 2011 | 515 | 57 | 4 | 32 | 608 |
| $Wastewater_{inflow}$ [1000m$^3$] | 2011 | 25,734 | 2,857 | 207 | 1,708 | 30,506 |
| Number of residential property | 2011 | 205,874 | 114,279 | 8,278 | 1,321 | 329,752 |
| $BOD_{inflow}$ [tonne] | 2010 | 11,742 | 1,213 | 88 | 528 | 13,571 |
| $TN_{inflow}$ [tonne] | 2010 | 2,359 | 974 | 71 | 136 | 3,541 |
| $TP_{inflow}$ [tonne] | 2010 | 536 | 55 | 4 | 32 | 628 |
| $Wastewater_{inflow}$ [1000m$^3$] | 2010 | 26,808 | 2,768 | 202 | 1,736 | 31,514 |
| Number of residential property | 2010 | 214,463 | 110,733 | 8,078 | 1,305 | 334,579 |
| $BOD_{inflow}$ [tonne] | 2009 | - | - | - | - | 0 |
| $TN_{inflow}$ [tonne] | 2009 | - | - | - | - | 0 |
| $TP_{inflow}$ [tonne] | 2009 | - | - | - | - | 0 |
| $Wastewater_{inflow}$ [1000m$^3$] | 2009 | - | - | - | - | 0 |
| Number of residential property | 2009 | - | - | - | - | 0 |
| $BOD_{inflow}$ [tonne] | 2008 | 11,346 | 1,102 | 116 | 220 | 12,784 |
| $TN_{inflow}$ [tonne] | 2008 | 2,280 | 886 | 93 | 60 | 3,319 |
| $TP_{inflow}$ [tonne] | 2008 | 518 | 50 | 5 | 12 | 586 |
| $Wastewater_{inflow}$ [1000m$^3$] | 2008 | 25,904 | 2,516 | 265 | 820 | 29,505 |
| Number of residential property | 2008 | 207,232 | 100,630 | 10,617 | 1,036 | 319,515 |
| $BOD_{inflow}$ [tonne] | 2006 | 11,441 | 1,098 | 114 | 236 | 12,888 |
| $TN_{inflow}$ [tonne] | 2006 | 2,299 | 882 | 91 | 64 | 3,336 |
| $TP_{inflow}$ [tonne] | 2006 | 522 | 50 | 5 | 16 | 594 |
| $Wastewater_{inflow}$ [1000m$^3$] | 2006 | 26,121 | 2,506 | 259 | 876 | 29,762 |
| Number of residential property | 2006 | 208,965 | 100,237 | 10,373 | 1,171 | 320,746 |
| $BOD_{inflow}$ [tonne] | 2004 | 13,141 | 1,074 | 116 | 220 | 14,551 |
| $TN_{inflow}$ [tonne] | 2004 | 2,640 | 863 | 93 | 60 | 3,657 |
| $TP_{inflow}$ [tonne] | 2004 | 600 | 49 | 5 | 12 | 666 |
| $Wastewater_{inflow}$ [1000m$^3$] | 2004 | 30,002 | 2,453 | 264 | 824 | 33,543 |
| Number of residential property | 2004 | 240,017 | 98,106 | 10,578 | 1,036 | 349,737 |
| $BOD_{inflow}$ [tonne] | 2003 | - | - | - | 216 | 216 |
| $TN_{inflow}$ [tonne] | 2003 | - | - | - | 60 | 60 |
| $TP_{inflow}$ [tonne] | 2003 | - | - | - | 12 | 12 |

| *Continued* | | | | | | |
|---|---|---|---|---|---|---|
| $Wastewater_{inflow}$ [1000m$^3$] | 2003 | - | - | - | 796 | 796 |
| Number of residential property | 2003 | - | - | - | - | - |
| $BOD_{inflow}$ [tonne] | 2002 | 12,696 | 1,214 | 120 | 212 | 14,242 |
| $TN_{inflow}$ [tonne] | 2002 | 2,551 | 976 | 97 | 56 | 3,679 |
| $TP_{inflow}$ [tonne] | 2002 | 580 | 55 | 5 | 12 | 653 |
| $Wastewater_{inflow}$ [1000m$^3$] | 2002 | 28,985 | 2,772 | 274 | 764 | 32,795 |
| Number of residential property | 2002 | 231,882 | 110,861 | 10,970 | 1,015 | 354,728 |
| $BOD_{inflow}$ [tonne] | 1997 | 12,696 | 1,214 | 120 | 48 | 14,078 |
| $TN_{inflow}$ [tonne] | 1997 | 2,551 | 976 | 97 | 12 | 3,635 |
| $TP_{inflow}$ [tonne] | 1997 | 580 | 55 | 5 | 4 | 645 |
| $Wastewater_{inflow}$ [1000m$^3$] | 1997 | 28,985 | 2,772 | 274 | - | 32,031 |
| Number of residential property | 1997 | 231,882 | 110,861 | 10,970 | 1,015 | 354,728 |

The category "Other" includes settlements with an atypical household wastewater load such as schools, institutions, office buildings, restaurants etc.

The person equivalents (PE) per property per permanent habitation is set to 25 (DME, 2003) and unit numbers are 219 kg organic matter in BOD/PE/year, 44 kg N/PE/year, 10 kg P/PE/year and 50 m$^3$ wastewater/year.

For summer houses and allotment a load value of 2 PE/property with a load period of 3 months a year. For permanent habitation, the load is set equal to 2.5 PE/property throughout the year.

Table B 3 Effluent in percent of inflow from scattered settlements grouped according to settlement type.

| Residential Properties | Year | Permanent habitation | Summer house | Allotment | Other | Total |
|---|---|---|---|---|---|---|
| $BOD_{inflow}$ | 2012 | 26% | 4% | 24% | 25% | 24% |
| $TN_{inflow}$ | 2012 | 34% | 1% | 8% | 25% | 24% |
| $TP_{inflow}$ | 2012 | 33% | 5% | 31% | 25% | 31% |
| $Wastewater_{inflow}$ | 2012 | 38% | 5% | 35% | 25% | 35% |
| $BOD_{inflow}$ | 2011 | 27% | 7% | 25% | 25% | 25% |
| $TN_{inflow}$ | 2011 | 35% | 2% | 8% | 25% | 25% |
| $TP_{inflow}$ | 2011 | 35% | 9% | 24% | 25% | 32% |
| $Wastewater_{inflow}$ | 2011 | 39% | 10% | 36% | 25% | 36% |
| $BOD_{inflow}$ | 2010 | 28% | 4% | 26% | 25% | 26% |
| $TN_{inflow}$ | 2010 | 36% | 1% | 8% | 25% | 26% |
| $TP_{inflow}$ | 2010 | 36% | 5% | 25% | 25% | 33% |
| $Wastewater_{inflow}$ | 2010 | 40% | 5% | 37% | 25% | 36% |
| $BOD_{inflow}$ | 2009 | na | na | na | na | na |
| $TN_{inflow}$ | 2009 | na | na | na | na | na |
| $TP_{inflow}$ | 2009 | na | na | na | na | na |
| $Wastewater_{inflow}$ | 2009 | na | na | na | na | na |
| $BOD_{inflow}$ | 2008 | 28% | 3% | 2% | 25% | 26% |
| $TN_{inflow}$ | 2008 | 37% | 1% | 0% | 25% | 26% |
| $TP_{inflow}$ | 2008 | 36% | 4% | 0% | 25% | 33% |
| $Wastewater_{inflow}$ | 2008 | 42% | 5% | 2% | 25% | 38% |
| $BOD_{inflow}$ | 2006 | 26% | 4% | 2% | 25% | 27% |
| $TN_{inflow}$ | 2006 | 33% | 1% | 0% | 25% | 27% |
| $TP_{inflow}$ | 2006 | 33% | 4% | 0% | 25% | 35% |
| $Wastewater_{inflow}$ | 2006 | 38% | 6% | 2% | 25% | 40% |
| $BOD_{inflow}$ | 2004 | 27% | 4% | 2% | 25% | 25% |
| $TN_{inflow}$ | 2004 | 34% | 1% | 0% | 25% | 25% |
| $TP_{inflow}$ | 2004 | 34% | 4% | 0% | 25% | 32% |
| $Wastewater_{inflow}$ | 2004 | 39% | 6% | 2% | 25% | 36% |
| $BOD_{inflow}$ | 2003 | na | na | na | 25% | na |
| $TN_{inflow}$ | 2003 | na | na | na | 25% | na |
| $TP_{inflow}$ | 2003 | na | na | na | 25% | na |
| $Wastewater_{inflow}$ | 2003 | na | na | na | 25% | na |
| $BOD_{inflow}$ | 2002 | 29% | 5% | 1% | 25% | 27% |
| $TN_{inflow}$ | 2002 | 37% | 1% | 1% | 25% | 103% |
| $TP_{inflow}$ | 2002 | 37% | 5% | 18% | 25% | 34% |
| $Wastewater_{inflow}$ | 2002 | 42% | 7% | 1% | 25% | 38% |

Table B 4 TOW produced per property type as reported by the Danish EPA, back-calculated from reported effluents from scattered settlements assuming that the reported effluents corresponds to 30 % of the inlet TOW.

| Residential Properties | Year | Permanent habitation | Summer house | Allotment | Other | Weighted Average | %RSD |
|---|---|---|---|---|---|---|---|
| $BOD_{inlet}$/Property type [tonne BOD/property type] | 2002 | 0.0530 | 0.0018 | 0.0003 | 0.1741 | 0.0357 | 4.1 |
| | 2004 | 0.0488 | 0.0014 | 0.0006 | 0.1770 | 0.0344 | 4.2 |
| | 2006 | 0.0473 | 0.0014 | 0.0006 | 0.1679 | 0.0364 | 3.9 |
| | 2008 | 0.0515 | 0.0013 | 0.0006 | 0.1770 | 0.0344 | 4.2 |
| | 2010 | 0.0508 | 0.0014 | 0.0095 | 0.3372 | 0.0346 | 8.0 |
| | 2011 | 0.0490 | 0.0025 | 0.0093 | 0.3230 | 0.0330 | 7.6 |
| | 2012 | 0.0471 | 0.0013 | 0.0088 | 0.3119 | 0.0320 | 7.4 |
| | 2013 | 0.0454 | 0.0013 | 0.0114 | 0.3027 | 0.0309 | 7.1 |
| | Average | 0.0496 | 0.0016 | 0.0043 | 0.2383 | 0.0344 | |
| | Rel. Stdev. [%] | 0.09 | 0.02 | 0.18 | 2.76 | 0.07 | |
| | National PE | 0.0548 | 0.0110 | 0.0110 | - | 0.0548 | |
| | IPCC PE | 0.0566 | 0.0113 | 0.0113 | | 0.0566 | |
| $COD_{inlet}$/Property type [tonne BOD/property type] | 2002 | 0.1431 | 0.0049 | 0.0008 | 0.4700 | 0.0964 | 11.0 |
| | 2004 | 0.1318 | 0.0039 | 0.0017 | 0.4778 | 0.0930 | 11.2 |
| | 2006 | 0.1277 | 0.0038 | 0.0017 | 0.4535 | 0.0982 | 10.6 |
| | 2008 | 0.1391 | 0.0034 | 0.0017 | 0.4778 | 0.0929 | 11.2 |
| | 2010 | 0.1372 | 0.0037 | 0.0256 | 0.9103 | 0.0933 | 21.6 |
| | 2011 | 0.1322 | 0.0069 | 0.0250 | 0.8721 | 0.0891 | 20.6 |
| | 2012 | 0.1272 | 0.0036 | 0.0239 | 0.8422 | 0.0864 | 20.0 |
| | 2013 | 0.1226 | 0.0035 | 0.0307 | 0.8172 | 0.0833 | 19.3 |
| | Average | 0.1326 | 0.0042 | 0.0139 | 0.6651 | 0.0916 | |
| | Rel. Stdev. [%] | 0.24 | 0.04 | 0.47 | 7.45 | 0.18 | |
| | National PE | 0.1478 | 0.0296 | 0.0296 | - | 0.1478 | |
| | IPCC PE | 0.1414 | 0.0283 | 0.0283 | - | 0.1414 | |

Table B 4 shows the TOW produced in scattered settlements. The inlet TOW is estimated based on reported estimations of BOD in the effluent from scattered settlements assuming an average loss of nutrient and organic matter with the effluent wastewater of 30 % (DME, 2003). In DME (2014) it is stated that scattered settlements are likely to have the same cleaning efficiency as mechanical wastewater treatment plant, reported as 26 % for BOD (Table D.1).

The estimated amount of BOD and COD produced per property type based on data reported by the Danish Nature Agency is compared to the estimated amounts based on the default IPCC value and the national PE unit value (grey shaded rows) respectively.

Table B 5  Percent of the population not connected to the collective sewer system based on residential property types.

| Year | Permanent habitation | Summer house | Allotment | Other | Total |
|---|---|---|---|---|---|
| | Residential property not connected to the collective sewer system | | | | |
| 2013 | 204,627 | 105,728 | 10,635 | 1,304 | 322,294 |
| 2012 | 207,316 | 107,716 | 8,293 | 1,293 | 324,618 |
| 2011 | 205,874 | 114,279 | 8,278 | 1,321 | 329,752 |
| 2010 | 214,463 | 110,733 | 8,078 | 1,305 | 334,579 |
| 2008 | 207,232 | 100,630 | 10,617 | 1,036 | 319,515 |
| 2006 | 208,965 | 100,237 | 10,373 | 1,171 | 320,746 |
| 2006 | 208,965 | 100,237 | 10,373 | 1,171 | 320,746 |
| 2004 | 240,017 | 98,106 | 10,578 | 1,036 | 349,737 |
| 2002 | 231,882 | 110,861 | 10,970 | 1,015 | 354,728 |
| Settlements in the whole country* | | | | | |
| 2014 | 1,539,664 | 19,930 | na | 49,502 | 1,609,096 |
| 2013 | 1,533,468 | 19,501 | na | 52,256 | 1,605,225 |
| 2012 | 1,527,391 | 18,861 | na | 52,400 | 1,598,652 |
| 2011 | 1,523,129 | 18,305 | na | 52,710 | 1,594,144 |
| 2010 | 1,516,530 | 17,857 | na | 54,293 | 1,588,680 |
| Percent of the population not connected to the collective sewer system | | | | | |
| 2013 | 13.3 | | | | |
| 2012 | 13.6 | | | | |
| 2011 | 13.5 | | | | |
| 2010 | 14.1 | | | | |

*The Danish statistics do not differentiate between summerhouses and allotments, but instead they use a grouping into leisure houses.

Na: not available

Table B 5 shows the number of residential property types not connected to the collective sewer system in the time period 2002-2013 compared to national statistics on the total number of residential property types in the whole country for the time range 201-2014. For the overlapping time range 2010-2012 covered by both data sets, the fraction of the population not connected to the collective sewer system were derived for the property type permanent habitation.

# Annex C. Biogas conversion factors

The methane content of biogas depends on various factors, i.e. the production process, the raw material used for anaerobic digestion etc. Typical for biogas is that the main constituents of the gas are methane and carbon dioxide. Table C 1 shows a comparison between landfill gas, biogas from anaerobic digestion and natural gas.

Table C 1  Content of biogas.

| Parameter | Unit | Landfill gas | Biogas from AD | Natural gas | Methane |
|---|---|---|---|---|---|
| Calorific value, lower | MJ/Nm³ | 16.00 | 23.00 | 40.00 | 35.38 |
| | kWh/Nm³ | 4.40 | 6.50 | 11.00 | 10.00 |
| | GJ/kWh | 0.0036 | 0.0036 | 0.0036 | 0.0036 |
| | MJ/kg | 12.3 | 20.20 | 48.00 | 31.08 |
| Density | kg/Nm³ | 1.30 | 1.20 | 0.83 | 0.72 |
| Methane | vol-% | 45.00 | 65.00 | 89.00 | 100.00 |
| Methane, range | vol-% | 35-65 | 60-70 | - | 100.00 |
| Long-chain hydrocarbons | vol-% | 0.00 | 0.00 | 10.00 | |
| Hydrogen | vol-% | 0-3 | 0.00 | 0.00 | |
| Carbon monoxide | vol-% | 0.00 | 0.00 | 0.00 | |
| Carbon dioxide | vol-% | 40.00 | 35.00 | 0.90 | |
| Carbon dioxide, range | vol-% | 15-50 | 30-40 | - | |
| Nitrogen | vol-% | 15.00 | 0.20 | 0.30 | |
| Nitrogen, range | vol-% | 14732.00 | - | - | |
| Oxygen | vol-% | 1.00 | 0.00 | 0.00 | |
| Oxygen, range | vol-% | 0-5 | - | - | |
| Hydrogen sulphide | ppm | < 100 | < 500 | 3.00 | |
| Hydrogen sulphide, range | ppm | 0-100 | 0-4000 | 42217.00 | |
| Ammonia | ppm | 5.00 | 100.00 | 0.00 | |
| Total chlorine as $Cl^-$ | mg/N | 20-200 | 0-5 | | |

# Annex D. N flows and COD/N ratios at WWTPs

Table D 1 Distribution of WWTPs according to type, treatment capacity, effluents and reduction efficiency in 1998.

| | WWTPs | | Effluents [tonne] | | | Reduction efficiency [%] | | |
|---|---|---|---|---|---|---|---|---|
| Plant type | Number | 1000 PE | Tot-N | Tot-P | BI5 | Tot-N | Tot-P | BI5 |
| Untreated | 2 | 1 | 4 | 1 | 15 | - | - | - |
| Mechanical | 433 | 89 | 219 | 37 | 594 | 36 | 20 | 26 |
| MC | 24 | 150 | 123 | 7 | 286 | 81 | 48 | 85 |
| MB | 501 | 383 | 498 | 82 | 208 | 81 | 43 | 48 |
| MBC | 237 | 863 | 857 | 45 | 294 | 87 | 58 | 87 |
| MBND | 10 | 107 | 47 | 11 | 28 | 88 | 76 | 56 |
| MBNDC | 268 | 10,466 | 3,419 | 418 | 2,100 | 92 | 85 | 92 |
| Total | 1,475 | 12,059 | 5,166 | 601 | 3,525 | - | - | - |

The abbreviations represent the following treatment levels: MC - mechanical/chemical; MB - mechanical/biological; MBC - mechanical/biological/chemical; MBND - mechanical/biological/nitrogen removal; MBNDC - mechanical/biological/nitrogen removal/chemical. (DMEE, 1999b).

# Annex E. Separate Industry - Industrial effluents, treatment levels and direct emissions

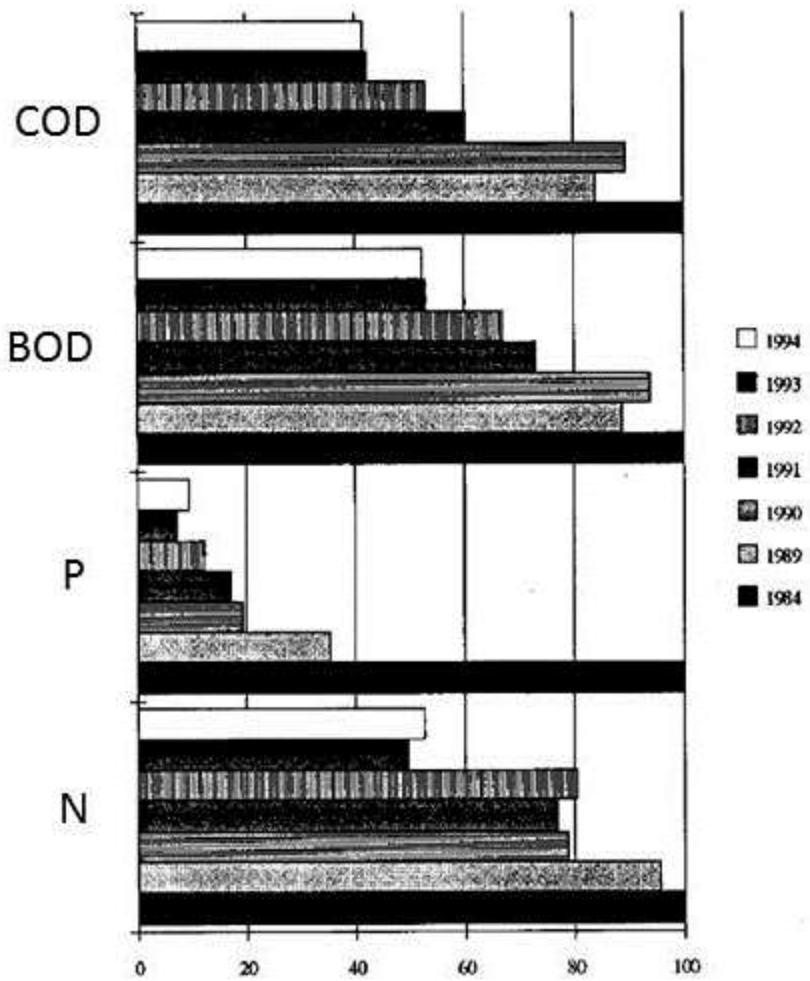


Figure E 1 Industrial effluents in percent of the effluent data for 1984.

Table E 2 Percentage distribution of industrial wastewater process configurations.

| Plant type/ Treatment level | 1986 [%] | 1993 [%] |
|---|---|---|
| U | 0.7 | 0.1 |
| M | 19.4 | 2.3 |
| MB | 65.8 | 5 |
| MBN | 5.4 | 1.1 |
| MBND | 2.3 | 0.3 |
| MC | 1.5 | 0.2 |
| MBC | 3.3 | 0.1 |
| MBNC | 0.7 | 10.1 |
| MBNDC | 0.9 | 80.8 |

Table E 3  Effluents, back-calculated influent N loads and direct $N_2O$ emissions from separate industries.

| Year | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 |
|---|---|---|---|---|---|---|
| Number of companies | 103 | 100 | 107 | 99 | - | - |
| Effluent wastewater [1000 $m^3$] | 78,215 | 86,257 | 462,692 | 482,927 | - | 63,562 |
| N in the effluent wastewater [tonne] | 2,574 | 1,737 | 2,472 | 1,731 | 1,801 | 0 |
| P in the effluent wastewater [tonne] | 246 | 320 | 206 | 120 | 145 | 0 |
| BOD in the effluent wastewater [tonne] | 26,029 | 25,684 | 13,768 | 8,962 | 11,366 | 10,733 |
| COD in the effluent wastewater [tonne] | 53,619 | 54,572 | 36,811 | 28,326 | - | 24,081 |
| COD/N ratio | 20.8 | 31.4 | 14.9 | 16.4 | - | - |
| N in the influent wastewater [tonne] | 32,175 | 21,713 | 30,900 | 21,638 | 22,513 | - |
| $N_2O$ emission, direct, separate industries [tonne $N_2O$] | 160.5 | 108.3 | 154.2 | 107.9 | 112.3 | - |
| Year | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 |
| Number of companies | - | - | 192 | 183 | 179 | - |
| Effluent wastewater [1000 $m^3$] | 65,000 | 73,684 | 65,070 | 61,186 | 54,007 | - |
| N in the effluent wastewater [tonne] | 970 | 902 | 813 | 753 | 509 | 469 |
| P in the effluent wastewater [tonne] | 73 | 59 | 52 | 50 | 33 | 31 |
| BOD in the effluent wastewater [tonne] | 8,322 | 4,918 | 4,301 | 5,913 | 3,754 | 1,022 |
| COD in the effluent wastewater [tonne] | 16,444 | 9,661 | 8,182 | 9,952 | 7,915 | - |
| COD/N ratio | 17.0 | 10.7 | 10.1 | 13.2 | 15.6 | - |
| N in the influent wastewater [tonne] | 12,125 | 11,275 | 10,163 | 9,413 | 6,363 | 5,863 |
| $N_2O$ emission, direct, separate industries [tonne $N_2O$] | 60.5 | 56.3 | 50.7 | 47.0 | 31.7 | 29.2 |
| Year | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
| Number of companies | 176 | 159 | 114 | 121 | 197 | 178 |
| Effluent wastewater [1000 $m^3$] | 61,527 | 48,353 | 61,298 | 49,151 | 54,395 | 52,796 |
| N in the effluent wastewater [tonne] | 441 | 325 | 398 | 245 | 338 | 312 |
| P in the effluent wastewater [tonne] | 24 | 19 | 20 | 13 | 23 | 20 |
| BOD in the effluent wastewater [tonne] | 1,154 | 839 | 1,415 | 608 | 1,098 | 740 |
| COD in the effluent wastewater [tonne] | 3,420 | 1,820 | 2,392 | 827 | 2,650 | 1,651 |
| COD/N ratio | 7.8 | 5.6 | 6.0 | 3.4 | 7.8 | 5.3 |
| N in the influent wastewater [tonne] | 5,513 | 4,063 | 4,975 | 3,063 | 4,225 | 3,900 |
| $N_2O$ emission, direct, separate industries [tonne $N_2O$] | 27.5 | 20.3 | 24.8 | 15.3 | 21.1 | 19.5 |
| Year | 2012 | 2013 | | | | |
| Number of companies | 178 | 178 | | | | |
| Effluent wastewater [1000 $m^3$] | 44,752 | 45,512 | | | | |
| N in the effluent wastewater [tonne] | 221 | 271 | | | | |
| P in the effluent wastewater [tonne] | 18 | 23 | | | | |
| BOD in the effluent wastewater [tonne] | 455 | 874 | | | | |
| COD in the effluent wastewater [tonne] | 1,890 | - | | | | |
| COD/N ratio | 8.6 | - | | | | |
| N in the influent wastewater [tonne] | 2,763 | 3,388 | | | | |
| $N_2O$ emission, direct, separate industries [tonne $N_2O$] | 13.8 | 16.9 | | | | |

# WASTEWATER TREATMENT AND DISCHARGE

This sector report present a verification of the country-specific methane emissions factor of 1.3 % of the reported methane recovery in terms of biogas production at Danish wastewater treatment plants from anaerobic sludge treatment. The verification is based on a combination of national level COD balance, as recommended by the UNFCCC review team, supplemented by plant level reported data. Secondary, the correctness of the percentage of the Danish population not connected to the collective sewer system is documented. Lastly a first approach for including direct N2O emissions from separate industries is presented.

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