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MONITORING AND REDUCING CARBON FOOTPRINT OF RUSSIAN WATER AND WASTEWATER COMPANIES

METHODOLOGY FOR ASSESSING CARBON FOOTPRINT OF WASTEWATER TREATMENT PLANTS

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This methodology for determination of carbon footprint of wastewater treatment plants has been prepared in conformity with the new version of the IPCC Guidance. It contains significant refinements with respect to calculation of water and wastewater company-specific methane and nitrous oxide emissions from wastewater treatment and sludge utilization processes.

Contents

Foreword

The methodology for carbon footprint assessment of wastewater treatment plants was prepared within the framework of "Carbon Footprint of Russian Vodocanals" project. This project had been implemented in 2012-2013 by NGO Ecoline and Saint-Petersburg research Centre for Environmental Safety of Russian Academy of Sciences with the support of Foreign and Commonwealth Office within the framework of the Prosperity Fund programme.

Saint-Petersburg Vodocanal (Water and Wastewater Treatment Company) and the Russian Association for Water and Wastewater Treatment acted as key project partners.

Carbon footprint (as a part of the ecological footprint) is a measure of the total amount of greenhouse gases emissions of a defined person, population, organization, or a region associated with certain activities, services, production processes and life cycle of a product as a whole. To assess carbon footprint it is necessary to calculate emissions of greenhouse gases and first of all, emissions of carbon dioxide, methane, dinitrogen monoxide and a number of fluorine containing compounds.

Wastewater treatment plants are in fact nature protection enterprises. Their main objective is "wiping off footprints" of their clients, reducing thereby negative environmental impacts. But efficiency of wastewater treatment itself should be studies with regards to energy consumption for sewage treatment, sludge transportation, and other processes. As the result, carbon footprint of wastewater treatment plant can be assessed as an integral measure of sewage treatment as a whole.

The methodology developed complies with new recommendations of the Intergovernmental Panel on Climate Change (IPCC) and contains also significant elaborations concerning assessment of methane and dinitrogen monoxide emissions specific for wastewater treatment processes and sludge disposal sites.

The methodology was developed in the collaboration with project partners and presented to colleagues working at specialized higher school establishments and research institutions. A number of specialists took active part in discussing the methodology, including:

- Olga Rublevskaya, Vice-Director of Development Department, SUE "Vodokanal of Saint-Petersburg";
- Tatiana Perednya, Director of the Environmental Department, SUE "Vodokanal of Saint-Petersburg";
- Irina Alexeyeva, deputy Director of the Environmental Department, SUE "Vodokanal of Saint-Petersburg";
- Doctor Dmitry Danilovich, Deputy of the Russian Association for Water and Wastewater Treatment, Chief Technologist, JSC "Institute MosVodocanalNIIProject";
- Professor Victor Panfilov, Head of Industrial Biotechnology Department , D. Mendeleyev University of Chemical Technology of Russia;
- Professor Irina Pavlinova, Head of Municipal and Industrial Water Supply, Moscow State Academy of Municipal Economy and Construction;
- Doctor Victor Bazhenov, Professor of Municipal and Industrial Water Supply Department, Moscow State Academy of Municipal Economy and Construction;
- Professor Eugene Alexeyev, Head of Department "Wastewater Treatment and Environment Department, Moscow State University of Civil Engineering (MGSU);
- Professor Arcady Denisov, Head of Division of Sanitary and Environmental Conservation, All-Russia Research and Technological Institute of Biotechnological Industry, Russian Academy for Agricultural Sciences;
- Professor Natalia Zhmur, deputy Director of "AquaRos" Company;

– Professor Eugene Venitsianov, Head of Water Quality Laboratory, Institute for Water Problems, Russian Academy of Sciences.

Project implementers are grateful to specialists of the Department of State Policy and Regulation in the Field of minimization of Negative Environmental Impacts and Environmental Monitoring (the Ministry of Natural Resources and Environment of the RF), as well as specialists of the Department of Natural Resources and Environmental Protection of Moscow and JSC “Mosvodocanal” for their support and most useful recommendations.

We are grateful to Russian and foreign experts of Mott McDonald, Ecovod and Pöyry companies who greatly contributed towards the project implementation.

Project implementers would like to thank everybody who supported development of the methodology, took part in workshops, field studies, information collection and analysis.

In 2012-2013 the methodology was tested within the course of carbon footprint assessment of wastewater treatment plants of SUE “Vodokanal of Saint- Petersburg”.

Materials presented in this brochure can applied for calculating greenhouse gases emissions of wastewater treatment plants and can also be used for training purposes while teaching special disciplines and tutoring diploma essays.

Abbreviations

BOD	Biological oxygen demand
COD	Chemical oxygen demand
GHG	Greenhouse gases
IPCC	The Intergovernmental Panel on Climate Change
MSW	Municipal solid waste
MWTP	Municipal wastewater treatment plants

1. INTRODUCTION

Mankind's movement towards sustainable development is impossible without a compass showing the right direction. The system of sustainable development indicators provides such a compass.

The need to develop sustainable development indicators was emphasized for first time in Agenda-21 adopted at the UN Conference on Environment and Development in Rio de Janeiro (1992). Since then, the development of indicators has followed two pathways:

1. Construction of systems of indicators, i.e., groups of indicators characterizing the ecological, economic, and social development.
2. Creation of integrated indicators providing a comprehensive assessment of the situation in a particular region, sector, etc.

Examples of integrated indicators can be found in "ecological footprint" and "carbon footprint". The ecological footprint indicator was developed in 1995, on the basis of the concept of assimilative capacity of the biosphere.

The very idea of an indicator based on a land area is not novel in itself. French historian Fernand Braudel (1902 – 1985) is one of the first Europeans who took this approach. Specifically, Braudel used land areas to monitor the trade**,** consumption, and production patterns of agricultural products, being of opinion that the hectare was a far more reliable comparative indicator of economic activity, providing a stable **'**currency**'** suitable for tracking environmental impacts. Some modern ecological economists are attracted to the hectare for very much the same reason.

The modern approach to considering public consumption expressed in units of area, i.e., the ecological footprint concept, was proposed in 1996 year by W. Rees and M. Wackernagel.[1]

This concept interprets a population’s ecological footprint as an indicator representing the total area of productive land or sea needed to produce all the crops, meat, seafood, wood, and fibre it consumes, to meet its energy consumption, to give space for its infrastructure, to absorb its wastes, etc. An ecological footprint measures human consumption of natural resources against the Earth’s ecological **c**apacity (biocapacity) to regenerate them. The biological capacity and ecological footprint are expressed in units of global hectares (gha)[2].

Six areas are considered in an ecological footprint evaluation: (1) crop; (2) pasture (livestock production); (3) forest (timber and firewood); (4) sea (fish and aquatic plants); (5) area for carbon fixation; and (6) building area (living and dam areas).

The carbon footprint indicator provides the sum of emissions of greenhouse gases (GHG), caused directly or indirectly by any individual, organization, or region, via undertaking an activity, providing services, products, or implementing the entire life cycle. The carbon footprint can be assessed by calculating emissions of greenhouse gases, above all, carbon dioxide, methane, nitrous oxide, and some fluorinated compounds.

How can the ecological footprint be calculated for a water and wastewater company, specifically for a wastewater treatment plant (WWTP)?

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[1] Wackernagel, Mathis, and Rees, William 1996. Our Ecological Footprint: Reducing Human Impact on the Earth. Gabriola Island, British Columbia: New Society Publishers

[2] Global hectare (gha): one hectare of bioproductive territory or sea area with the global average productivity.

In the wastewater treatment context, the matter in question is clearly the carbon, rather that ecological, footprint, because wastewater treatment plants (essentially environment-oriented facilities) are destined to undertake "deletion" of the ecological footprints of their subscribers, thereby reducing their environmental impact. However, the wastewater treatment efficiency in terms of the energy consumption, treatment technology, and sludge transportation can constitute the subject of a special research aimed to obtain the carbon footprint as providing an integrated measure of the wastewater treatment efficiency by a specific water and wastewater company.

Overall, the carbon footprint determination requires that the following steps be applied:
1. Defining temporal and spatial boundaries of assessment (time period of assessment, production stages).
2. Analysis of the available data and compilation of the entire chain of the life cycle stages, with assessing whether the data available are sufficient for evaluation to be made for each stage of the life cycle, or only the input-output based assessment is possible.
3. Identification of the existing assessment rules applying to a particular production process, sector, etc.
4. Searching information about each individual technological process, including resource (in particular energy) consumption, energy self-generation, and waste generation by a facility, etc.).
5. Verification.

2. CARBON FOOTPRINT OF WASTEWATER TREATMENT PLANTS

The World Resources Institute[3] defined three 'scopes' for GHG accounting and reporting as follows.

Scope 1.

Scope 1 accounts for GHG emissions from on-site activities, including direct stack emissions due to fossil fuel combustion and fugitive emissions, e.g., HFC emissions during the use of air conditioning equipment.

Scope 2.

Scope 2 deals with indirect emissions associated with on-site consumption of the electricity and heat Electricity is typically imported from centralized grid, and to calculate the Scope 2 emissions, the energy consumed is to be multiplied by the GHG emission factor of the national grid, CO_2eq per unit (kWh) of electricity consumed.

Scope 3.

Scope 3 accounts for other indirect off-site emissions that are not associated with energy production: GHG emissions from vehicles used by a facility, in particular, employee business travel by personal and public service vehicles. Also, emissions from production of imported materials (e.g., of cement and bricks used by a building company) can be included. Some methodologies, however, do not incorporate these emissions in the carbon footprint calculation for a facility in order that double counting, with two different entities including the same emissions in their respective inventories, will be avoided when compiling national inventories.

For a wastewater treatment plant (WWTP), Scope 1 emissions include:

- ✓ GHG emissions due to treatment process;
- ✓ emissions due to consumption of exported fuel for maintaining the wastewater treatment process;
- ✓ emissions due to on-site transportation activities.

Fugitive emissions of GHG include:

- ✓ methane (CH_4) emissions due to anaerobic processes in primary sedimentation tanks;
- ✓ nitrous oxide (N_2O, called also dinitrogen monoxide) emissions due to nitrification and denitrification processes;
- ✓ methane emissions due to sludge fermentation and composting, gas transportation via transmission pipeline system, dehydration in drying beds and disposal at landfills.

Scope 2 considers the greenhouse gas emissions from generation of purchased electricity (intended for wastewater pumping, aeration, illumination (industrial building and site), and ultraviolet disinfection purposes), as well as of the energy generated for the consumed heat, steam, as well as for ventilation and air conditioning purposes, etc.

Scope 3 includes all GHG emissions not covered by Scopes 1 and 2, which are associated with the production process. These include, above all, emissions due to employee business travel (personal and public service vehicles) and supply of consumables to be used for wastewater treatment purposes (chemicals, spare parts). Some models also take into account the GHG emissions associated with production of chemicals. In this case the correct choice of the "point of release" of emissions is essential in order that double counting be avoided. For example, if metal (iron or aluminium) salts are applied by a WWTP to remove phosphorus from wastewater, the GHG emissions from their

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[3] World Resources Institute (2001). The greenhouse gas protocol: A Corporate Accounting and Reporting Standard. World Business Council for Sustainable Development. The Hague p. 27.

production should be included in the carbon footprint of this WWTP. The same applies to other chemicals (methanol, flocculants).

The GHG emission sources at a WWTP include:

- ✓ Methane sources: anaerobic processes in primary sedimentation tanks, sludge densification and dehydration at drying beds, sludge fermentation in anaerobic digesters, disposal to landfills.
- ✓ Nitrous oxide sources: nitrification and denitrification processes.

It should be noted that the currently accepted GHG accounting approaches do not incorporate the carbon dioxide emissions from wastewater treatment process, including sludge incineration: It is presumed that the carbon emitted into the atmosphere as a result of decomposition of the organic matter contained in wastewater is that which was earlier withdrawn from the atmosphere for production of this organic matter (foodstuffs, wood).

The GHG emissions from a WWTP can be estimated by a number of models, among which the most adequate are those based on the United Nations Framework Convention on Climate Change (UN FCCC) guidelines and methodologies intended for implementation of sustainable development mechanisms. All GHG emission accounting methodologies (which are focused, in particular, on GHG emissions from wastewater treatment plants) are developed by the Intergovernmental Panel on Climate Change (IPCC) and subjected to discussion at the UN FCCC website[4]. The methodologies presented are periodically undated and corrected. The currently used documents are as follows: “AMS-III.H: Methane recovery in wastewater treatment — Version 16.0”[5] and “Approved baseline and monitoring methodology AM0080: Mitigation of greenhouse gases emissions with treatment of wastewater in aerobic wastewater treatment plants» — Version 1.0”[6].

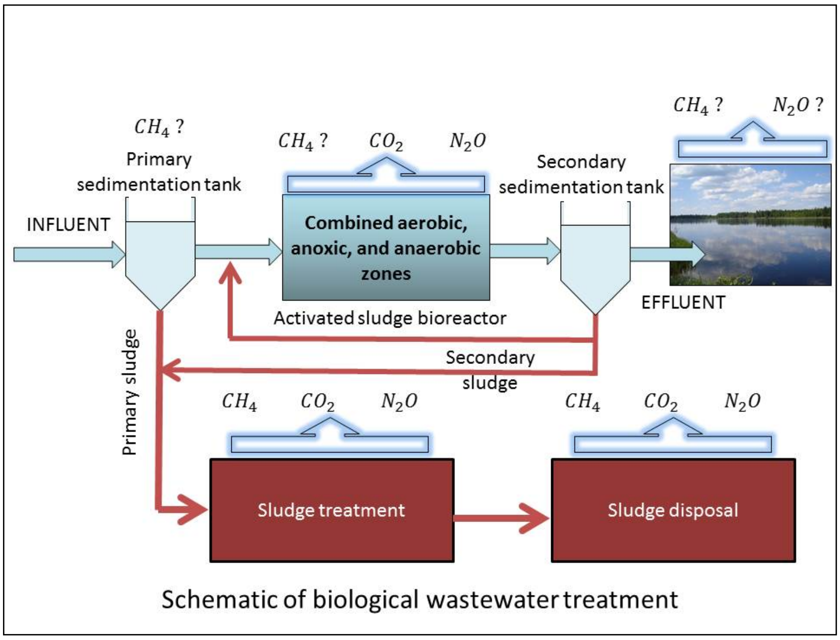

Figure 1 — Greenhouse gas emissions from biological wastewater treatment

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[4] http://unfccc.int/2860.php

[5] AMS-III.H. Methane recovery in wastewater treatment — Version 16.0 http://cdm.unfccc.int/methodologies/DB/4ND00PCGC7WXR3L0LOJTS6SVZP4NSU

[6] Approved baseline and monitoring methodology AM0080. «Mitigation of greenhouse gases emissions with treatment of wastewater in aerobic wastewater treatment plants» — Version 1.0 http://cdm.unfccc.int/methodologies/DB/6DITU9V0SFOR7EUYEBBVRHCAO2RD3Q

Figure 1 provides a schematic illustration of the most commonly applied biological wastewater treatment process employed at Russian water and wastewater companies. The activated sludge unit is either an ordinary aeration tank or combines anaerobic, anoxic, and aerobic zones, if intended for biological removal of nitrogen and phosphorus.

Primary sedimentation tank can be a source of methane emissions in case when sludge is allowed to remain for prolonged time and undergoes anaerobic decomposition therein. Typically, no methane emissions are generated by the bioreactor, because the sludge circulates among different zones and resides in the anaerobic zone for negligible time. Formation of methane in the activated sludge unit is indicative of overloading of the wastewater treatment plant and formation of "dead zones", where decay of the activated sludge occurs. Formation of nitrous oxide in the reactor is due to nitrification and denitrification processes. The major sources of methane are sludge treatment and disposal processes.

2.1. Greenhouse gas emission calculation methodologies recommended by IPCC Guidelines for National Greenhouse Gas Inventories

The IPCC methodologies are applicable to biological treatment plants intended for domestic, industrial, or mixed domestic-industrial wastewater treatment purposes. These methodologies consider the following wastewater and sludge treatment scenarios:

1. Biological treatment of wastewater, involving nitrification and denitrification processes, is accompanied by nitrous oxide emissions.
2. Improper operation of wastewater treatment plants (sludge remaining in primary sedimentation tanks for long time, activated sludge bioreactor overloading) causes methane formation.
3. Sludge is dehydrated at drying beds and disposed at landfill or as fertilizer on agricultural lands.
4. Sludge is treated in an anaerobic digester, with the biogas extracted from the anaerobic digester being flared and/or used to generate electricity and/or heat. The sludge from the anaerobic digester is dehydrated, stored before final disposal in a managed landfill, or applied to land.
5. Sludge is incinerated to produce electricity and/or heat.

Table 1 lists the major sources of accounted GHG emissions.

The IPCC guidelines provide calculation schemes for methane emissions both from anaerobic reactors and from essentially aerobic zones operating under off-design or increased load conditions, which situations can also result in formation of methane, though in negligible quantities. Also, if effluent containing residual organic matter is discharged into a fairly deep receiving water body with bad mixing conditions, this can also lead to formation of methane in the bottom layer.

Special consideration in the IPCC methodologies is given to GHG emissions associated with imported electricity and heat, as well as to emissions produced by vehicles employed, e.g., for transportation of sludge. Also (Scope 3), account may be taken of employee business travels using personal and public service vehicles, as well as of carbon footprints associated with chemicals applied in wastewater treatment processes.

Table 1 — GHG emission sources included in the project scope for WWTPs

Source	Gas	Included / Excluded	Justification / Explanation
Wastewater and sludge treatment	CH_4	Included	Major source of emissions
	N_2O	Included	Mainly in nitrification and denitrification processes. Sludge disposal as fertilizer on agricultural lands can be an important source of nitrous oxide emissions.
	CO_2	Excluded	CO_2 emissions from the decomposition of organic waste are not accounted for.
Electricity and heat generation	CO_2	Included	Emissions from electricity and heat generation due to: a) Imported electricity/heat used for the operation of wastewater/sludge treatment systems; b) Electricity/heat produced on the site from fossil fuels; GHG emissions associated with a part of electricity/heat produced from sludge incineration, or biogas flaring, are not included.
	CH_4	Excluded	Excluded for simplification. This is conservative.
	N_2O	Excluded	Excluded for simplification. This is conservative.
Transportation of sludge	CO_2	Included	Emissions from transportation of sludge may be included.
	CH_4	Excluded	Excluded for simplification. This emission source is assumed to be very small.
	N_2O	Excluded	Excluded for simplification. This emission source is assumed to be very small.
Other uses of motor vehicles	CO_2	Included	Transportation emissions may be included.
	CH_4	Excluded	Excluded for simplification. This emission source is assumed to be very small.
	N_2O	Excluded	Excluded for simplification. This emission source is assumed to be very small.
Application of chemicals	CO_2	Included	Emissions from application of chemicals may be included.
	CH_4	Excluded	Excluded for simplification. However, the process of production of a chemical is to be analyzed in some cases.
	N_2O	Excluded	Excluded for simplification. However, the process of production of a chemical is to be analyzed in some cases.
Effluent discharge to receiving body	CO_2	Excluded	CO_2 emissions from the decomposition of organic waste are not accounted for.
	CH_4	Included	May be included if the COD content for the effluent is substandard.
	N_2O	Excluded	Excluded for simplification. This emission source is assumed to be very small.

2.1.1. Calculation of the methane emissions

Methane is a highly potent greenhouse gas whose global warming potential was estimated at 25 times that for carbon dioxide. This value, refined by IPCC[7], was calculated over a time interval of 100 years.

Methane can account for by up to 75% (in CO_2eq) of the total greenhouse gas emissions from wastewater/sludge treatment.[8] Since methane results from anaerobic decomposition of organic matter, its emission estimation typically involves the parameters expressing the organic

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[7] Changes in Atmospheric Constituents and in Radiative Forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter2.pdf

[8] Foley, J., Lant, P., 2007. Fugitive Greenhouse Gas Emissions from Wastewater Systems. WSAA Literature Review No.01. Water Services Association of Australia, Melbourne and Sydney, Australia.

contamination of wastewater: BOD (biological oxygen demand) or COD (chemical oxygen demand). As to major sources of methane, these are above all variously designed anaerobic reactors. Russian water and wastewater companies do not use anaerobic reactors; only anaerobic digesters find limited use. Box 1 illustrates the chemical and microbiological processes occurring in an anaerobic reactor.

Box 1.

Since methane results from anaerobic decomposition of organic matter, the estimation of its emissions typically involves the parameters expressing the organic contamination of wastewater: BOD (biological oxygen demand) or COD (chemical oxygen demand). As to the major sources of methane, these are above all variously designed anaerobic reactors. Russian water and wastewater companies do not use anaerobic reactors; only anaerobic digesters find limited use.

Anaerobic reactors serve for pretreatment of industrial wastewater characterized by high content of organic matter, as well as of municipal wastewater. Anaerobic treatment allows the biological oxygen demand to be reduced by 60%, if the wastewater temperature is 20-25°C, and the hydraulic retention time (HRT) of wastewater in the reactor is no less than 1–2 days.

In the absence of dissolved oxygen, anaerobic microorganisms convert the organic matter into carbon dioxide and methane. The decomposition process consists of two interconnected phases: formation of acids and formation of methane. During the "acidic" phase, the bacteria transform complex organic substances (carbohydrates, fats, proteins) into simpler substances, volatile organic acids: acetic, propionic, lactic. In the next phase, the bacteria initially convert organic acids to acetate, hydrogen, and carbon dioxide, after which formation of methane by methanogenic microbes follows two pathways:

1. Acetic acid decomposition into methane and carbon dioxide.

$$CH_3COOH \rightarrow CH_4 + CO_2 \qquad (1)$$

2. Reduction of carbon dioxide with hydrogen into methane

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \qquad (2)$$

Formation of methane in anaerobic reactors can occur in a fairly narrow range of environmental conditions, among which the temperature and acidity (pH) are the most important.

Processes similar to those described for anaerobic reactors occur in anaerobic digesters, with the only difference that, in the latter, the particulate concentration is many times higher.

Anaerobic processes and decay of sludge may occur if primary sludge is allowed to remain in a primary sedimentation tank for prolonged time.

The new version of the IPCC methodologies prescribes the use of the so-called “methane conversion factor method” for calculation of methane emissions from anaerobic treatment of the wastewater:

$$E_{CH4,wwt,an,y} = \left(Q_{an,y} * \Delta COD_{an,y} * MCF_{ww}\right) * B_{ww} * \ GWP_{CH4} \qquad (3)$$

where $E_{CH4,wwt,an,y}$ are the methane emissions from anaerobic treatment of the wastewater in the year *y* (t CO_2eq/year);
$Q_{an,y}$is the quantity of wastewater entering the anaerobic wastewater treatment plant in the year *y* (m^3/year);
$\Delta COD_{an,y}$ is the quantity of chemical oxygen demand (COD) removed over the anaerobic wastewater treatment in the year *y* (t COD/m^3);
MCF_{ww} is the average methane conversion factor (MCF) in the year *y*, representing the fraction of organic load that would be degraded to CH_4 (fraction). This parameter depends, in particular, on the

design features of the wastewater treatment plants. For small-scale wastewater treatment plants, the MCF values from Table 2 can be used;
B_{ww} is the maximum methane producing capacity of wastewater, expressing the maximum quantity of CH_4 that can be produced if the given quantity of chemical oxygen demand will be removed (kg CH_4/kg COD);
GWP_{CH4} is the Global Warming Potential of methane (t CO_2eq/t CH_4).

For each specific case, determination of $\Delta COD_{an,y}$ is of principal importance. This requires knowledge of the primary sedimentation tank effluent COD, along with the influent wastewater COD. The larger the proportion of COD consumed under the anaerobic conditions of the primary sedimentation tank, the larger the methane emissions. As demonstrated below, at adequately operating WWTPs, the aerobic treatment in aeration tanks leads to insignificant methane emissions.

Determination of MCF_{ww}

The quantity of methane generated from COD in open lagoons depends mainly on the depth of the lagoon and ambient temperature. Therefore, the MCF is to be calculated based on a factor f_d expressing the influence of the depth of the lagoon on methane generation and a factor $f_{T,y}$ expressing the influence of the temperature on the methane generation. Therefore,

$$MCF_{ww} = f_d * f_{T,y} \tag{4}$$

The default IPCC values for f_d are as follows: 0.7 at the average depth of open lagoon above 5 m, 0.5 at a depth within 1–5 m, and 0 at a depth under 1 m.[9]

In some regions, where the ambient temperature varies significantly throughout the year, $f_{T,y}$ is to be calculated in terms of a monthly stock change model which aims to assess how much COD degrades in each month. Therefore,

$$f_{T,y} = \frac{\sum_{m=1}^{12} f_{T,m} * \Delta COD_{an,m}}{12 * \sum_{m=1}^{12} \Delta COD_{an,m}} \tag{5}$$

where $f_{T,y}$ is the factor expressing the influence of the temperature on the methane generation in the year *y* (fraction);
$f_{T,m}$, a factor expressing the influence of the temperature on the methane generation in the month *m* (fraction);
$\Delta COD_{an,m}$, quantity of organic matter (chemical oxygen demand) removed over anaerobic treatment in the month *m* (t COD/month).

The monthly average factor expressing the influence of the temperature on methane generation is calculated on the basis of the van't Hoff-Arrhenius approach which describes the temperature dependence of the rate constant of a chemical reaction:

$$f_{T,m} = 0, \text{ if } T_m < 283K$$
$$f_{T,m} = exp\left(\frac{Ea * (T_m - T_1)}{R * T_m * T_1}\right), \text{ if } 283K < T_m < 303K \tag{6}$$
$$f_{T,m} = 1, \text{ if } T_m > 303K$$

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[9] Some Russian experts consider the dependence of the methane generation on the depth of open lagoon as being mythical. In actual practice, the depth of open lagoons at WWTP is under 2.5 m.

where $f_{T,m}$ is the factor expressing the influence of the temperature on the methane generation in the anaerobic zone in the month m (fraction);
Ea is the activation energy constant (63,533 J/mole);
T_1= 303.16 K (273.16 K +30 K);
R is the ideal gas constant (8,314 J/K*mole);
T_m is the average wastewater temperature at the site (during the month in the anaerobic zone (K) [recall that Kelvin (T) and Celsius ($t°C$) scale temperatures are related as $T = t°C + 273.15$].

Equation (6) shows that the $f_{T,m}$ value cannot exceed unity and should be assumed to be zero if the ambient temperature is below 10°C.

For simplified calculations, MCF_{ww} values from Table 2 can be used.

Table 2 — Values of methane conversion factor in relation to the design features of WWTP[10]

Type of treatment and discharge pathway or system	Domestic wastewater		Industrial wastewater	
	MCF_{ww}	Range	MCF_{ww}	Range
Untreated	0.1	0 – 0.2	0.1	0 – 0.2
Properly operating aerobic treatment plant	0	0 – 0.1	0	0 – 0.1
Improper operation. Overloading.	0.3[11]	0.2 – 0.4	0.3	0.2 – 0.4
Anaerobic digester for sludge. CH_4 recovery is not considered here.	0.8	0.8 – 1.0	0.8	0.8 – 1.0
Anaerobic reactor. CH_4 recovery is not considered here	0.8	0.8 – 1.0	0.8	0.8 – 1.0
Anaerobic shallow lagoon (depth < 2 m)	0.2	0 – 0.3	0.2	0 – 0.3
Anaerobic deep lagoon (depth > 2 m)	0.8	0.8 – 1.0	0.8	0.8 – 1.0

Determination of B_{ww}

Of much importance is B_{ww}parameter, the maximum methane producing capacity, expressing the maximum quantity of CH_4 that can be produced from a given quantity of COD. The IPCC default value is 0.25 kg CH_4/kg COD[12]. The theoretical maximum yield of methane per gram of chemical oxygen demand was calculated in studies[13,14] (Box 2).

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[10] IPCC Guidelines for National Greenhouse Gas Inventories (2006). Volume 5, chapter 6 "Wastewater Treatment and Discharge" http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html

[11] Some Russian experts consider this value as overestimated, and methane conversion factor in this as no greater than 0.15.

[12] For cases where no COD measurements are done, the IPCC methodology recommends 0.6 kg CH_4/kg BOD, equally applicable to BOD_5 and BOD_{20}, which suggests COD/BOD= 1.5. In our opinion, experimentally measured COD/BOD ratios should be applied. According to State Unitary Enterprise (GUP) "Vodokanal of St. Petersburg", the COD/BOD_5 ratio for combined sewer to be treated at the WWTP ranges from 1.5 to 3. For domestic wastewater, COD/BOD_5 =2.1 is suitable as the average value.

[13] Crites, R., and Tchobanoglous, G., 1998. Small and Decentralized Wastewater Management Systems. WCB McGraw-Hill, Boston

[14] Direct Methane and Nitrous Oxide emissions from full-scale wastewater treatment systems, Occasional Paper N 24, October 2009. Water Services Association of Australia

Box 2.

The reaction of conversion of glucose to carbon dioxide and methane proceeds as follows:

$$C_6H_{12}O_6 \rightarrow 3\,CO_2 + 3\,CH_4 \qquad (7)$$

Complete oxidation of the resulting methane is achieved by six oxygen molecules:

$$3\,CH_4 + 6\,O_2 \rightarrow 3\,CO_2 + 6\,H_2O \qquad (8)$$

Thus, considering the molar masses of one glucose molecule (6*12 + 12 + 6*16 = 180 g/mole) and of the six oxygen molecules required for its oxidation (192 g/mole), the chemical oxygen demand for one gram of glucose is

$$\frac{g\mathrm{O}_2}{\mathrm{gC}_6\mathrm{H}_{12}\mathrm{O}_6} = \frac{192}{180}$$

Therefore, the yield of methane per g glucose is:

$$\frac{\mathrm{gCH}_4}{\mathrm{gC}_6\mathrm{H}_{12}\mathrm{O}_6} = \frac{48}{180}$$

Therefore, the yield of methane per g of chemical oxygen demand is

$$\frac{gCH_4}{gO_2} = \frac{48/180}{192/180} = 0{,}25 \qquad (9)$$

The same expression can be derived from equation (2), based on the reduction reaction stoichiometry.

Calculation of methane emissions from treatment of sludge

The wastewater treatment sludge contains a significant proportion of organic matter whose decomposition under anaerobic conditions will also result in methane emission. The quantity of methane thereby emitted depends on the type of sludge disposal site. If sludge is placed on a drying bed or is disposed at a landfill, the IPCC methodology recommends that the methane emissions from treatment of sludge during a year ($E_{CH4,wwt,sl,y}$) be determined as follows:

$$E_{CH4,wwt,sl,y} = M_{sl,dry,y} * MCF_{sl} * DOC_{sl,dry} * DOC_F * F * \frac{16}{12} * GWP_{CH4} \qquad (10)$$

where $E_{CH4,wwt,sl,y}$ are the methane emissions from decomposition of sludge in the year *y* (tCO$_2$eq/year);
$M_{sl,dry,y}$ is the quantity of sludge dry matter (t/year);
MCF_{sl} is the methane conversion factor, which depends on the type of sludge disposal site (fraction);
$DOC_{sl,dry}$ is degradable organic content in the dry matter of sludge disposed in the year *y* (fraction). The IPCC default values are 0.5 for domestic sludge and 0.257 for industrial sludge. These data may be refined for specific wastewater treatment plants;
DOC_F is the fraction of degradable organic content dissimilated to biogas (fraction). The IPCC default value of 0.5 should be used;
F is the fraction of methane in the gas. The IPCC default value of 0.5 should be used (fraction) (actually, [15] the fraction of methane is higher, 0.6–0.75);
$\frac{16}{12}$ is the ratio of molar masses of methane and carbon;
GWP_{CH4} is the Global Warming Potential of methane (tCO$_2$eq/tCH$_4$).

If sludge is dried under managed and aerobic conditions and then disposed to a landfill with methane recovery or disposed as fertilizer on agricultural lands, the corresponding methane emissions are considered to be negligible and should not be accounted for. Therefore:

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[15] Wastewater Treatment: Biological and Chemical Processes, 3rd edition, Henze, M., Harremoes, P., la Cour Jansen, J., and Arvin, E. - Berlin, Springer Verlag, 2000 - 383 pp.

$$E_{CH4,wwt,sl,y} = 0 \quad (11)$$

Table 3 lists the IPCC default values for MCF_{sl} in relation to the type of sludge disposal site.

Table 3 — Methane conversion factors in relation to the type of sludge disposal site.

Type of sludge disposal site	MCF_{sl}
Anaerobic managed solid waste disposal sites. These are sites with controlled placement of waste and with controlled scavenging and fires, having at least one of the following structures: ground or other inert cover material; mechanical compacting; levelling of the waste.	1.0
Semi-anaerobic managed solid waste disposal sites. These are sites with controlled placement of waste, which include all of the following structures: permeable cover material; leachate drainage system; regulating pondage; gas ventilation system.	0.5
Unmanaged solid waste disposal site (deep and/or with high water table). These are all solid waste disposal sites that do not meet the criteria of managed solid waste disposal sites and that have depths of greater than or equal to 5 m and/or high water, e.g., those with filling inland water (pond, river, or wetland) by waste.	0.8
Unmanaged shallow solid waste disposal sites. These are all solid waste disposal sites that do not meet the criteria of managed solid waste disposal sites and that have depths of less than 5 m. Also, sludge drying beds with natural and artificial subsurface are included here.	0.4
Unmanaged shallow solid waste disposal sites. These are all solid waste disposal sites that do not meet the criteria of managed solid waste disposal sites and that have depths of less than 5 m.	0.6

Calculation of methane emission if the sludge is treated in a new anaerobic digester

If the sludge is treated in a new anaerobic digester, and this is followed by biogas flaring to produce electricity or heat energy, possible methane emissions may include the leakage of methane from the digester and pipelines and emissions due to incomplete combustion of biogas in flaring equipment. It is typically assumed that the latter is negligible. The IPCC formula for calculating the emissions due to leakage of methane from the digester is as follows:

$$E_{CH4,wwt,digest,y} = F_{biogas,y} * FL_{biogas,digest} * w_{CH4,biogas,y} * GWP_{CH4} * 0{,}001 \quad (12)$$

where $E_{CH4,wwt,digest,y}$ are the methane emissions due to physical leakage of methane from the anaerobic digester [in the year y] (t CO_2eq/year);
$F_{biogas,y}$ is the quantity of biogas collected at the new digester outlet in the year *y* (m^3/year);
$FL_{biogas,digest}$ is the fraction of biogas that leaks from the digester. The IPCC default value is 0.05 m^3 biogas leaked/m^3 biogas produced (fraction);
$w_{CH4,biogas,y}$ is the concentration of methane in the biogas at the outlet of the new digester (kgCH_4/m^3);
GWP_{CH4} is the Global Warming Potential of methane (tCO_2eq/tCH_4);
0.001 is the kilogram to tonne conversion factor.

Box 3 presents an alternative approach.

Box 3.

Formula (12) is inconvenient for calculations, because it is a practically difficult task to determine the concentration of methane in the biogas collected at digester outlet. Below, a different formula will be proposed for determining the GHG emissions due to leakage of methane from the digester.

Under presumption that biogas is composed exclusively of methane and carbon dioxide, with minor impurities of hydrogen and hydrogen sulphide neglected, the biogas composition can be represented as follows:

$$Biogas = F * CH_4 + (1 - F) * CO_2, \tag{12a}$$

where F is the mass fraction of methane in the gas, which ranges from 0.6 to 0.75 (see above).

Under normal conditions methane density is equal to 0.7168 kg/m^3, while CO_2 density is equal to 1.9768 kg/m^3.

Therefore, formula (12a) gives for the biogas density:

$$Dencity\ Biogas = F * 0{,}7168 + (1 - F) * 1{,}9768 = (1{,}9768 - 1{,}26 * F)\frac{kg}{m3}.$$

After rounding, the following formula for calculating the GHG emissions due to leakage of methane from the digester can be obtained:

$$E_{CH4,wwt,digest,y} = F_{biogas,y} * FL_{biogas,digest} * (1{,}98 - 1{,}26 * F) * GWP_{CH4} * F * 0{,}001 \quad (12b),$$

where

$E_{CH4,wwt,digest,y}$ — are the methane emissions due to physical leakage of methane from the anaerobic digester (t CO_2eq/year),

$F_{biogas,y}$— is the quantity of biogas collected at the new digester outlet in the year y (m^3/year),

$FL_{biogas,digest}$ — is the fraction of biogas that leaks from the digester (fraction). The IPCC default value is 0.05 m^3 biogas leaked/m^3 biogas produced,

$(1{,}98 - 1{,}26 * F)$ — is the biogas density (kg/m^3),

F — is the mass fraction of methane in the gas,

GWP_{CH4}— is the Global Warming Potential of methane (t CO_2eq/t CH_4),

0,001 — is the kilogram to tonne conversion factor.

Aerobic wastewater treatment

There should be no methane emissions associated with aerobic wastewater treatment. However, emissions can arise because of formation of areas with an oxygen deficit due to improper operation and/or overloading of WWTP. Also, the decay of degradable organic carbon contained in aerobic wastewater treatment effluent may lead to methane emissions (depending on the receiving body characteristics).

Therefore, methane emissions from an aerobic wastewater treatment plant due to improper operation and/or overloading can be calculated as follows:

$$E_{CH4,wwt,a,y} = \sum_{i=1}^{365} \Delta COD_{a,i} * Q_{a,i} * B_{ww} * GWP_{CH4} * MCF_{ww,o}, \text{ if } OR_i < 0{,}8 \tag{13}$$

$$E_{CH4,wwt,a,y} = 0, \text{ if } OR_i \geq 0.8$$

where $E_{CH4,wwt,a,y}$ are the methane emissions from aerobic wastewater treatment plant in the year *y* due to improper operation and/or overloading (tCO_2eq/year);
$\Delta COD_{a,i}$ is the quantity of the chemical oxygen demand removed over aerobic wastewater treatment in the day *i* of the year *y* (t/m^3). In fact, this is the difference between the quantity of the chemical oxygen demand at the inlet of the aerobic zone in the day *i* of year *y* (tCOD) minus the

quantity of the chemical oxygen demand at the outlet of the aerobic zone in the day *i* of year *y* (tCOD);
$Q_{a,i}$ is the quantity of the influent wastewater in the aerobic wastewater treatment plant in the day *i* of the year *y* (m^3);
B_{ww} is the maximum methane producing capacity of wastewater treated in the year *y*, expressing the maximum quantity of CH_4 that can be produced from a given quantity of chemical oxygen demand (t CH_4/t COD). The default IPCC value for $B_{ww}$is 0.25 kg CH_4/kg COD (see above);
$MCF_{ww,o}$ is the average MCF in the year *y*, representing the fraction of organic load that would be degraded to CH_4 (fraction). In the case of overloading of a plant or improper operation, $MCF_{ww,o}$ is to be taken as 0.3, in accordance with Table 2. As noted above, some Russian experts consider this value as being strongly overestimated;
$GWP_{CH4}$is the Global Warming Potential of methane (tCO_2eq/tCH_4);
OR_i is the oxidisation ratio, i.e., a ratio between the quantity of the chemical oxygen demand removed over aerobic wastewater treatment and the quantity of the chemical oxygen demand at the inlet of the aerobic wastewater treatment plant in day *i* of the year *y* (fraction), i.e.,

$$OR_i = \frac{\Delta COD_{a,i}}{COD_{in,a,i}}, \tag{14}$$

where $COD_{in,a,i}$ is the quantity of chemical oxygen demand at the inlet of the aerobic wastewater treatment plant in the day *i* of the year *y* (t COD).

Setting $MCF_{ww,o}$

Aerobic wastewater treatment plants are designed in a way such that their operation proceeds under aerobic conditions and, consequently, negligible emissions of methane are produced. However, the IPCC Guidelines recognize that different operational problems may arise in aerobic treatment systems, that will lead to the development of anaerobic conditions and to conversion of a fraction of the organic matter to CH_4. The IPCC default values for MCF in aerobic treatment plant, ranging from 0 to 0.4, are destined to account for these problems which include:

Box 4.

- ✓ The general hydraulic design and operation of wastewater treatment plants aims to maximise gravity flow, maintain full flow through different treatment units (e.g., primary sedimentation tanks, aeration tanks, secondary clarifiers), so as to prevent the development of “dead zones”.
- ✓ Regular desludging of tanks is essential to avoid decay of sludge (excessive sludge buildup within treatment units can lead to development of anaerobic conditions within the tank sludge blanket).
- ✓ In activated sludge plants or biofilter plants, sludge bulking within treatment units may occur due to formation of large sludge flocks, as well as nozzle blocking on rotor distribution arms in biofilter plants. The lack of mixing in the areas of sludge buildup can result in development of anaerobic conditions and, thereby, to formation of methane.
- ✓ Overloading of the plant can lead to evolution of poor hydraulic conditions, with residence time in the treatment units insufficient for bacteria to breakdown organic matter, which results in poor performance of the biological treatment processes. These problems are augmented by large variations in flow to the plant.
- ✓ Maintaining sufficient dissolved oxygen levels in the aeration tank for the given level of load is essential.
- ✓ Development of a bulky sludge can lead to the evolution of microanaerobic environments within sludge flocks, which can lead to CH_4 formation. In this situation, chemical addition can be undertaken.

To summarise, for properly operating plants, $MCF_{ww,o} = 0$ (0–0.1 range). For improperly operating plants (overloading or arising of the above-described problems), $MCF_{ww,o}$ is assumed to be equal to 0.3 (0–0.4 range). The IPCC methodology applies a proxy parameter, the oxidisation ratio OR_i, to determine the CH_4 emissions for plants under improper operational conditions (formula 14). For aerobic wastewater treatment plants this is the degree of removal of organic matter (assessed via COD decrease).

Methane emissions due to the presence of degradable organic carbon in the effluent

The methane emissions due to discharge of effluent containing degradable organic carbon into a receiving waterbody can be calculated as follows:

$$E_{CH4,wwt,effl,y} = B_{ww} * GWP_{CH4} * MCF_{ww,effl,y} * \sum_{m=1}^{12} COD_{effl,m} * Q_{effl,m} \,, \qquad (15)$$

where $E_{CH4,wwt,effl,y}$ are the methane emissions due to the presence of degradable organic carbon in the effluent in the year *y* (tCO_2eq/year);
B_{ww} is the maximum methane producing capacity of wastewater treated in the year *y*, expressing the maximum quantity of CH_4 that can be produced from a given quantity of chemical oxygen demand (tCH_4/tCOD). The default IPCC value for this parameter is 0.25 kg CH_4/kg COD (see above);
$GWP_{CH4}$is the Global Warming Potential of methane (tCO_2eq/tCH_4);
$MCF_{ww,effl,y}$ is the average methane conversion factor in the year *y*, representing the fraction of organic load in the effluent that is degraded to CH_4 in the year *y* (fraction);
$COD_{effl,m}$ is the quantity of chemical oxygen demand in the effluent of the wastewater treatment plant in the month *m* of the year *y* (tCOD/m^3 in a month);
$Q_{effl,m}$ is the quantity of effluent containing the degradable organic carbon, that is discharged into the receiving body in the month *m* of the year *y* (m^3 in a month).

Determination of $MCF_{ww,effl,y}$

The annual average methane conversion factor is calculated using the factor f_d expressing the influence of the receiving body depth and the factor $f_{T,y}$ expressing the influence of the temperature on the methane generation. Therefore,

$$MCF_{ww} = f_d * f_{T,y} \qquad (16)$$

The IPCC default value for f_d is as follows: 0.7 at a depth of water body > 5 m, $f_d = 0.5$ at a depth of 1–5 m, and $f_d = 0$ at a depth < 1 m.

Therefore, the factor $f_{T,y}$ is to be calculated with the help of a monthly stock change model which assesses how much COD degrades in each month. Based on monthly values of $f_{T,m}$ the annual value $f_{T,y}$ can be calculated as follows:

$$f_{T,y} = \frac{\sum_{m=1}^{12} f_{T,m} * COD_{effl,m}}{12 * \sum_{m=1}^{12} COD_{effl,m}} \qquad (17)$$

where $f_{T,y}$ is the annual average factor expressing the influence of the temperature on the methane generation*,* $f_{T,m}$ is the monthly average factor expressing the influence of the temperature on the methane generation, and $COD_{effl,m}$ is the average quantity of chemical oxygen demand in the effluent, that is discharged into the receiving body in the month *m* (tCOD/month).

The average factor expressing the influence of temperature on the methane generation in the month *m* is calculated by equation (6).

In our opinion, the inclusion of this component into calculation of the carbon footprint of a water and wastewater company is debatable. Methane emissions due to discharge of effluent into the receiving body can rather be attributed to the carbon footprint of the whole agglomeration served by this company. In the case when organic matter content of the effluent (treated wastewater_ is compliant with the appropriate standard, the contribution from the company to this component should be considered zero: The WWTP has reduced the carbon footprint of the agglomeration, and the COD quantity in the effluent was brought into compliance with the standard This component may be accounted and assigned to the company in the case of substandard COD quantity in the effluent that was discharged into a water body. In this event, calculations by formula (15) should include the difference between the actual and standard COD.

2.1.2. Calculation of the nitrous oxide emissions associated with sludge disposal as fertilizer on agricultural lands

As seen from Table 1, the emissions of nitrous oxide (N_2O) are accounted for sludge if the wastewater treatment sludge is disposed as fertilizer on agricultural lands

$$E_{N2O,sl,y} = M_{sl,dry,y} * w_{N,sl,y} * EF_{N2O,sl,land} * \frac{44}{28} * GWP_{N2O} \quad (18)$$

where $E_{N2O,sl,y}$ are the N_2O emissions from land application of sludge in the year *y* (tCO_2eq/year);
$M_{sl,dry,y}$ is the mass of sludge applied to land in the year *y* (t sludge, dry mass);
$w_{N,sl,y}$ is the mass fraction of nitrogen in the sludge applied to land in the year *y* (tN/t sludge);
$EF_{N2O,sl,land}$is the N_2O conversion factor from decomposition of sludge applied to land. The average emission factor to be used is 0.01 tN_2O-N/t N[16];
44/28 is value inverse to the molar mass of Nitrogen in N_2O;
$GWP_{N2O}$is the Global Warming Potential of nitrous oxide (tCO_2eq/tN_2O) (298).

If sludge is dried under controlled and aerobic conditions, and then disposed to a landfill, or treated in a new anaerobic digester, and the residues from the anaerobic digester are dehydrated, [limed] and stored before final disposal in a controlled landfill, $E_{N2O,sl,y} = 0$.

2.1.3. Calculation of the GHG emissions associated with electricity generation and consumption

The electricity consumed at a WWTP for wastewater treatment purposes can be imported from centralized grid, or generated on the site (e.g., using biogas), or imported from a single cogeneration plant.

The basic formula for calculation of GHG emission in this case is as follows:[17]

$$E_{electr,y} = \sum_j C_{electr,j\,y} * EF_{electr,j,y} \quad (19)$$

where $E_{electr,y}$ are the GHG emissions associated with electricity consumption in the year *y* (tCO_2/year);
$C_{electr,j\,y}$ is the quantity of electricity consumed on the WWPT site at the source *j* in the year *y* (MWh/year);

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[16] Stehfest, E. and Bouwman, A.F. N_2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modelling of global annual emissions. Nutr. Cycl. 29 Agroecosyst., in press.

[17] «Tool to calculate baseline, project and/or leakage emissions from electricity consumption» (Version 01) http://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-05-v1.pdf

$EF_{electr,j,y}$ is the [annual average] CO_2 emission factor for the electricity source *j* in the year *y* (tCO_2/MWh);
j are the sources of electricity.

The IPCC methodology considers several scenarios:

1. The electricity is imported from the grid only.

   In this case, the CO_2 emission factor is equated to the regional/national electricity grid emission factor: $EF_{electr,j,y} = EF_{electr,grid,y}$. The "Tool to calculate baseline, project and/or leakage emissions from electricity consumption" indicates that, for electricity grids where hydropower plants constitute less than 50% of total grid, depending on the proportion of «nonclean» (fossil fuel-fired cogeneration) and clean energy technologies (hydropower plants, wind turbines, solar voltaic panels, cogeneration plants based on renewable raw materials), $EF_{electr,grid,y}$ can vary from 1.3 to 0.25 tCO_2/MWh.

2. Electricity is imported from an off-grid/single source power plant(

   In case where none of these sources is a cogeneration plant or where the heat generation is ignored, the annual average CO_2 emission factor can be calculated as follows:

$$EF_{electr,j,y} = \frac{\sum_n \sum_i FC_{n,i,t} * NCV_{i,t} * EF_{CO2,i,t}}{\sum_n EG_{n,t}} \quad (20)$$

where $EF_{electr,j,y}$ is the CO_2 emission factor for electricity generation for the source *j* in the year *y* (t CO_2/MWh);
$FC_{n,i,t}$ is the quantity of fossil fuel type *i* fired in the electricity source *n* in the time period *t* (mass or volume unit);
$NCV_{i,t}$ is the average net calorific value of the fossil fuel type *i* fired in the period *t* (GJ/mass or volume unit);
$EF_{CO2,i,t}$ is the average CO_2 emission factor of the fossil fuel type *i* fired in the period *t* (tCO_2 /GJ);
$EG_{n,t}$ is the quantity of electricity generated in the electricity source *n* in the time period *t* (MWh);
n are the sources of electricity exporting energy to the site;
i are the fossil fuel types fired in the electricity source *n* in the time period *t.*

In the case of cogeneration plants at which both electricity and heat are generated for on-site consumption, the annual average CO_2 emission factor can be calculated as follows:

$$EF_{CO2,electr,j,y} = \frac{\sum_n \left[\sum_i \left(FC_{n,i,t} * NCV_{i,t}\right) - \frac{HG_{n,t}}{\mu_{boiler}}\right] * EF_{CO2,i,t}}{\sum_n EG_{n,t}} \quad (21)$$

where $EF_{CO2,electr,j,y}$ is the CO_2 emission factor for electricity generation for electricity consumption source *j* in the year *y* (t CO_2/MWh);
$FC_{n,i,t}$ is the quantity of the fossil fuel type *i* fired in the electricity source *n* in the time period *t* (mass or volume unit);
$NCV_{i,t}$ is the average net calorific value of the fossil fuel type *i* fired in the period *t* (GJ/mass or volume unit);
$HG_{n,t}$ is the quantity of heat cogenerated in electricity source *n* in the time period *t* (GJ);

μ_{boiler} is the efficiency of the boiler plant in which heat is assumed to be generated in the absence of a cogeneration plant;
$EF_{CO2,i,t}$ is the average CO_2 emission factor of fossil fuel type *i* fired in the time period *t* (tCO_2/GJ);
$EG_{n,t}$ is the quantity of electricity generated in the electricity source *n* in the time period *t* (MWh);
n are the sources of electricity exporting energy to the WWTP site;
i are the fossil fuel types fired in the electricity source *n* in the time period *t.*

In the case when one single fuel type *i* is fired in the electricity source *plant*, $EF_{CO2,n,t} = EF_{CO2,i,t}$ holds for the emission factor in formulas (20, 21); in the case when multiple fuel types are fired in the electricity source, the emission factor is calculated as

$$EF_{CO2,n,t} = \frac{\sum_i FC_{n,i,t} * NCV_{i,t} * EF_{CO2,i,t}}{\sum_i FC_{n,i,t} * NCV_{i,t}} \tag{22}$$

where $EF_{CO2,n,t}$ is the average CO_2 emission factor of the fossil fuels fired in the electricity source *n* in the time period *t* (t CO_2/GJ);
$FC_{n,i,t}$ is the quantity of the fossil fuel type *i* fired in electricity source *n* in the time period *t* (mass or volume unit);
$NCV_{i,t}$ is the average net calorific value of the fossil fuel type *i* used in the period *t* (GJ/mass or volume unit);
$EF_{CO2,i,t}$ is the average CO_2 emission factor of the fossil fuel type *i* fired in the time period *t* (tCO_2/GJ);
n are the sources of electricity exporting electricity to the WWTP site;
i are the fossil fuel types fired in the electricity source *n* in the time period *t.*

2.1.4. Calculation of the GHG emissions associated with fossil fuel combustion

In the case of on-site fossil fuel (waste) combustion for manufacturing purposes (steam, hot water, heating) the GHG (CO_2) emissions can be calculated by the formula[18]:

$$E_{FC,j,y} = \sum_i FC_{i,j,y} * COEF_{i,y} \tag{23}$$

where $E_{FC,j,y}$ are the CO_2 emissions from fossil fuel combustion in process *j* during the year *y* (tCO_2/year);
$FC_{i,j,y}$ is the quantity of the fuel type *i* combusted in the process *j* during the year *y* (mass or volume unit/year);
$COEF_{i,y}$ is the CO_2 emission coefficient of the fuel type *i* in the year *y* (tCO_2/mass or volume unit);
i are the fuel types combusted in process *j* during the year y.

The CO_2 emission factor $COEF_{i,y}$ can be calculated using either of the two options, depending on the available data on the fossil fuel type *i*, as follows:

Option 1: The CO_2 emission coefficient $COEF_{i,y}$ is calculated based on the chemical composition of the fossil fuel type *i*, using the following approach:

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[18] «Tool to calculate project or leakage CO2 emissions from fossil fuel combustion», (Version 02) http://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-03-v2.pdf

If $FC_{i,j,y}$ is measured in a mass unit,

$$COEF_{i,y} = w_{C,i,y} * 44/12 \tag{24a}$$

If $FC_{i,j,y}$ is measured in a volume unit,

$$COEF_{i,y} = w_{C,i,y} * \rho_{i,y} * 44/12 \tag{24b}$$

where $w_{C,i,y}$ is the weighted average mass fraction of carbon in the fuel type *i* in the year *y* (tC/fuel mass unit);
$\rho_{i,y}$ is the weighted average density of the fuel type *i* in the year *y* (tC/fuel volume unit);
44/12 is the carbon dioxide to carbon molar mass ratio.

Option 2: The CO_2 emission coefficient $COEF_{i,y}$ is calculated based on net calorific value and CO_2 emission factor of the fuel type *i*, as follows:

$$COEF_{i,y} = NCV_{i,y} * EF_{CO2,i\,y} \tag{24c}$$

where $NCV_{i,y}$ is the weighted average net calorific value of the fuel type *i* in the year y (GJ/fuel mass or volume unit)

$EF_{CO2,i,y}$ is the weighted average CO_2 emission factor of the fuel type *i* in the year *y* (t CO_2/GJ)

Option 1 should be the preferred approach in terms of higher accuracy of the calculations.

This approach does not account for emissions of other greenhouse gases originating from incomplete combustion of fuel and considers them insignificant compared to the emission of carbon dioxide.

In the event that sludge is used as fuel, the CO_2 emissions are not accounted, considering the general principle of accounting of carbon dioxide emissions from decomposition (in particular, thermal decomposition) of organic matter. Account can be made of emissions of other greenhouse gases released by burning organic matter (methane, nitrous oxide), but being low compared to other components of the carbon footprint, these emissions can be neglected.

The thermal energy/heat or electricity resulted from sludge incineration is subtracted from the total quantity of the imported energy, demanded by WWTP.

2.1.5. Calculation of the GHG emissions associated with heat consumption

In the case when the demand for heat energy is satisfied by import from an off-site source (e.g., a boiler plant or a cogeneration plant), the GHG emission calculations should take into account the heat loss by transportation. There exists an IPCC methodology in which such approach is considered [19]; like in the case discussed above, only CO_2 emissions are accounted.

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[19] Approved baseline and monitoring methodology AM0107 «New natural gas based cogeneration plant» http://cdm.unfccc.int/methodologies/DB/KI6WT9JQAOZU9181ESQN61EQHN6AJC

The CO_2 emission associated with heat consumption during a year (for simplification, it is assumed that the heat is supplied by a single source) is calculated by the formula:

$$E_{CO2,heat,y} = HC_y * EF_{CO2,heat,y} * (1 + \delta_{net}) \tag{25}$$

where $E_{CO2,heat,y}$ are the CO_2 emissions associated with heat consumption in the year *y* (t CO_2/year);
HC_y is the heat consumed on the WWYP site in the year *y* (GJ/year);
$EF_{CO2,heat,y}$ is the CO_2 emission factor for heat generation in the source supplying the heat in the year *y* (tCO_2/GJ);
δ_{net} is the average heat loss of the heat network (fraction).

For heat only boiler plants, the emission factor can be easily calculated by formula (25). It can be assumed that, in this case

$$EF_{CO2,heat,y} = \frac{EF_{CO2,i,y}}{\mu_{boiler,i}},$$

Consequently,

$$E_{CO2,heat,y} = HC_y * \frac{EF_{CO2,i,y}}{\mu_{boiler,i}} * (1 + \delta_{net}) \tag{26}$$

where $E_{CO2,heat,y}$ are the CO_2 emissions associated with heat consumption in the year *y* (tCO_2/GJ);
$\mu_{boiler,i}$ is the efficiency of boiler plant fired by the fuel type *i* (fraction);
$EF_{CO2,i,y}$ is the average CO_2 emission factor of the fuel *i* in the year y (tCO_2/GJ);
δ is the average heat loss of the heat network (fraction).

A more difficult situation with $EF_{CO2,heat,y}$calculations arises when heat is supplied by a cogeneration plant, because the plant generates both heat and electricity. In this case of much importance is the heat-to-electricity ratio of the cogeneration plant during a year

$$\theta_y = \frac{HG_{y,total}}{EG_{y,total}*3.6} \tag{27}$$

where θ_y is the heat-to-electricity ratio of the cogeneration plant in the year *y*. This is the parameter whose value for a specific cogeneration plant is known and identical for all users;
$HG_{y,total}$ is the total quantity of heat generated by the cogeneration plant in the year *y* (GJ);
$EG_{y,total}$ is the total quantity of electricity generated by the cogeneration plant, that is fed into the electric power grid in the year *y* (MWh);
3.6 is the conversion factor, expressed as GJ/MWh.

The quantity of heat generated is related to the quantity of the fuel type *i* combusted as follows:

$$\frac{HG_y}{\mu_{heat,i}} + \frac{EG_y}{\mu_{electr,i}} = FC_{i,y} * NCV_{i,y} \tag{28}$$

where $\mu_{heat,i}$ is the thermal efficiency of the cogeneration plant fired by the fuel type *i* (fraction);
$\mu_{electr,i}$ is the electrical efficiency of the cogeneration plant fired by the fuel type *i* (fraction);
$FC_{i,y}$ is the quantity of the fuel type *i* combusted by the energy source *j* in the year *y* (mass or volume units);
$NCV_{i,y}$ is the average net calorific value of the fuel type *i* in the year *y* (GJ/mass or volume units).

Substituting HG_y instead of EG_y in equation (28) with the use of θ_y gives:

$$HG_y * \left(\frac{1}{\mu_{heat,i}} + \frac{1}{3.6*\theta_y*\mu_{electr,i}}\right) = FC_{i,y} * NCV_{i,y}.$$

Use of equation (23) leads, for one fuel type, to:

$$E_{FC,y} = FC_{i,y} * COEF_{i,y} = FC_{i,y} * NCV_{i,y} * EF_{CO2,i\,y} ,$$

which gives for each fuel type *i* taken separately

$$E_{FC,y} = HG_y * \left(\frac{1}{\mu_{heat,i}} + \frac{1}{3.6 * \theta_y * \mu_{electr,i}}\right) * EF_{CO2,i\,y}$$

where $E_{FC,y}$are the CO$_2$ emissions corresponding to the heat HG_y generated by a cogeneration plant in the year *y* (tCO$_2$/year);
$EF_{CO2,i,y}$ is the average CO$_2$ emission factor for the fuel type *i* in the year *y* (tCO$_2$eq/GJ).

Considering the relationship $HG_y = HC_y * (1 + \delta_{net})$, between the generated and consumed heat, the final formula for calculation of CO$_2$ emissions associated with consumption of heat HC_y generated by a cogeneration plant is as follows:

$$E_{FC,y} = HC_y * \left(\frac{1}{\mu_{heat,i}} + \frac{1}{3.6*\theta_y*\mu_{electr,i}}\right) * EF_{CO2,i\,y} * (1 + \delta_{net}) \qquad (29)$$

The CO$_2$ emission coefficients for various fossil fuels are provided in IPPC Guidance[20] available in different languages, including Russian, as well as in other guidelines[21] addressing issues of assessment of GHG emission implications for the climate change.

2.1.6. Calculation of the GHG emissions associated with transportation of sludge

When sludge is transported to the disposal or treatment site by a motor vehicle, the GHG emissions from transportation fuel combustion are to be taken into account. The largest contribution to the greenhouse effect in this case comes from carbon dioxide, and the emissions of other GHG are neglected.

The CO$_2$ emissions are calculated by the formula6:

$$E_{TR,sl,y} = \sum_j \sum_i N_{i,y} * D_{i,y} * F_{i,y} * NCV_{j,y} * EF_{j,y} \qquad (30)$$

where $E_{TR,sl,y}$ are the CO$_2$ emissions from transportation of sludge in the year *y* (tCO$_2$/year);
$N_{i,y}$ is the number of trips (by vehicles of the type *i* with similar loading/vehicular capacity) for transportation of sludge in the year *y* (trips);
$D_{i,y}$ is the average distance per trip, travelled by the transportation vehicle of the type *i*, for transportation of sludge in the year *y* (km);

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[20] Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories 2000, http://www.ipcc-nggip.iges.or.jp/public/gp/english/

[21] ENERGY STAR Portfolio Manager Methodology for Greenhouse Gas Inventory and Tracking Calculations, http://www.energystar.gov/ia/business/evaluate_performance/Emissions_Supporting_Doc.pdf

$F_{i,y}$ is the specific fuel consumption of the transportation vehicle of the type *i* in the year *y* (mass or volume units of fuel/km);
$NCV_{j,y}$ is the net calorific value of the transportation fuel *j* in the year y (GJ/mass or volume units);
$EF_{j,y}$ is the CO_2 emission factor of the transportation fuel *j* in the year y (tCO_2/ GTJ);
i is the vehicle type;
j is the fuel type used in vehicles.

The number of trips of the transportation vehicle of the type *i* is calculated as:

$$N_{i,y} = \frac{Q_{sl,y}}{q_i} \tag{31}$$

where $Q_{sl,y}$ is the quantity of sludge produced and due to be transported in the year *y* (t);
q_i is the average vehicular capacity of the transportation vehicle of the type *i* in the year *y* (t/trip).

The values of the CO_2 emission factors are available in various guidelines, including the IPCC guidebook[22], or in the instruction document for local authorities[23].

2.2. Nitrous oxide emissions from the wastewater treatment process

As stated above, nitrous oxide (N_2O) emissions are not addressed by the IPCC methodologies considered in the present study, although there may be situations (with high nitrogen content in the influent wastewater), where the N_2Oemission is a factor of much significance. Below, the existing approaches to calculation of nitrous oxide emissions from wastewater treatment will be described.

Domestic wastewater contains from 20 to 40 mg/dm^3, on the average, of nitrogen compounds represented mostly by ammonia (NH_3) and ammonium ions (NH_4^+). Also, there are a number of organic substances that are transformed to ammonium compounds during the treatment process.

For wastewater to be discharged into the receiving body, its nitrogen content needs to be significantly reduced, since ammonia is toxic to fish and other aquatic organisms. Also, water bodies are adversely affected by nitrogen because of euthrophication.

Most commonly, nitrogen compounds are removed from wastewater in an activated sludge aerated reactors or in biofilters via nitrification and denitrification processes (for details, see Box 5).

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[22] IPCC Guidebook: Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories http://www.ipcc-nggip.iges.or.jp/public/gp/bgp/2_3_Road_Transport.pdf

[23] Technical annex to the SEAP template instructions document: THE EMISSION FACTORS http://www.eumayors.eu/IMG/pdf/technical_annex_en.pdf

Box 5.

Nitrification is carried out in the aerobic zone with bacteria; the process consists of two stages. In the first stage, ammonium is oxidized to nitrite by a group of ammonia-oxidizing bacteria (AOB) from Nitrosomonas, Nitrosococcus, Nitrosopira, Nitrosovibrio, and Nitrosolobus genera.

Oxidation of ammonium by bacteria can be described by the following reaction:

$NH_4^+ + 1{,}5\ O_2 \rightarrow NO_2^- + H_2O + 2H^-$. The reaction proceeds with liberation of heat:

$\Delta G = -272$ KJ/mole $NH_4^+ - N.$

Nitrite is further oxidized to nitrate by nitrite-oxidizing bacteria (NOB) of Nitrobacter, Nitrospira, Nitrjococcus, and other genera:

$NO_2^- + 0{,}5O_2 \rightarrow NO_3^-$. This reaction is also accompanied by liberation of heat:
$\Delta G = -75$ KJ/mole $NO_2^- - N.$

The liberated heat goes to maintaining the activity of nitrobacteria and increasing the wastewater temperature.

The intermediate in the first of these two reactions, which is catalyzed by ammonium monooxygenase, is hydroxylamine (NH_2OH). Monooxygenase is an enzyme that causes, via various metabolic pathways, a hydroxyl group to attach itself to a substance molecule. Hydroxylamine, in turn, is oxidized to NO_2^-. under the action of oxygen and enzyme oxidoreductase. [24] Also, nitrous oxide results from chemical decomposition of intermediates, e.g.,NH_2OH formed in the NH_4^+ conversion to NO_3^-[25].

The nitrification reaction can be represented schematically as follows:

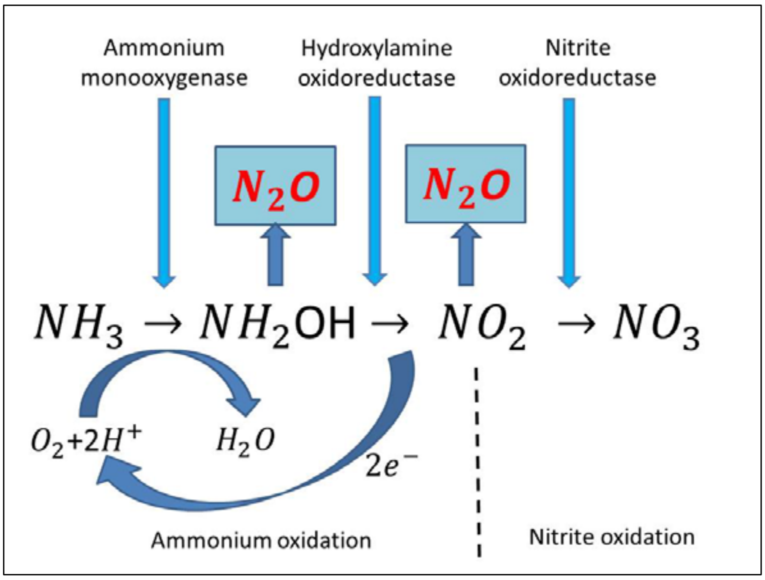

Figure 2 — Schematic of the nitrification reaction

Another route to N_2O is via denitrification reactions which convert nitrates (O_3^-) and nitrites (NO_2^-) into nitrogen gas via a series of intermediate transformations which lead eventually to

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[24] Hooper, A.B., Terry, K.R. «Hydroxylamine oxidoreductase of Nitrosomonas production of nitric oxide from hydroxylamine». Biochimica et Biophysica Acta, no. 571 (1979): 12-20.

[25] Wrage, N., Velthof, G.L., van Beusichem, M.L., Oenema, O. «Role of nitrifier denitrification in the production of nitrous oxide». Soil Biology & Biochemistry (PERGAMON), no. 33 (2001): 1723-1732.

gaseous nitrogen oxides: nitrogen monoxide (NO) and nitrous oxide N_2O. The same processes occur as metabolic reactions of bacteria of *Paracoccus*, *Denitrificans*, and *Pseudomonads genera*.

The N_2Oemission during denitrification process is the more intense the lower the content of organic matter in the wastewater and that of dissolved oxygen in the presence of nitrites. The most intense is the process occurring in anoxic zones[26] in the absence of oxygen. The denitrification reaction can be schematically represented as follows:

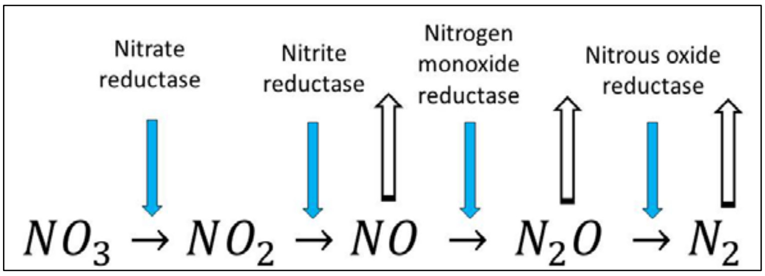

Figure 3 — Schematic of the denitrification reaction

Emission of nitrous oxide, a potent greenhouse gas, is undesirable, which stimulated in the mid-1990s, numerous studies aimed to identify the factors affecting the N_2Oemission, whose results are reviewed, e.g., in study[27]

In particular, that study indicated that, in the nitrification stage, the nitrous oxide emissions are controlled by the concentration of oxygen dissolved in wastewater, HRT for sludge, pH, and dissolved organic matter concentration. Low dissolved oxygen concentrations and brief retention time favour formation of $N_2O$from nitrification of activated sludge. The degree of conversion of ammonium to N_2Oincreases by 8% as the dissolved oxygen concentration decreases to < 1mg/dm^3. Experiments show that oxidation of organic matter under, e.g., the lack of oxygen and brief retention time for activated sludge, creates a risk of significant enhancement of nitrous oxide emission in the nitrification stage.

In the denitrification stage, N_2Oemissions are favoured by low COD/ $NO_3^- - N$ ratios, as well as by brief sludge retention times and low pH values. Among these parameters, the most important is COD/$NO_3^- - N$, which parameter determines the completeness of denitrification. In some cases, easily assimilable carbon sources such as methanol or ethanol are added as a "nutritional support" for the denitrifying bacteria. As a result, the denitrification process will be brought to completion, and N_2Oemissions will be minimized.

In the event that nitrification and denitrification occur sequentially in a single reactor, as shown in study[28] for a model wastewater, up to 20–30% ammonium can be converted to N_2Oat COD/$NO_3^- - N$ratios under 3.5. At COD/$NO_3^- - N$=5, denitrification went to completion, and N_2Oemissions were negligible.

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[26] The difference in the anaerobic and anoxic zone consists in that the former provides a strictly oxygen-free atmosphere, and in the latter oxygen is present, though bound, as nitrates and nitrites (NO_2, NO_3), rather than as dissolved oxygen.

[27] Nitrous oxide production in nitrogen removal process treating domestic sewage from combined sewer system, Pages 153-164, K. Hanaki, T. Nakamura, T. Matsuo. In the book «Advances in Water and Wastewater Treatment Technology Molecular Technology, Nutrient Removal, Sludge Reduction and Environmental Health» Copyright © 2001 Elsevier B.V. Edited by: Tomonori Matsuo, Keisuke Hanaki, Satoshi Takizawa and Hiroyasu Satoh

[28] Itokawa H, Hanaki K, Matsuo T. Nitrous oxide production in high-loading biological nitrogen removal process under low COD/N ratio condition. Water Res. 2001 Mar;35(3):657-64

Laboratory tests with real domestic wastewater[29] showed that up to 4% nitrogen removed from wastewater can be converted to nitrous oxide, with the nitrification process being the main source of N_2O. The dissolved $N_2O - N$concentration was 1.85 mg/dm^3. In the process of denitrification, the dissolved nitrous oxide was partially converted into gaseous nitrogen at the end of aeration. It was concluded that N_2Oemissions can be limited by controlling the denitrification process (for details, see Box 6).

Box 6.

Nitrous oxide emission during nitrification and denitrification processes in wastewater treatment is a phenomenon that still remains to be fully understood and that cannot be mathematically modelled in an adequate way. At least, this conclusion was derived in presentation[30] made at the WWTmod2012 Conference held at the end of February, 2012, in Canada. In that study, four mathematical models were tested, and laboratory experiments were conducted, with the aim to determine which substances are involved in the nitrification and denitrification processes during wastewater treatment. All the models adequately described the behaviour of $NH_4^+,\ NO_2^-,\ NO_3^-$ ions but could not reproduce the measured N_2Odata.

This uncertainty and failure to develop theoretical models, coupled with a high Global Warming Potential of nitrous oxide (298), encourage researchers to develop semi-empirical models based on experimental data.

An extensive study, conducted in 2009-2011 at Columbia University[31], contains a literature review providing evidence that, from the total nitrogen loading at the wastewater treatment plants (total Kjeldahl nitrogen, TKN), up to 7% can be emitted as gaseous nitrous oxide and nitrogen monoxide. That study covered 12 wastewater treatment plants in the United States, at which nitrogen compounds are removed by biological (nitrification - denitrification) methods. It was found that N_2O emissions vary with the quantity of total nitrogen removed over treatment, ΔTKN_{pr}., and were estimated at 0.01 to 3.3 % (by mass) of ΔTKN_{pr}.

Until 2009, it was believed (based on the US Environmental Protection Agency (USEPA) data)[32], that N_2O is emitted mostly in the anoxic zone of the activated sludge plants. The results of the study at Columbia University showed that the main source of nitrous oxide is the aerated zone of the reactor.

Based on the findings reported in the cited study, USEPA experts developed a GHG emission calculation methodology for a number of biological processes/facilities: waste disposal, wastewater treatment, and ethanol production[33]. We suggested that the formula recommended by EPA for N_2O emission calculation can be modified in order that monthly variations in the wastewater quality be taken into account:

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[29] Wunderlin P, Mohn J, Joss A, Emmenegger L, Siegrist H. Mechanisms of N_2O production in biological wastewater treatment under nitrifying and denitrifying conditions. Water Res. 2012 Mar 15;46(4):1027-37. Epub 2011 Dec 8.

[30] Bing-Jie Ni, Zhiguo Yuan, Kartik Chandran, Peter A. Vanrolleghem, Sudhir Murthy «Evaluating mathematical models for N2O production by ammonia-oxidizing bacteria: towards a unified model».

[31] «Greenhouse Nitrogen Emission from Wastewater Treatment Operations» Interim Report by: Kartik Chandran, Ph.D. Department of Earth and Environmental Engineering Director, CUBES Program Columbia University 2010 http://www.google.ru/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&sqi=2&ved=0CCsQFjAB&url=http%3A%2F%2Fwww.werf.org%2Fc%2F_FinalReportPDFs%2FU%2FU4R07a.aspx&

[32] U.S. EPA (2009) Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006, EPA 430-R-08-005. Washington, D.C. http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html

[33] Greenhouse Gas Emissions Estimation Methodologies for Biogenic Emissions from Selected Source Categories:
Solid Waste Disposal, Wastewater Treatment, Ethanol Fermentation. U.S. Environmental Protection Agency, Sector Policies and Programs Division, Measurement Policy Group. Submitted by: RTI International. December, 2010. http://www.epa.gov/ttnchie1/efpac/ghg/GHG_Biogenic_Report_draft_Dec1410.pdf

$$E_{N2O,wwt,y} = \sum_{i=1}^{12}\left(Q_{wwt,i} * TKN_{infl,i}\right) * EF_{N2O} * \frac{44}{28} * GWP_{N2O} * 10^{-6} \quad (32)$$

where $E_{N2O,wwt,y}$ are the N_2O emissions from biological treatment process in the year *y* (tCO_2/year);
$Q_{wwt,i}$ is the quantity of influent wastewater to the biological treatment plant in the month *i* of the year *y* (m^3);
$TKN_{infl,i}$ is the Total Kjeldahl Nitrogen in the influent wastewater (mg/dm^3 or g/m^3);
EF_{N2O} is the N_2O conversion factor. The IPCC[10] default value for the conversion factor is 0.005 g N released into atmosphere as $N_2O/gTKN_{infl}$. The N_2Oconversion factor range being 0.0005 – 0.25, this value needs to be refined (see 2.3);
44/28 — value inverse to the molar mass of Nitrogen in N_2O;
GWP_{N2O} is the Global Warming Potential of N_2O (298);
10^{-6} is the gram to tonne conversion factor.

As follows from formula (32), the USEPA experts used the average N_2O emission value of 0.005*44/14=0.0157 TKN_{infl}, or 1.57%TKN_{infl}, in the influent wastewater.

The USEPA methodologies[33] provide simplified formulas for estimating the N_2O conversion factor for projected wastewater treatment plants. The N_2O conversion factor EF_{N2O,PE_US} is normalized to the population equivalent, which gives the following values of the N_2O conversion factor:

$EF_{N2O,PE\_US} = 7.0\ g\,\frac{N_2O}{PE_{US}}$ during a year for wastewater treatment plants at which nitrogen is removed by biological methods, and

$EF_{N2O,PE\_US} = 3.2\ g\,\frac{N_2O}{PE_{US}}$ during a year for wastewater treatment plants at which nitrogen is removed by nonbiological methods (without dedicated denitrification)

The use of these formulas should take into account the fact that, for the US, the population equivalent is 100 gallons (378 litres) of wastewater per capita per day against 200 litres of wastewater, or 60 g BOD_5 per capita per day, in the EU countries and in the Russian Federation.

Formula (32) can be modified into formula (32a) (see below) by normalizing the N_2Oconversion factor to the total nitrogen removed over the denitrification process, rather than to the total nitrogen in the influent wastewater. This normalization is more adequate to the physics of the process; moreover, there are a lot of experimental data on the conversion factor normalized in this way (see 2.3 below). Therefore, the N_2O emissions can be calculated as follows:

$$E_{N2O,wwt,y} = \sum_{i=1}^{12}\left(Q_{wwt,i} * \left(TKN_{infl,i} - TKN_{effl,i}\right)\right) * EF_{N2O/\Delta N} * \frac{44}{28} * GWP_{N2O} * 10^{-6} \quad (32a),$$

where $TKN_{effl,i}$ is total Kjeldahl nitrogen in the effluent (mg/dm^3 or g/m^3);
$EF_{N2O/\Delta N}$ is the N_2O conversion factor (for total nitrogen) normalized to the nitrogen removed over the denitrification process (for details of the measurement procedure and the values of this factor, see 2.3).

For other designations, see (32).

2.3. Refining the IPCC Methodologies

The last decade has seen a large number of studies, mostly experimental, dedicated to refining the IPCC methodologies. Those refinements are typically concerned with methane and nitrous oxide conversion factors. For example, the Water Services Association of Australia (WSAA) conduced laboratory tests and fieldwork aimed to determine emissions of methane and nitrous oxide[34].

The methane emissions from wastewater treatment processes were investigated at four full-scale wastewater treatment plants in Australia:

- ✓ Bird-in-Hand WWTP, Adelaide Hills, South Australia: flow rate 1.2 thousand m^3/day; combination of domestic wastewater and industrial wastewater; 2 uncovered aerobic/anaerobic/facultative lagoons (UAFL) (in parallel); aerated lagoon (2 mechanical surface aerators); 7 maturation lagoons.

- ✓ 25W Western Treatment Plant, Melbourne: flow rate 230 thousand m^3/day; combination of domestic and industrial wastewater; 650 thousand m^3 covered anaerobic lagoon (CAL) with biogas recovery for energy generation; 713 thousand m^3 aerated lagoon (50 mechanical surface aerators); activated sludge plant receiving ca. 200 thousand m^3/day from CAL; 9 maturation lagoons.

- ✓ North Head WWTP, Sydney Water: flow rate 275 thousand m^3/day; combination of domestic and industrial wastewater (4 primary sedimentation tanks (ca. 0.5 h HRT); sludge thickening, anaerobic digestion, centrifuge mechanical dewatering.

- ✓ Yatala Brewery Treatment Plant, Fosters Queensland: flow rate 3.3 thousand m^3/day; brewery wastewater only; 4 0.66-thousand m^3 Upflow Anaerobic Sludge Blanket (UASB) reactors[35]; 2 air flotation units; sludge dewatering.

Three to four sampling rounds were conducted at each plant in August-November period. For each round, the CH_4 emissions within different zones of the plant and the chemical oxygen demand values were determined. It was found that methane generation was the largest at Western Treatment Plant (CAL), where the methane generated was recovered in the biogas, and only 7–11% was lost as dissolved methane in the CAL effluent to the activated sludge plant and the downstream aerated lagoon. However, for a large plant such as Western Treatment Plant, Melbourne, this still represents a potentially large source of GHG emissions (13.400 – 21.600 tCO_2eq/year).

Based on the mass balance analysis of the CAL, it was calculated that 0.22 – 0.23 kg CH_4 is generated per kg of COD removed. In the context of the IPCC methodologies (formulas 3–5, Table 2) this represents a $\mathrm{MCF_{ww}}$ value of 0.87 – 0.93, rather than the maximal value of 0.7 (formulas 4–5) or 0.8 (the IPCC default value for MCF).

The mass balance analysis of the aerated lagoon at Western Treatment Plant showed that the estimated MCF value for this aerated lagoon is 0.03 – 0.20, which is similar to the MCF for “shallow anaerobic lagoon” in Table 2, in accordance with the IPCC guidelines.

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[34] WSAA Occasional Paper No.24 - Direct Methane and Nitrous Oxide emissions from full-scale wastewater treatment systems (2009). https://www.wsaa.asn.au/WSAAPublications/Pages/Occasional-Papers.aspx#.UFOG5I1gJm4

[35] Upflow Anaerobic Sludge Blanket (UASB) is a reactor in which wastewater flows upwards in a vertical reactor through a blanket of granulated sludge.

At North Head WWTP, Sydney, virtually no methane is emitted into the atmosphere. As shown by the WSAA study, this may be due to consumption of dissolved methane by methanotrophic bacteria which occur in aerobic surface environments of primary sedimentation tanks and utilise methane as their sole source of carbon and energy[36]. Methane oxidation proceeds as follows:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

An adequate description of this effect is provided, e.g., in studies by Alla Kozhevnikova (Vinogradskii Institute of Microbiology, Russian Academy of Sciences) concerned with methane emission from solid domestic waste landfills. Methane oxidation in the aerobic surface environment tends to enhance with increasing temperature and may reach 10–100%; at negative temperatures, methanotrophic bacteria get inactive. Table 4 lists the corrected MCF_{ww} values for the four wastewater treatment plants investigated.

Table 4 — Methane conversion factors derived for the full-scale WWTPs from field studies.

Wastewater treatment plant	Comments	MCF_{ww}	Range/Comments
Bird-in-Hand WWTP, Adelaide Hills, flow rate 1.2 thousand m³/day	Aerated lagoon, specific aeration power ~1.5 W/m³	0.10	0.03 – 020
25W Western Treatment Plant, Melbourne, flow rate 230 thousand m³/day	Covered anaerobic lagoon, depth 8 m	0.90	0.87 – 0.93
North Head WWTP, Sydney, flow rate 275 thousand m³/day	primary sedimentation tank, depth 3.2 m; HRT 0.5 h	0.00	Possible methane oxidation in the surface environment of the primary sedimentation tanks
Fosters Brewery, Yatala, Queensland, flow rate 3.3 thousand m³/day	UASB reactor, depth 5.5 m	1.0	0.80 – 1.0

Seven full-scale wastewater treatment plants with different flow rates, designs, and degree of nitrogen removal were involved in studies of N_2O emissions from biological wastewater treatment plants:

✓ "Ox. Ditch" Brisbane, Queensland: flow rate 38 thousand m^3/day; HRT~13 days; anaerobic contact tank; 2 extended aeration oxidation ditches (in parallel); secondary sedimentation; mechanical sludge thickening and dewatering; Effluent Total Nitrogen < 3 mg/dm^3.

✓ "Johannesburg" Toowoomba, Queensland: flow rate 10 thousand m^3/day; HRT~20 days; 2 extended aeration Johannesburg bioreactors[37] (in parallel) with submerged aspirating OKI aerator mixers; secondary sedimentation**;** sludge thickening; aerobic digestion, mechanical and solar dewatering; Effluent Total Nitrogen < 5 mg/dm^3.

✓ "SBR" Woodman Point WWTP Perth, Western Australia: flow rate 137 thousand m^3/day; HRT~16 days; primary sedimentation, sequencing batch reactor (4 compartments) with diffused aeration and bio-selector zone; sludge thickening, anaerobic digestion, and mechanical dewatering; Effluent Total Nitrogen < 15 mg/dm^3.

✓ Subiaco WWTP, Perth, Western Australia: flow rate 63 thousand m^3/day, HRT~13 days; primary sedimentation; 11 covered Modified Ludzack Ettinger bioreactors (MLE)[38] (in parallel)

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[36] According to Russian experts, a brief residence time of sludge may be an alternative reason.

[37] The Johannesburg Process is a 4-stage system (anoxic, anaerobic, anoxic, and aerobic zones) with enlarged basin.

[38] The Modified Ludzack-Ettinger (MLE) Process is a modification of the conventional activated sludge process for wastewater treatment with an initial anoxic stage followed by an aerobic stage; an internal recycle pump brings nitrates formed in the aerobic zone, with mixed activated sludge and wastewater, to the anoxic zone.

with diffused aeration; secondary sedimentation; sludge thickening, mechanical dewatering, and lime stabilization; Effluent Total Nitrogen < 12 mg/dm^3.

- ✓ Adelaide WWTP, South Australia: flow rate 49 thousand m^3/day, HRT~8 days; primary sedimentation; 2 Integrated Fixed Film Activated Sludge bioreactors; 1 MLE bioreactor (in parallel) with diffused aeration; secondary sedimentation, mechanical thickening and anaerobic digestion; Effluent Total Nitrogen < 11 mg/dm^3.
- ✓ 25W Western Treatment Plant, Melbourne: flow rate 230 thousand m^3/day, HRT~15 days; 650 m^3 covered anaerobic lagoon (CAL) with biogas recovery for energy generation; 713 m^3 aerated lagoon (50 mechanical surface aerators); 1 MLE bioreactor with diffused aeration; secondary sedimentation; 9 maturation lagoons; Effluent Total Nitrogen < 13 mg/dm^3.
- ✓ St Mary's, Sydney: flow rate 25 thousand m^3/day, HRT~14 days; 2 parallel trains: (1) primary sedimentation; Bardenpho bioreactor[39] with diffused aeration; secondary sedimentation and (2) pre-fermenter; four-stage bioreactor (similar to A2/O configuration[40]) with diffused aeration; secondary sedimentation; tertiary filtration; sludge thickening, aerobic digestion; sludge lagoon; and mechanical dewatering; Effluent Total Nitrogen < 3 mg/dm^3.

Table 5 summarizes the data on the N_2O conversion factors (for total nitrogen) normalized to nitrogen removed by nitrification, which were obtained in a series of 20 sampling rounds at the 7 wastewater treatment plants.

Table 5 — The N_2O conversion factor values (for total nitrogen*)* normalized to nitrogen removed by denitrification.

Wastewater treatment plant	$EF_{N2O/N}$ (kg $N_2O - N/\Delta N$) $-N_2O$ conversion factor (for total nitrogen) normalized to nitrogen removed by denitrification			
	Round 1	Round 2	Round 3	Round 4
Brisbane	**0.008** (0.005-0.016)	**0.006** (0.003-0.012)	**0.013** (0.008-0.023)	**0.006** (0.003-0.013)
Toowoomba	**0.014** (0.008-0.025)	**0.021** (0.011-0.039)	**0.011** (0.004-0.025)	
Woodman Point	**0.010** (0.009-0.021)	**0.017** (0.015-0.034)	**0.071** (0.064-0.146)	
Subiaco	**0.027** (0.018-0.045)			
Adelaide	**0.022** (0.014-0.034)	**0.078** (0.056-0.134)	**0.007** (0.004-0.010)	**0.096** (0.068-0.166)
Melbourne	**0.253** (0.177-0.451)	**0.010** (0.005-0.021)	**0.006** (0.003-0.011)	
St Mary's	**0.018** (0.014-0.036)		**0.010** (0.007-0.019)	

Bold items are the averaged conversion factors, and parenthesized items, the ranges of the results. It is seen that the highest nitrous oxide conversion factors were obtained for those WWTPs where the total nitrogen content of the effluent is high. This fact well correlates with the above-mentioned finding that the largest nitrous oxide emissions accompany incomplete denitrification.

The minimal N_2O generation factor was 0.006 kg $N_2O - N/\Delta N$, and the maximal, 0.253 kg $N_2O - N/\Delta N$. The average for the 20 sampling rounds was $EF_{N2O/N}$ = 0.035 ± 0.027 kg $N_2O - N/\Delta N$, which is close to the maximal value reported in study[28]: $EF_{N2O/N}$ = kg 0.033 $N_2O - N/\Delta N$. However, a number of average values from Table 5 are skewed upwards by some of the results and therefore need appropriate statistical processing.

The degree of nitrate removal in anoxic zone is a function of internal recycle rate and of the available organic carbon under anoxic conditions in upward flow.

[39] The Bardenpho Process consists of wastewater treatment in an anoxic stage and alternating stages of anaerobic and aerobic conditions.

[40] The A2/O Process consists of anoxic, anaerobic, and aerobic stages of wastewater treatment process.

Thu use of the criterion proposed in study[41] for discarding the results leads to

$$X_b = \overline{X} * \left(1.55 + 0.8 * \log\frac{n}{10} * \sqrt{\varepsilon - 1}\right),$$

where X_b is sample censoring limit, $\overline{X}$ is the arithmetic mean of a sample, n is the number of series values (observation number), and ε is kurtosis.

As shown in that study , calculation of the censoring limit by this formula works well, if unreliable value are excluded for a wide range of non-normal distributions. Based on this criterion, the average generation factor for nitrous oxide was estimated at $EF_{N2O/N}$ = 0.013 kg $N_2O - N/\Delta N$, which value will be used in further calculations.

This value exceeds by a factor of 2.6 that recommended by the IPCC methodology (2006): $EF_{N2O/N}$ = 0.005 kg $N_2O - N/\Delta N$. However, the most recent (February 2013) EPA investigation[42] («Waste" Chapters) recognized the need to refine the conversion factors on the basis of specifically the materials used in the present study.

The WSAA study also showed that more than 95% of N_2O formed is subsequently emitted to the atmosphere.

Of much interest are also the data provided in that study about the zones (anaerobic, aerobic, anoxic) in which the N_2Ogeneration is the largest. It was found that the net generation of N_2O-N in the various anaerobic zones, primary sedimentation tanks, and secondary sedimentation tanks is generally positive, but small in comparison to the net generation in the anoxic and aerobic zones. The most significant variation in nitrous oxide emission is observed in aerobic zones (from high generation intensity of the gas to its total absence). These processes are very sensitive to changes in the wastewater parameters: nitrogen loading, pH, dissolved oxygen concentration, and presence of oxidizable organic matter.

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[41] Novitskii P.V., Zograf I.A., Estimation of the uncertainties of measurement results. – 2nd edition. – Leningrad: Energoatomizdat, 1991. – 304 pp.

[42] http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html [Electronic resource]

3. STEP-BY-STEP CALCULATION OF THE CARBON FOOTPRINT OF WASTEWATER TREATMENT PLANTS

Before proceeding to calculations, it is necessary to define the scope for calculation of the carbon footprint of a water and wastewater company. Most likely, the calculations will cover the WWTP site and the sludge disposal sites, as well as vehicles employed for sludge transportation to disposal sites (and for other uses) and office buildings.

The default time period for the carbon footprint calculation will be set on one year.

Step 1. Carbon footprint due to the consumption of purchased electricity on the site and in the office premises

For electricity imported from centralized grid the following calculation scheme should be applied:

Table 6 — Calculation of GHG emissions associated with the grid electricity consumption

Imported electricity (MWh/year)	CO_2 emission factor for electricity consumed (tCO_2/MWh)	GHG emissions associated with the grid electricity consumption (tCO_2/year)
1	2	3
A	B	A*B

In 2010, the Lahmeyer International Group undertook the “Development of the Electricity Carbon Emission Factors for Russia and Ukraine” project for the period from 2009 to 2020 by order of the European Bank of Reconstruction and Development. As regards the Russian Federation, the study was dedicated to several Integrated Power Systems (IPS)[43]. Table 7 lists the CO_2 emission factors for the period 2009–2016. The differences in the tabulated values are due to different “sets” of electricity generation capacities and other regional differences (nuclear power generation, heat energy generation, different fuel types, hydropower plants, length of power transmission line, loss of power in transmission line, etc.).

Table 7 — Electricity carbon emission factors for different Integrated Power Systems in Russia and for Russia as a whole

Year/Integrated Power System		**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
$EF_{electr,j,y}$ (t CO_2/MWh)	Russia	0.617	0.616	0.624	0.642	0.632	0.629	0.640	0.632
	IPS Centre	0.576	0.593	0.574	0.614	0.635	0.623	0.614	0.620
	IPS East	0.661	0.559	0.834	0.968	0.948	0.950	0.969	0.968
	IPS North West	0.448	0.425	0.419	0.420	0.407	0.397	0.417	0.423
	IPS Siberia	1.003	1.006	0.993	0.949	0.955	0.949	0.960	0.954
	IPS South	0.376	0.352	0.369	0.374	0.379	0.428	0.413	0.373
	IPS Urals	0.576	0.582	0.609	0.649	0.581	0.564	0.588	0.573
	IPS Middle Volga	0.356	0.359	0.362	0.387	0.375	0.380	0.385	0.382

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[43] European Bank of Reconstruction and Development. Development of the Electricity Carbon Emission Factors for Russia and Ukraine, October 14, 2010.
http://www.ebrd.com/downloads/sector/eecc/Baseline_Study_Russia_Final_Russian.pdf

With the known electricity sources, the values of the emission factors (Table 6, column 2) can be requested directly from managers of the respective electricity generation capacities, which will allow the GHG emissions to be calculated more accurately. Where heat energy generation is the source of electricity, formulas (20–22) from Section 2 can be applied for calculating the emission factors. In the case where renewable power generation serves as the source of electricity, the GHG emission factors are assumed to be zero.

It should be noted that, in this Step, the carbon footprint due to consumption of electricity from external sources solely will be determined.

Step 2. Carbon footprint due to the heat consumption

Step 2.1. On-site heat generation

The GHG (CO_2) emissions associated with on-site combustion of fossil fuel (waste) for steam and hot water generation, as well as for heating purposes, are calculated as follows:

Table 8 — Calculation of GHG emissions associated with fossil fuel (waste) combustion

Quantity of the fuel of one type combusted during a year (t/year or m^3/year)	Weighted average net calorific value of the fuel (GJ/t or GJ/ m^3)	CO_2 emission factor for the fuel (t CO_2/GJ)	GHG emissions associated with fuel combustion during a year (t CO_2/year)
1	2	3	4
A	B	C	A*B*C

In the case of on-site combustion of several types of fossil fuels or waste, the GHG emissions (column 4) are to be calculated for each fossil fuel type (waste) in separate, and the resulting values are to be added together.

The net calorific values for different types of fuel, as well as CO_2 emission factors can be found elsewhere, e.g., in the materials of the Covenant of Mayors EU[44] committed to local sustainable energy (over 4000 cities), listed in Table 9. Most of relevant materials are available in different, including Russian, languages. All the data obtained are in conformity with the IPCC Guidelines (2006). Table 8 lists the net calorific values and CO_2 emission factors for the most common fuel types; column 9 provides the emission factors in tCO_2/MWh units (recall that 1 MWh is equal to 3.6 GJ).

For the CO_2 emission factors of other fuel types, see Guidebook "How to Develop a Sustainable Energy Action Plan (SEAP)"[45].

Table 9 — Net calorific values and CO_2 emission factors for selected fuels

Fuel type	Net calorific value (GJ/t)	CO_2 emission factor (tCO_2/GJ)	CO_2 emission factor (tCO_2/MWh)
Crude oil	42.3	0.0733	0.264
Natural gas liquids	44.2	0.0642	0.231
Motor gasoline	44.3	0.0693	0.249
Aviation gasoline	44.3	0.0700	0.252
Jet kerosene	44.1	0.0715	0.257
Other kerosene	43.8	0.0719	0.259

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[44] http://www.soglasheniemerov.eu/about/covenant-of-mayors_ru.html

[45] http://www.eumayors.eu/IMG/pdf/guidebook_part__2_ru_seapcorrection-eng.pdf

Fuel type	Net calorific value (GJ/t)	CO_2 emission factor (tCO_2/GJ)	CO_2 emission factor (tCO_2/MWh)
Shale oil	38.1	0.0733	0.264
Gas/diesel oil	43.0	0.0741	0.267
Residual fuel oil	40.4	0.0774	0.279
Liquefied petroleum gases	47.3	0.0631	0.227
Anthracite	26.7	0.0983	0.354
Coking coal	28.2	0.0946	0.341
Other bituminous coal	25.8	0.0946	0.341
Lignite	11.9	0.1010	0.364
Brown Coal Briquettes	20.7	0.0975	0.351
Bricketed fuel	20.7	0.0975	0.351
Coke	28.2	0.1070	0.385
Natural gas	48.0	0.0561	0.202
Municipal wastes (non-biomass fraction)	10	0.143	0.515
Waste oil	40.2	0.0733	0.264
Peat	9.76	0.106	0.382
Sludge (dry mass)[46]	25.12	0.1096	0.395

For natural gas quantities measured in m^3, the net calorific value of natural gas will be 0.035 GJ/m^3, considering the density of natural gas of 0.73 kg/m^3.

If a tabulated value of the average net calorific value of a fuel with the known chemical composition is lacking, the CO_2 emission factor is to be calculated by formulas (24a–24b) from Section 2.

According to IPCC Guidelines (2006)[47], the average values of total carbon content of dry weight sludge range from 40 to 50%, but in study[48] it was reported that they may vary from 44% to 76% (on dry weight basis). In the above-cited study[41], the average total carbon content in dry weight sludge (recalculated according to the data in Table 9) was assumed to be 75%; the carbon dioxide emissions associated with sludge incineration are incorporated in the carbon footprint calculation, which operation is methodologically incorrect.

Step 2.2. Heat is imported from a single heat source

If the heat energy demand is satisfied by import from a single heat source (e.g., a boiler plant or a cogeneration plant), the GHG emission calculations should take into account the heat transportation loss.

If heat is supplied by an off-site boiler plant, the GHG emissions are to be calculated as follows:

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[46] «Inventory of greenhouse gas emissions at GUP “Vodokanal of St. Petersburg” State Unitary Enterprise, “Scientific Research Institute for Atmospheric Air Protection” Federal State Unitary Enterprise, St. Petersburg, 2007.

[47] 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 5: Incineration and Open Burning of Waste. http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_5_Ch5_IOB.pdf

[48] Sedova, E.A., Ecological and energetic aspects of utilization of wastewater treatment sludge, E. A. Sedova, Scientific search. Technical sciences: Proc. Third Sci. Conf. of PhD Students and Doctoral Students, S.D. Vaulin (Ed.), South Urals State University, Chelyabinsk: South Urals State University Publishing Center, 2011. – Vol. 1. – P. 74-78. http://dspace.susu.ac.ru/bitstream/handle/0001.74/1199/20.pdf?sequence=1

Table 10 — Calculation of the GHG emissions if heat is imported from an off-site boiler plant using the known boiler plant efficiency and the average heat loss of the heat network

Heat imported from the boiler plant [during a year] (GJ/year)	CO_2 emission factor for the fossil fuel fired in the boiler plant (tCO_2/GJ)	Energy efficiency of the boiler plant (fraction)	Average heat loss of the heat network (fraction)	GHG emissions if heat is imported from the boiler plant during a year (tCO_2/year)
1	2	3	4	5
A	B	C	D	A*B*(D+1)/C

The CO_2 emission factors for the fossil fuel fired in the boiler plant (Table 10, column 2) are listed in Table 9.

The average heat loss for the heat network (Table 10, column 4) is measured in fraction units; this is the ratio of the loss in heat network to the heat consumed. It depends on a number of factors, e.g., regional climate features, distance separating the boiler plant from the user, design features of heat transmission line, etc. According to study[49], in Russia's heat networks the heat loss may reach 0.4.

For the purposes of the present study, a suitable approach to assessment of the average heat loss in the heat network is that based on the heat carrier temperature measured at the heat energy meter on the site (T_{site}) and the heat carrier temperature at the boiler plant outlet (T_{boiler}). Thus, the average heat loss of the heat network $\delta_{net}$is determined as follows:

$\delta_{net} = \frac{T_{boiler} - T_{site}}{T_{site}}$, where temperature is measured on the Kelvin scale [recall that Kelvin (*T*) and Celsius (*t°C*) scale temperatures are related as $T = t°C + 273.15$]. In this case, Table 10a is to be used for calculations.

Table 10a — Calculation of the GHG emissions if heat is imported from an off-site boiler plant using the known boiler plant efficiency and the heat carrier temperatures at the boiler plant outlet and at the site inlet.

Heat imported from the boiler plant during a year (GJ/year)	CO_2 emission factor for the fossil fuel fired in the boiler plant (tCO_2/GJ)	Energy efficiency of the boiler plant (fraction)	Temperature of the heat carrier at the boiler plant outlet (K)	Temperature of the heat carrier at the site inlet (K)	GHG emissions if heat is imported from the boiler plant during a year (t CO_2/year)
1	2	3	4		5
A	B	C	D	E	A*B*D/C/E

The boiler plant efficiency data (Tables 10–10a, column 3) are to be requested from the boiler plant managers (the efficiency of boiler plant should not be confused with that of boiler, which can be very high).

Tentative values of the efficiencies of modern boiler plants are listed in Table 11[50].

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[49] E.G. Gasho, V. S. Puzankov, Realities in modern heat supply sector http://solex-un.ru/sites/solex-un/files/energo_review/konsolidirovannyy_obzor_--problemy_effektivnogo_teplosnabzheniya--.pdf

[50] Information system on heat energy supply http://www.rosteplo.ru/Tech_stat/stat_shablon.php?id=416

Table 11 — Tentative values of the efficiencies of modern boiler plants

Boiler plant capacity	Efficiency range (fraction)
< 100 kW	0.6 – 0.80
100 – 1000 kW	0.65 – 0.90
> 1000 kW	0.70 – 0.90

When heat is supplied by a cogeneration plant producing both heat energy and electricity, the GHG emissions can be calculated as follows:

Table 12 — Calculation of the GHG emissions, if heat is imported from an off-site cogeneration plant using the known thermal efficiency and electrical efficiency of the cogeneration plant and the average heat loss of the heat network

Heat imported from the cogeneration plant (GJ)	CO_2 emission factor for the fuel fired in the cogeneration plant (tCO_2/GJ)	Thermal efficiency of the cogeneration plant (fraction)	Electrical efficiency of the cogeneration plant (fraction)
1	2	3	4
A	B	C	D

Quantity of heat cogenerated during a year (GJ)	Quantity of electricity cogenerated during a year (MWh)	Average heat loss of the heat network (fraction)	GHG emissions if heat is imported from the cogeneration plant (tCO_2)
5	6	7	8
E	F	G	A*B*(1/C+F/(3.6*E*D))*(G+1)

Calculations using Table 12 require the knowledge of the thermal efficiency and electrical efficiency data for the cogeneration plant to be requested from the cogeneration plant managers. These values are to be known. With missing average heat loss data for the heat network, calculations will follow the scheme of Table 12a, in which the heat loss is estimated from the decrease in the heat carrier temperature.

Table 12a — Calculation of the GHG emissions if heat is imported from an off-site cogeneration plant using the known thermal efficiency and electrical efficiency of the cogeneration plant and the known heat carrier temperatures at the cogeneration plant outlet and at the site inlet.

Heat imported from the cogeneration plant (GJ)	CO_2 emission factor for the fuel fired in cogeneration plant (tCO_2/GJ)	Thermal efficiency of the cogeneration plant (fraction)	Electrical efficiency of the cogeneration plant (fraction)
1	2	3	4
A	B	C	D

Quantity of heat cogenerated during a year (GJ)	Quantity of electricity cogenerated during a year (MWh)	Temperature of the heat carrier at the cogeneration plant outlet (K)	Temperature of the heat carrier at the site inlet(K)	GHG emissions if heat is imported from the cogeneration plant (tCO_2)
5	6	7		8
E	F	G	I	A*B*(1/C+F/(3.6*E *D))*G/I

Where several fossil fuel types are used for heat generation, the calculations using the schemes in Tables 10, 10a and 12, 12a are to be carried out several times, depending on the number of the fossil fuel types used during the year, after which the values in the last columns are to be added together.

Step 3. Carbon footprint due to the use of transportation vehicles

The main use of transportation vehicles at WWTP is transportation of sludge, in which case the largest contribution to the GHG emissions comes from carbon dioxide whose emissions are calculated as follows:

Table 13 — Calculation of the GHG emissions if sludge is transported by transportation vehicles of one type.

Number of trips made by the transportation vehicle of one type during a year (trips)	Average distance per trip, travelled by the transportation vehicle of one type (km)	Average? specific fuel consumption of the transportation vehicle (t/km or m^3/km)	Average? net calorific value of the transportation fuel (GJ/t or GJ/m^3)	CO_2 emission factor of the transportation fuel (tCO_2/GJ)	GHG emissions from transportation of sludge (tCO_2)
1	2	3	4	5	6
A	B	C	D	E	A*B*C*D*E

If all the sludge is transported by vehicles of one type, the number of trips (A) is to be determined by dividing the entire quantity the sludge produced on the site and due to be transported during a year by the vehicular capacity of the vehicle. If the vehicles employed by the WWTP have different vehicular capacities and operate on different fuel types, the carbon footprint is to be calculated via accounting the trips of the vehicles of all the types in separate. The calculations using Table 13 are to be carried out for each vehicle and fuel type, after which the results in column 6 are to be added together.

The specific fuel consumption (column 3, Table 13) is determined from the transportation vehicle certificate or experimentally. The latter option is preferable in terms of higher accuracy of the carbon footprint calculations.

The net calorific values of the transportation fuel (column 4) and CO_2 emission factors (column 5) are listed in Table 8.

The carbon footprint will be determined more accurately if all the transportation vehicle trips, including those for transportation of chemicals and employee business travel, will be taken into account. To this end, the transportation fuel consumed should be accounted for at the facility for each fuel type in separate. The calculation is carried out as follows:

Table 14 — Calculation of the GHG emissions from use of transportation vehicles at the facility.

Transportation fuel of one type used during a year (t or m^3)	Average net calorific value of the transportation fuel (GJ/t or GJ/m^3)	CO_2 emission factor of the transportation fuel (tCO_2/GJ)	GHG emissions from use of transportation vehicles (tCO_2)
1	2	3	4
A	B	C	A*B*C

The calculations using Table 14 are to be carried out for each fuel type, after which the results in column 4 are to be added together.

Step 4. Carbon footprint due to the methane emissions from wastewater treatment

Methane emissions from wastewater treatment occur in those areas of water treatment plants, where anaerobic conditions exist, e.g., in deep primary sedimentation tanks and in anaerobic zones of aeration tanks.

In aeration tanks methane is generated only if wastewater treatment plants are overloaded or improperly operating, where methane emissions may be due to sludge decay.

Also, the effluent discharged into the receiving body contains residual organic matter. Under favourable conditions in the receiving body, this organic matter may undergo anaerobic decay with methane emission. This component of the carbon footprint will be assigned to the water and wastewater company in the case of a substandard organic matter content of the effluent discharged into a water body.

In the current version of the IPCC Guidance, the parameter determining the methane emissions is the quantity of the chemical oxygen demand (ΔCOD), or of the biological oxygen demand (ΔBOD), removed over the wastewater treatment in the zone of interest.

Step 4.1. Primary sedimentation tanks

Methane emissions in the anaerobic zone (in a primary sedimentation tank, for the present conditions) are to be calculated by formula 3 from 2.1. This requires the knowledge of the methane conversion factor representing the proportion of organic matter (fraction) that will be converted to methane. This factor depends, in particular, on the design features of the WWTP. The default IPCC values for the simplified calculation procedure are as follows:

Table 15 — Methane conversion factors (a simplified calculation procedure).

Design of anaerobic zone	Conversion factor
Anaerobic shallow lagoon or sedimentation tank (depth less than 2 m)	0.2
Anaerobic deep lagoon or sedimentation tank (depth more than 2 m)	0.8

Table 15a — Calculation of the methane emissions from anaerobic wastewater treatment (a simplified calculation procedure).

Quantity of the chemical oxygen demand removed over the anaerobic wastewater treatment during a year (tCOD/m³)	Quantity of the influent wastewater in the anaerobic zone during a year (m³)	Methane emissions from anaerobic wastewater treatment (tCO_2eq)	
		Primary sedimentation tank depth < 2 m	Primary sedimentation tank depth >2 m
1	2	3.1	3.2
A	B	25*0.25*0.2*A*B	25*0.25*0.8*A*B

The methane conversion factor can be calculated more accurately via taking into account the average temperature of the wastewater in the anaerobic zone (the activity of methanogenic bacteria varies with the temperature) and the «anaerobic rate» (which is dependent on the depth of primary sedimentation tank). Thus, the methane conversion factor can be represented as the product $C = C_T * C_d$ where C_T is the factor expressing the influence of the temperature on the methane generation, and C_d is the factor expressing the influence of the depth of primary sedimentation tank on methane generation.

The factor expressing the influence of the temperature on the methane generation is to be calculated in columns (4–5) of Table 16 with the use of formulas (5–6) from Section 2.

The default IPCC values for different depths of primary sedimentation tank are as follows: 0.7 at a depth >5 m, $C_d = 0.5$ at a depth within 1–5 m, and $C_d = 0$ at a depth < 1 m. However, considering the refined experimental data from 2.3, we can recommend the following values: $C_d = 0.9$ for deep primary sedimentation tanks, $C_d = 0.6$ for intermediate depths, and $C_d = 0.02$ for shallow primary sedimentation tanks. These values are listed in column 7, Table 16.

The maximum methane producing capacity of the wastewater, which is the maximum quantity of CH_4 that can be produced for a given quantity of chemical oxygen demand removed over the anaerobic wastewater treatment, can be taken equal to 0.25 $tCH_4/tCOD$ (column 9, Table 16), considering the theoretical (2.1.1) and experimental (see 2.3) data.

Thus, the methane emissions can be calculated in Table 16 using formula (3) from 2.1.1.

Table 16 — Calculation of the methane emissions from anaerobic wastewater treatment (primary sedimentation tank).

	Month	Quantity of the chemical oxygen demand removed over the wastewater treatment in the primary sedimentation tank in a month ($tCOD/m^3$)	Quantity of the influent wastewater in the primary sedimentation tank in a month (m^3)	Average temperature of the wastewater in the primary sedimentation tank (K)
	1	2	3	4
		ΔCOD_i	Q_i	T_i
1	January	ΔCOD_1	Q_1	T_1
2	February	ΔCOD_2	Q_2	T_2
3	March	ΔCOD_3	Q_3	T_3
4	April	ΔCOD_4	Q_4	T_4
5	May	ΔCOD_5	Q_5	T_5
6	June	ΔCOD_6	Q_6	T_6
7	July	ΔCOD_7	Q_7	T_7
8	August	ΔCOD_8	Q_8	T_8
9	September	ΔCOD_9	Q_9	T_9
10	October	ΔCOD_{10}	Q_{10}	T_{10}
11	November	ΔCOD_{11}	Q_{11}	T_{11}
12	December	ΔCOD_{12}	Q_{12}	T_{12}

Table 16. Contd. 1 — Calculation of the methane emissions from anaerobic wastewater treatment (primary sedimentation tank)

Month	Monthly average factor expressing the influence of the temperature on the methane generation $C_{i,T}$			Methane conversion factor in relation to the depth of the primary sedimentation tank		
5	6			7		
	T_i <283 K	283K<T_i<303.16K	T_i>303.16 K	Depth > 5m	Depth 1–5 m	Depth < 1 m
January	0	$C_1 = Exp[(T_1-303.16)/T_1]$	1	0.9	0.6	0.02
February	0	$C_2 = Exp[(T_2-303.16)/T_2]$	1	0.9	0.6	0.02
March	0	$C_3 = Exp[(T_3-303.16)/T_3]$	1	0.9	0.6	0.02

Month	Monthly average factor expressing the influence of the temperature on the methane generation $C_{i,T}$			Methane conversion factor in relation to the depth of the primary sedimentation tank		
5	6			7		
April	0	$C_4 = Exp[(T_4-303.16)/T_4]$	1	0.9	0.6	0.02
May	0	$C_5 = Exp[(T_5-303.16)/T_5]$	1	0.9	0.6	0.02
June	0	$C_6 = Exp[(T_6-303.16)/T_6]$	1	0.9	0.6	0.02
July	0	$C_7 = Exp[(T_7-303.16)/T_7]$	1	0.9	0.6	0.02
August	0	$C_8 = Exp[(T_8-303.16)/T_8]$	1	0.9	0.6	0.02
September	0	$C_9 = Exp[(T_9-303.16)/T_9]$	1	0.9	0.6	0.02
October	0	$C_{10} = Exp[(T_{10}-303.16)/T_{10}]$	1	0.9	0.6	0.02
November	0	$C_{11} = Exp[(T_{11}-303.16)/T_{11}]$	1	0.9	0.6	0.02
December	0	$C_{12} = Exp[(T_{12}-303.16)/T_{12}]$	1	0.9	0.6	0.02

Table 16. Contd. 2 — Calculation of the methane emissions from anaerobic wastewater treatment (primary sedimentation tank).

	Month	Maximum methane producing capacity of the wastewater ($tCH_4/tCOD$)	Global Warming Potential for methane	Methane emissions from anaerobic wastewater treatment (tCO_2eq)
	8	9	10	11
1	January	0.25	25	(2)*(3)*(6)*(7)*(9)*(10)
2	February	0.25	25	(2)*(3)*(6)*(7)*(9)*(10)
3	March	0.25	25	(2)*(3)*(6)*(7)*(9)*(10)
4	April	0.25	25	(2)*(3)*(6)*(7)*(9)*(10)
5	May	0.25	25	(2)*(3)*(6)*(7)*(9)*(10)
6	June	0.25	25	(2)*(3)*(6)*(7)*(9)*(10)
7	July	0.25	25	(2)*(3)*(6)*(7)*(9)*(10)
8	August	0.25	25	(2)*(3)*(6)*(7)*(9)*(10)
9	September	0.25	25	(2)*(3)*(6)*(7)*(9)*(10)
10	October	0.25	25	(2)*(3)*(6)*(7)*(9)*(10)
11	November	0.25	25	(2)*(3)*(6)*(7)*(9)*(10)
12	December	0.25	25	(2)*(3)*(6)*(7)*(9)*(10)
	Annual total			Sum of rows 1–12

Step 4.2. Aerobic treatment

Methane emissions in aerobic zones depend on whether the wastewater treatment plant operates properly or not. If the load on the WWTP exhibits daily variations, the IPCC methodology recommends daily measurements of COD values at the inlet and outlet of the aerobic zone (formula 13). In the case of stable operation, decadal or monthly measurements will be sufficient. Given below is the scheme for decadal measurements.

As the parameter determining the overload of the WWTP will serve the oxidisation ratio representing the ratio between the quantity of the chemical oxygen demand removed over aerobic wastewater treatment during a decade and the quantity of the chemical oxygen demand at the inlet of the aerobic wastewater treatment plant during a decade (formula 14).

Further calculation of the methane emissions proceeds as follows:

Table 17. — Calculation of methane emissions from aerobic wastewater treatment.

Decadal average COD at the inlet of the aerobic zone (t/m^3)	Decadal average COD at the outlet of the aerobic zone (t/m^3)	Oxidisation ratio	Choosing further calculation route	Methane emissions from aerobic wastewater treatment (tCO_2eq)
1	2	3	4	5
A	B	(A-B)/A	If (3) ≥ 0.8, go to column (5); If (3) < 0.8, go to columns (6–11)	0

Table 17. Contd. — Calculation of methane emissions from aerobic wastewater treatment.

Decade in which the condition (3) < 0.8 is satisfied	Quantity of the influent wastewater in the aerobic zone during a decade (m^3)	Quantity of the COD removed over the aerobic wastewater treatment during a decade ($tCOD/m^3$)	Maximum methane producing capacity of the wastewater ($tCH_4/tCOD$)	Methane conversion factor	Global Warming Potential for methane (tCO_2eq/tCH_4)	Methane emissions from aerobic wastewater treatment (tCO_2eq)
6	7	8	9	10	11	12
Decade 1	Q_1	$\Delta COD_1 = (1)_1 - (2)_1$	0.25	0.4	25	(7)*(8)*(9)*(10)*(11)
Decade 2	Q_2	$\Delta COD_2 = (1)_2 - (2)_2$	0.25	0.4	25	(7)*(8)*(9)*(10)*(11)
…….	…..	…..	…..		……	……
Decade *n*	Q_n	$\Delta COD_n = (1)_n - (2)_n$	0.25	0.4	25	(7)*(8)*(9)*(10)*(11)
Annual total						Sum over all decades

Step 4.3. Simplified version of the calculation procedure for the methane emissions from biological wastewater treatment

With missing data on the quantity of the COD removed in the primary sedimentation tank, the methane emissions from wastewater treatment can be determined by a simplified procedure, following the scheme in Table 17a.

Table 17a — Calculation of the methane emissions from biological wastewater treatment (simplified calculation procedure).

Quantity of the COD removed over the biological wastewater treatment during a year ($tCOD/m^3$)	Quantity of the influent wastewater in the aerobic zone during a year (m^3)	Annual average methane conversion factor			Methane emissions from biological wastewater treatment (tCO_2eq)
		Properly operating WWTP	Slightly overloaded WWTP	Heavily overloaded WWTP	
1	2	3			4
A	B	0*)	0.2	0.4	25*0.25*A*B*(3)

*) The IPCC methodology (2006) provides the 0–0.1 range for this factor in the case of aerobic wastewater treatment. However, IPCC experts consider the methane emissions for properly operating WWTP as insignificant, so that this factor should be assumed to be zero. The choice between “properly and “improperly” can be based on the value of the oxidisation ratio to be determined from the quantities of the COD at the inlet and outlet of the WWTP (see Step 4.2).

Step 5. Carbon footprint due to the GHG emissions from sludge utilization

Possible alternative scenarios for wastewater treatment sludge utilization are as follows: sludge is disposed to a landfill, incinerated, or used for biogas production in digesters.

Step 5.1. Sludge incineration

The GHG emissions for sludge incineration are not calculated; the heat or electricity thereby generated is deducted from the overall energy demand of a water and wastewater company.

Step 5.2. Sludge is disposed to a landfill or dehydrated in a drying bed

In this case, the GHG emissions will be determined by the methane conversion factor which depends on the design features of the sludge disposal site. The corresponding IPCC default values for the methane conversion factor are presented in Table 18:

Table 18 — Methane conversion factors in relation to the type of sludge disposal site.

Type of sludge disposal site	MCF_{sl}
Anaerobic managed solid waste disposal sites. These are sites with controlled placement of waste and with controlled scavenging and fires, having at least one of the following structures: ground or other inert cover material; mechanical compacting; levelling of the waste.	1.0
Semi-anaerobic managed solid waste disposal sites. These are sites with controlled placement of waste, which include all of the following structures: permeable cover material; leachate drainage system; regulating pondage; gas ventilation system.	0.5
Unmanaged solid waste disposal site (deep and/or with high water table). These are all solid waste disposal sites that do not meet the criteria of managed solid waste disposal sites and that have depths of greater than or equal to 5 m and/or high water, e.g., those with filling inland water (pond, river, or wetland) by waste.	0.8
Unmanaged shallow solid waste disposal sites. These are all solid waste disposal sites that do not meet the criteria of managed solid waste disposal sites and that have depths of less than 5 m. Also, sludge drying beds with natural and artificial subsurface are included here.	0.4
Unmanaged shallow solid waste disposal sites. These are all solid waste disposal sites that do not meet the criteria of managed solid waste disposal sites, which have depths of less than 5 m.	0.6

After choosing the methane conversion factor value, the methane emissions if sludge is disposed to a landfill are calculated as follows (Table 19):

Table 19 — Calculation of the GHG emissions if sludge is disposed to a landfill.

Quantity of the sludge disposed to a landfill (dry weight basis)	Methane conversion factor (fraction) (column 2, Table 18)	Degradable organic content of sludge (dry weight basis) (fraction)	Fraction of degradable organic content dissimilated to biogas (fraction)	Fraction of methane in the gas (fraction)	GHG emissions if sludge is disposed to a landfill (tCO_2eq)
1	2	3	4	5	6
A	B	C	D	E	25*A*B*C*D*E*16/12

Column 3 contains the degradable organic content sludge (dry weight basis) (fraction). The IPCC default values to be used are as follows: 0.5 for domestic sludge and 0.257 for industrial sludge. These data can be refined for specific wastewater treatment plants.

Column 4 provides the fraction of degradable organic content dissimilated to biogas. The IPCC default value of 0.5 (fraction) should be used.

Column 5 contains the fraction of methane in the gas, for which the IPCC default value of 0.5 (fraction) should be used. According to, the actual fraction of methane in the gas is higher: 0.6 – 0.75.

Step 5.3. Sludge is treated in a new anaerobic digester

The GHG emissions in the case where sludge is treated in a new anaerobic digester are calculated by the scheme from Table 19. These emissions are due to physical leakage of methane from a new digester, for which the "standard leakage" notion can be introduced. For the fraction of biogas that leaks from the digester, the IPCC default value is 0.05 m^3 biogas leaked/m^3 biogas produced. Clearly, the digester that has been operated for a long time is characterized by a different value to be determined experimentally.

For sludge treated in a new anaerobic digester, with the biogas extracted from the anaerobic digester being flared and/or used to generate electricity and/or heat, the corresponding emissions should account for fugitive emissions of methane from the digester, and for methane emissions due to incomplete combustion of biogas in flaring equipment. The latter factor is considered negligible. The fugitive emissions of methane will be accounted for by using formula (12b):

Table 20 — Calculation of the GHG emissions if sludge it treated in a new anaerobic digester.

Quantity of biogas collected at the outlet of the new digester during a year (m^3)	Fraction of biogas that leaks from the digester (fraction)	Mass fraction of methane in the gas (fraction)	GHG emissions if sludge is treated in a new anaerobic digester (tCO_2eq)
1	2	3	6
A	B	C	25*A*B*C*(1.96 – 1.25*C)*0.001

The mass fraction of methane in the gas (column 3, Table 20) is to be taken from the experimental data. If these data are missing, the recommended value for sludge of combined sewer is C = 0.6.

Step 5.4. Nitrous oxide emissions if raw sludge is applied to land or disposed to a landfill

Nitrous oxide emissions are assumed to be negligible and need not be accounted for if sludge is dried under controlled and aerobic conditions and then disposed to a landfill, or if it is treated in a new anaerobic digester, after which the residues from the anaerobic digester are dehydrated, limed, and stored before final disposal in a managed landfill.

If raw sludge is applied to land or disposed to an unmanaged landfill, the nitrous oxide emissions are calculated using formula (18) in Table 21.

Table 21 — Calculation of the nitrous oxide emissions if sludge is applied to land or disposed to an unmanaged landfill.

Quantity of the sludge applied to land during a year (t sludge)	Mass fraction of nitrogen in the sludge applied to land (t N/t sludge)	N_2O conversion factor from decomposition of the sludge applied to land (t N_2O/t N)	Global Warming Potential of nitrous dioxide (tCO_2eq)/tN_2O)	Nitrous oxide emissions if sludge is applied to land or disposed to an unmanaged landfill during a year (t CO_2eq)
1	2	3	4	5
A	B	0.016	298	298*0.016*A*B

The mass fraction of nitrogen in the sludge (column 2) is determined by chemical analysis of the sludge. The conversion factor (column 3) was taken on the basis of the conversion for Total Kjeldahl Nitrogen (0.01 t N_2O-N/t N) as recommended by IPCC (see 2.1.2), multiplied by 44/28 (value inverse to the molar mass of Nitrogen in N_2O).

Step 6. Carbon footprint due to the nitrogen oxide emissions from wastewater treatment process

The IPCC methodology does not take into account the carbon footprint component associated with nitrous oxide emissions from wastewater treatment. Below, we will calculate this component with the use of formula (32) from 2.2; based on the experimental data from 2.3, the N_2O conversion factor will be assumed to be $EF_{N2O/N}$ = 0.013 kg $N_2O - N/\Delta N$.

The calculations will follow the scheme from Table 22.

Table 22 — Calculation of the nitrous oxide emissions from wastewater treatment process.

	Month	Total Kjeldahl Nitrogen in the influent wastewater (g/m^3)	Total Kjeldahl Nitrogen in effluent from the WWTP? (g/m^3)	Quantity of the influent wastewater in a month (m^3)	Nitrous oxide emissions from wastewater treatment (tCO_2eq)
	1	2	3	4	5
		$C_{i,in}$	$C_{i,out}$	Q_i	$(C_{i,in} - C_{i,out})* Q_i$
1	January	$C_{1,in}$	$C_{1,out}$	Q_1	$(C_{1,in} - C_{1,out})* Q_1$
2	February	$C_{2,in}$	$C_{2,out}$	Q_2	$(C_{2,in} - C_{2,out})* Q_2$
3	March	$C_{3,in}$	$C_{3,out}$	Q_3	$(C_{3,in} - C_{3,out})* Q_3$
4	April	$C_{4,in}$	$C_{4,out}$	Q_4	$(C_{4,in} - C_{4,out})* Q_4$
5	May	$C_{5,in}$	$C_{5,out}$	Q_5	$(C_{5,in} - C_{5,out})* Q_5$
6	June	$C_{6,in}$	$C_{6,out}$	Q_6	$(C_{6,in} - C_{6,out})* Q_6$
7	July	$C_{7,in}$	$C_{7,out}$	Q_7	$(C_{7,in} - C_{7,out})* Q_7$
8	August	$C_{8,in}$	$C_{8,out}$	Q_8	$(C_{8,in} - C_{8,out})* Q_8$
9	September	$C_{9,in}$	$C_{9,out}$	Q_9	$(C_{9in} - C_{9,out})* Q_9$
10	October	$C_{10,in}$	$C_{10,out}$	Q_{10}	$(C_{10,in} - C_{10,out})* Q_{10}$
11	November	$C_{11,in}$	$C_{11,out}$	Q_{11}	$(C_{11,in} - C_{11,out})* Q_{11}$
12	December	$C_{12,in}$	$C_{12,out}$	Q_{12}	$(C_{12,in} - C_{12,out})* Q_{12}$
Annual total= 298*0.013*44*10^{-6}*(Sum of rows 1–12)/14					

Based on the data from 2.3, the N_2O conversion factor normalized to the quantity of total nitrogen removed (g N leaked/g N removed) was assumed to be equal to 0.013 g N/g ΔN.

The Global Warming Potential for N_2O was assumed to be 298.

Step 7. Carbon footprint due to the methane emissions if improperly treated wastewater is discharged into the receiving waterbody

In the case of improper wastewater COD removal, when the wastewater containing residual organic matter is discharged into the receiving body, the methane emission should be assigned to the carbon footprint of the water and wastewater company. The calculation of the methane emissions in this case follows formulas (15–17) and is reduced to the scheme from Table 23, which is virtually identical to Table 16.

The IPCC default values in relation to the depth of receiving waterbody are as follows: C_d= 0.7 at a depth > 5 m, $C_d = 0.5$ at a depth of 1–5 m, and $C_d = 0$ at a depth < 1 m. However, considering the refined experimental data from 2.3, we recommend the following values: $C_d = 0.9$ for deep receiving bodies $C_d = 0.6$ for intermediate depths, and $C_d = 0.02$ for shallow receiving bodies.

Table 23 — Calculation of the methane emissions if improperly treated wastewater is discharged into the receiving body.

	Month	Monthly average COD concentration of improperly treated wastewater discharged into the receiving body (tCOD/m³)	Standard COD concentration in the discharged into the receiving body (tCOD/m³)	Quantity of the influent wastewater in a month (m³)	Average temperature of the wastewater in the receiving waterbody (K)
	1	2	3	4	5
		COD_i	$COD_{standard}$	Q_i	T_i
1	January	COD_1	$COD_{standard}$	Q_1	T_1
2	February	COD_2	$COD_{standard}$	Q_2	T_2
3	March	COD_3	$COD_{standard}$	Q_3	T_3
4	April	COD_4	$COD_{standard}$	Q_4	T_4
5	May	COD_5	$COD_{standard}$	Q_5	T_5
6	June	COD_6	$COD_{standard}$	Q_6	T_6
7	July	COD_7	$COD_{standard}$	Q_7	T_7
8	August	COD_8	$COD_{standard}$	Q_8	T_8
9	September	COD_9	$COD_{standard}$	Q_9	T_9
10	October	COD_{10}	$COD_{standard}$	Q_{10}	T_{10}
11	November	COD_{11}	$COD_{standard}$	Q_{11}	T_{11}
12	December	COD_{12}	$COD_{standard}$	Q_{12}	T_{12}

Table 23. Contd. 1 — Calculation of the methane emissions if improperly treated is discharged into the receiving waterbody.

Month	Monthly average factor expressing the influence of the temperature on the methane generation $C_{i,T}$			Methane conversion factor in relation to the receiving waterbody depth		
5	6			7		
	T_i<283K	283K<T_i<303.16K	T_i>303.16K	> 5 m	1–5 m	< 1 m
January	0	$C_1 = Exp[(T_1-303.16)/T_1]$	1	0.9	0.6	0.02
February	0	$C_2 = Exp[(T_2-303.16)/T_2]$	1	0.9	0.6	0.02
March	0	$C_3 = Exp[(T_3-303.16)/T_3]$	1	0.9	0.6	0.02
April	0	$C_4 = Exp[(T_4-303.16)/T_4]$	1	0.9	0.6	0.02
May	0	$C_5 = Exp[(T_5-303.16)/T_5]$	1	0.9	0.6	0.02
June	0	$C_6 = Exp[(T_6-303.16)/T_6]$	1	0.9	0.6	0.02
July	0	$C_7 = Exp[(T_7-303.16)/T_7]$	1	0.9	0.6	0.02
August	0	$C_8 = Exp[(T_8-303.16)/T_8]$	1	0.9	0.6	0.02

Month	Monthly average factor expressing the influence of the temperature on the methane generation $C_{i,T}$			Methane conversion factor in relation to the receiving waterbody depth		
5	6			7		
September	0	$C_9 = Exp[(T_9\text{-}303.16)/T_9]$	1	0.9	0.6	0.02
October	0	$C_{10} = Exp[(T_{10}\text{-}303.16)/T_{10}]$	1	0.9	0.6	0.02
November	0	$C_{11} = Exp[(T_{11}\text{-}303.16)/T_{11}]$	1	0.9	0.6	0.02
December	0	$C_{12} = Exp[(T_{12}\text{-}303.16)/T_{12}]$	1	0.9	0.6	0.02

Table 23. Contd. 2 — Calculation of methane emissions when improperly treated wastewater is discharged into the receiving waterbody.

	Month	Maximum methane producing capacity of the wastewater ($tCH_4/tCOD$)	Global Warming Potential for methane (tCO_2eq/tCH_4)	Methane emissions if improperly treated wastewater is discharged into the receiving waterbody (tCO_2eq)
	8	9	10	11
1	January	0.25	25	(2)*(3)*(6)*(7)*(9)*(10)
2	February	0.25	25	(2)*(3)*(6)*(7)*(9)*(10)
3	March	0.25	25	(2)*(3)*(6)*(7)*(9)*(10)
4	April	0.25	25	(2)*(3)*(6)*(7)*(9)*(10)
5	May	0.25	25	(2)*(3)*(6)*(7)*(9)*(10)
6	June	0.25	25	(2)*(3)*(6)*(7)*(9)*(10)
7	July	0.25	25	(2)*(3)*(6)*(7)*(9)*(10)
8	August	0.25	25	(2)*(3)*(6)*(7)*(9)*(10)
9	September	0.25	25	(2)*(3)*(6)*(7)*(9)*(10)
10	October	0.25	25	(2)*(3)*(6)*(7)*(9)*(10)
11	November	0.25	25	(2)*(3)*(6)*(7)*(9)*(10)
12	December	0.25	25	(2)*(3)*(6)*(7)*(9)*(10)
	Annual total			Sum of rows 1–12

After the step-by-step calculation is complete, the carbon footprint components are to be added together with due regard to the wastewater treatment and sludge utilization scenario used by a specific water and wastewater company.

Step 8. Carbon footprint due to the use of chemicals and consumables in the wastewater treatment processes

The wastewater treatment process typically employs various chemicals and consumables, among which methanol, lime, sand, polymers, and iron and aluminium sulphates are used most extensively.

Each of these substances was manufactured, which entailed certain energy consumption, and further transported from the manufacturing site to a water and wastewater company.

As mentioned above, this carbon footprint component can be accounted for by using either of two approaches. The first approach implies total assessment of the carbon footprint of the product, including the carbon footprint from manufacturing and the carbon footprint from transportation, with the total footprint to be incorporated into the carbon footprint of the water and wastewater company. In the second approach, only the carbon footprint due to transportation of the product is assigned to the WWTP, while the carbon footprint due to manufacture of chemicals is assumed to be already included in the total carbon footprint of the region where the product was manufactured.

In our opinion, the latter approach is preferable, and our recommendation is that suppliers of products be selected on the basis of not only the price they offer but also of the distance and mode of transportation. For selection and evaluation of the carbon footprint of a transportation vehicle, the use of one of carbon footprint calculators can be recommended, e.g., a calculator with multi-language (including Russian language) interface at http://calculator.carbonfootprint.com/calculator.aspx.

However, when comparing the carbon footprints of different water and wastewater companies, it is essential to know which of the carbon footprint components were included in the calculation. In the event that the carbon footprint due to manufacture of chemicals is taken into account in the benchmarking stage, it is necessary at least to know how much this activity contributes to the total carbon footprint. Also, if there is an alternative choice of a chemical, it would be useful to compare the products in terms of their associated carbon footprints.

Given below are the energy consumption and carbon footprint data (taken from foreign materials) for selected chemicals applied in wastewater treatment processes.

Lime. According to the Reference Document on Best Available Techniques in the Cement, Lime, and Magnesium Oxide Manufacturing Industries,[51] and to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change "Climate Change 2007"[52], the energy use for lime production is 3.6 to 7.5 GJ/t lime in the EU and 7.2 GJ/t in Canada. In EU, the fuel-related emissions are estimated at 0.2 to 0.45 tCO_2/t lime. Greenhouse gas emissions associated with the chemical process of lime production in EU is 0.8 tCO_2eq/t lime. By adding together these values, the carbon footprint for EU can be estimated at 1.0–1.2 tCO_2eq/t lime.

Methanol. According to the Institute of Methanol (USA)[53], in the early 2000s, a typical methanol manufacturing plant emitted 0.9–1.0 t CO_2eq/t methanol. Today, some facilities report emissions as low as 0.54 t CO_2eq/t methanol produced.

Aluminium sulphate. According to study[54], the carbon footprint of aluminium sulphate is negligible and, with bauxite extraction included, it was estimated at 0.12–0.15 tCO_2eq/t aluminium sulphate.

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[51] EU Reference Document on Best Available Techniques in the Cement, Lime, and Magnesium Manufacturing Industries, 2010/2009, http://14000.ru/brefs/BREF_Cement.pdf

[52] Climate Change 2007: Working Group III: Mitigation of Climate Change. 7.4.5.2 Lime http://www.ipcc.ch/publications_and_data/ar4/wg3/en/ch7s7-4-5-2.html

[53] Improving Methanol Production Efficiency and Reducing Carbon Dioxide Emissions [On-line] http://www.methanol.org/Methanol-Basics/Resources/Improving-Methanol-Production-Efficiency.aspx

[54]Coats, Erik R. Watkins, David L., Kranenburg, Dan. A Comparative Environmental Life-Cycle Analysis for Removing Phosphorus from Wastewater: Biological versus Physical/Chemical Processes // Water Environment Research, 2011. Vol. 83. # 8. P. 750-760. http://www.webs1.uidaho.edu/ecoats/Coats-WER-2011b.pdf

4. MONITORING OF THE PARAMETERS INVOLVED IN CALCULATION OF THE CARBON FOOTPRINT OF WASTEWATER TREATMENT PLANTS

To determine the carbon footprint on an annual basis, it is essential that information on those aspects of the company' activities, which affect the carbon footprint, be collected, throughout the year. Below, the parameters involved in the calculation of the carbon footprint of a WWTP will be presented, along with the frequency of their determination.

4.1. Energy

4.1.1. Consumption of imported electricity (MWh/year): to be measured continuously; can be determined by adding together the readings of the electricity meters installed at the facility's premises or from the readings of a single meter installed at the facility inlet, if any (to be used in Table 6).

4.1.2. Consumption of fossil fuels or waste for on-site heat/electricity generation (t or m^3): to be accounted for by using the delivery notes, or other documentation, on consumption of each type of fuel or waste in separate. In particular, sludge can be regarded as waste, if the technology employed at a WTPP involves its incineration procedure (to be used in Table 8).

4.1.3. Consumption of the heat energy supplied by an off-site boiler plant (GJ/year): it is assumed that this is an off-site (external) boiler plant, i.e., it is not part of the water and wastewater company structure (otherwise see 4.1.2) (to be used in Tables 10, 10a).

This parameter is to be determined from the heat energy meter readings over the year. The calculation also uses the data on the average efficiency of the boiler plant (to be requested from the boiler plant managers) and the heat loss in the distribution network from the boiler plant to the WWTP site. If the managers do not know the latter parameter, the annual average (or averaged over the heating period) temperature of the heat carrier in Kelvin degrees is to be requested. The heat carrier temperature (K) at the WWTP site inlet should be measured continuously, and these data should be further used to determine the average value over the year, or over the heating period.

4.1.4. Consumption of the heat energy supplied by an off-site cogeneration plant (GJ/year) (to be used in Tables 12, 12a).

This parameter is to be determined from the heat energy meter readings over the year. The calculation also uses the data on the average thermal efficiency and electrical efficiency of the cogeneration plant (to be requested from the cogeneration plant managers) and the heat loss in the distribution network from the cogeneration plant to the WWTP site. If the managers do not know the latter parameter, the annual average (or averaged over the heating period) temperature of the heat carrier in Kelvin degrees is to be requested. The heat carrier temperature (K) at the site inlet should be measured continuously, and these data should be further used to determine the average value over the year, or over the heating period.

4.2. Transport

4.2.1. The quantities of the various types of fuel spent for production purposes (t or m^3) are to be monitored. In the case of a water and waste company, vehicles are used mostly for sludge transportation purposes. However, correct calculation of the carbon footprint requires "accounted for" all the transportation services provided: transportation of various consumables, including chemicals to be applied for wastewater treatment, waste transportation, and employee business travel (to be used in Table 14).

In the event of difficulties arising for some reasons in the accounting of the fuel spent, the carbon footprint component associated with sludge transportation is to be calculated using Table 13. In this case, the quantity of the sludge transported over the year (t/year), as well as the vehicular capacity and types of vehicles employed are to be monitored.

4.3. Wastewater treatment process

4.3.1. Methane emissions from wastewater treatment. It will be assumed that conditions favourable tor methane formation can arise in the primary sedimentation tank. The COD value (t/m^3) is to be monitored at the zone boundaries, at the WWTP inlet, at the primary sedimentation tank outlet, and at the outlet of the WWTP as a whole. Decadal measurements, whose data can be further used for calculating the average value over a month and over a year, are considered to be the best option. Also monitored are the wastewater flow rate (m^3) and temperature (K) of the wastewater in the primary sedimentation tank and in the aeration tank.

In the case of proper operation of wastewater treatment plants, the monthly average values are used in the calculations (Table 17 and Table 17.Contd.). For improperly operating WWTPs, at which the load exhibits daily variations, the calculations should be based on the values of the parameters derived from decadal measurements (Table 17 and Table 17.Contd.). In the case when the calculation follows the simplified procedure, the annual average data will be sufficient (Tables 18a and 17a).

4.3.2. Nitrous oxide emissions from wastewater treatment. The Total Kjeldahl Nitrogen (t/m^3) is to be monitored at the inlet and outlet of the WWTP as a whole. The best option consists in decadal measurements whose data can be used for calculating the average value over a month. Also, the monthly flow rate (m^3) is to be monitored.

4.4. Sludge utilization

4.4.1. The calculation of the methane and nitrous oxide emissions for alternative sludge utilization scenarios requires monitoring of the following parameters:

- ✓ Total quantity of the sludge (dry basis) produced as a waste at the WWTP (t/year);
- ✓ Quantity of the sludge disposed at a landfill or applied to land (t/year);
- ✓ Quantity of the sludge treated in digesters (t/year);
- ✓ Quantity of the sludge incinerated (t/year);
- ✓ Quantity of the sludge utilized by any different scenario (t/year).

Also, the following analytical (annual average) data are needed:

- ✓ Degradable organic content of dry sludge;
- ✓ Degradable organic content dissimilated to biogas;
- ✓ Methane fraction in the gas;
- ✓ Mass fraction of nitrogen in the sludge (t N/t sludge).

For sludge treated in an anaerobic digester, the parameters to be monitored include:

- ✓ Quantity of the biogas collected at the digester outlet during a year (m^3);
- ✓ Fraction of biogas that leaks from the digester.

If no measurements are done for any of the above-listed parameters, it is possible to take the parameter values from Step 5.

5. CONCLUSION. RECOMMENDATIONS

The methodology developed complies with new recommendations of the Intergovernmental Panel on Climate Change (IPCC) and contains also significant elaborations concerning assessment of methane and dinitrogen monoxide emissions specific for wastewater treatment processes and sludge disposal sites.

The methodology is presented also in the table form and includes a brief monitoring chapter, containing information on the necessary set of parameters to be registered in order to calculate carbon footprint.

Since carbon footprint of municipal wastewater treatment plants to a larger extent depends on energy consumption, typical energy saving measures should be quite effective. But it is very important to decrease volume of wastewater treated. The necessary reduction can be achieved by decreasing water consumption in households and industry. To reduction targets such measures as setting new norms and standards, measuring amount of water used and increasing tariffs on potable and technical water should be applied along with running awareness raising and information campaigns.

Since wastewater treatment and sludge utilization processes are supplemented by methane and dinitrogen oxide emissions, some recommendations on decreasing emissions of these compounds should be made.

In terms of carbon footprint reduction, burning sludge is undeniably a better solution than disposing it at landfills. But digesting sludge in special reactors allows for collecting biogas formed (its caloric value is rater high, from 21 to 25 MJ/cubic metre). Burning biogas to generate electricity and heat used energy for wastewater treatment purposes provides for reducing carbon footprint.

In aerobic zones there should be no methane emissions. To achieve this, it is necessary to avoid extreme loads of wastewater treatment plants and formation of stagnation zones where sludge could be accumulated and decomposed.

To prevent dinitrogen oxide emissions from aerobic treatment zones, it is necessary to control such water parameters as dissolved oxygen concentration, period of hydraulic retention of active sludge, pH, and concentrations of dissolved organic substances.

In 2012-2013 the methodology described in this brochure was tested for assessing Carbon footprint of wastewater treatment plants of SUE “Vodokanal of Saint- Petersburg”. This enterprise implements an environmental policy as well as energy efficiency improvement policy, implementing practical measures for reducing negative environmental impacts and decreasing emissions of greenhouse gases.