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Algorithm of carbon footprint calculation for municipal wastewater treatment plant – part one

Algorytm obliczania śladu węglowego miejskiej oczyszczalni ścieków – część pierwsza

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Keywords: *GHG emissions, nitrous oxide, methane, carbon footprint, wastewater treatment, CSRD*

Abstract
In the forthcoming years, urban wastewater management utilities will be required by the European Union to perform CF calculations in accordance with the Corporate Sustainability Reporting Directive (CSRD) and European Sustainability Reporting Standards (ESRS) indicators. Yet, no standardized approach that expressly addresses the rules for WWTPs in respect to GHG emissions, giving the water bodies a clear instruction to calculate their CF is given. This paper provides an in-depth examination of the present approaches for calculating GHG emissions. An algorithm for calculating the carbon footprint of a wastewater treatment facility is developed and described in detail by the authors. Furthermore, the research evaluates the extent to which facility data is complete and suggests remedies to any detected information gaps. A data enhancement strategy is also offered. The primary goal of this research is to bridge a knowledge gap in the understanding of the carbon footprint associated with WWTPs and their organisational framework. The analysis also included a thorough investigation into the significance and sources of GHG Protocol Scope 1 (part one arcticle), 2, and 3 emissions (part two article) within the larger framework of carbon footprint, particularly in relation to the legislative goals of CSRD reporting with its upcoming obligations imposed on waterworks organizations.

Słowa kluczowe: *Emisje gazów cieplarnianych, podtlenek azotu, metan, ślad węglowy, oczyszczanie ścieków, CSRD*

Streszczenie
W nadchodzących latach Unia Europejska będzie wymagać od miejskich zakładów oczyszczania ścieków wykonywania obliczeń śladu węglowego (CF) zgodnie z Dyrektywą w sprawie sprawozdawczości dotyczącej zrównoważonego rozwoju przedsiębiorstw (CSRD) i wskaźnikami Europejskich Standardów Sprawozdawczości dotyczącymi Zrównoważonego Rozwoju (ESRS). Nie istnieje jednak żadne ustandaryzowane podejście, które wyraźnie odnosiłoby się do zasad dotyczących oczyszczalni ścieków w odniesieniu do emisji gazów cieplarnianych (GHG), dając organom wodnym jasne instrukcje dotyczące obliczania ich CF. Niniejszy artykuł zawiera dogłębną analizę obecnych podejść do obliczania emisji GHG. Algorytm obliczania śladu węglowego miejskiej oczyszczalni ścieków został opracowany i szczegółowo opisany przez autorów. Ponadto, w analizie oceniają zakres, w jakim dane dotyczące oczyszczalni ścieków są kompletne i sugerują środki zaradcze dla wszelkich wykrytych luk informacyjnych. Zaproponowano również strategię ulepszania danych. Głównym celem tego badania jest wypełnienie luki w wiedzy na temat śladu węglowego związanego z oczyszczalniami ścieków i ich ramami organizacyjnymi. Analiza obejmowała również dokładne zbadanie znaczenia i źródeł emisji z wg podziału na zakresy GHG Protocol 1 (część pierwsza), 2 i 3 (część druga) w szerszych ramach śladu węglowego, szczególnie w odniesieniu do celów legislacyjnych raportowania CSRD z nadchodzącymi obowiązkami nałożonymi na przedsiębiorstwa wodociągowe.

1. INTRODUCTION

In light of the escalating apprehension surrounding the phenomenon of global warming, numerous nations have made a steadfast commitment to attaining net-zero emission status by the year 2050 [44], fulfilling Intergovernmental Panel on Climate Change (IPCC) guidelines of not surpassing the 1.5°C threshold [38]. The wastewater treatment plants (WWTPs) have been identified as a significant source of direct greenhouse gas (GHG) emissions, especially N_2O and CH_4, accounting for approximately 3% of GHG emissions on a global [41, 56]. In addition, when considering indirect emissions, it is evident from an energy standpoint that WWTPs continue to consume a significant amount of energy, still primarily derived from fossil fuel sources. Given the current circumstances of the prevailing focus on climate change, escalating electricity costs, and the imperative to reduce carbon footprint (CF) emissions within an organisation or activity, the wastewater treatment facility is regarded as a dual prospect, presenting both challenges and opportunities for enhancement. As a final result, water utilities are at the forefront of efforts to mitigate GHG emissions, with a number of waterworks organisations setting their sights on achieving net-zero emissions in their operations within the upcoming decades [6, 7, 37, 47]. The very

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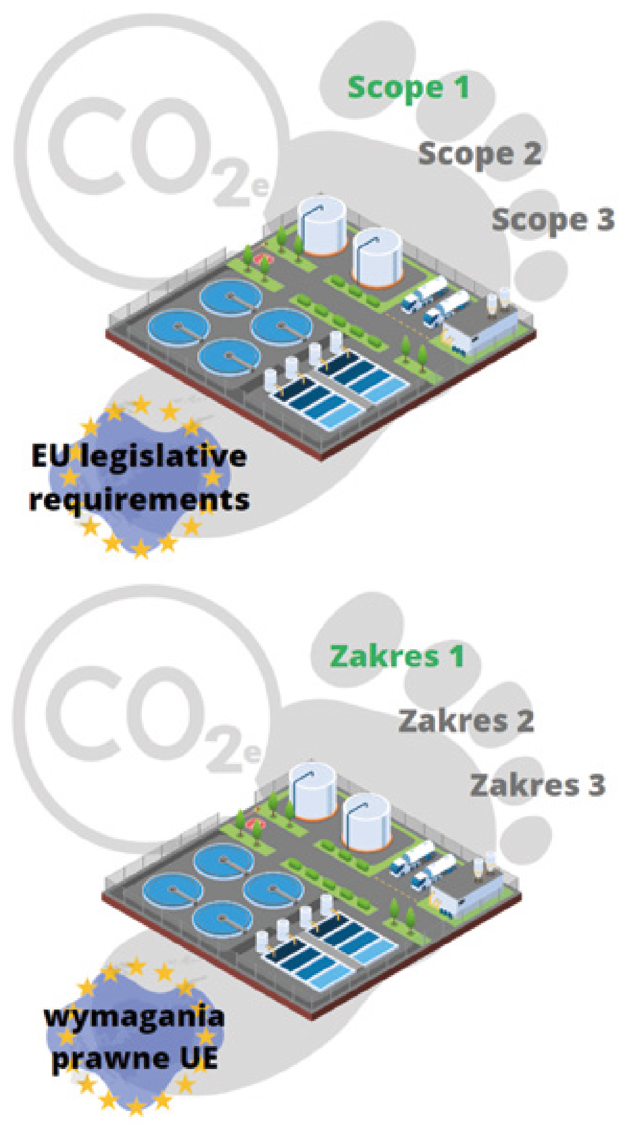


GRAPHICAL ABSTRACT

first step of building a GHG reduction strategy is the annual CF calculation enabling the transparency of comparison of the results between the facilities and other economic areas.

In the forthcoming year, the primary urban water management utilities will be required to perform CF calculations in accordance with the Corporate Sustainability Reporting Directive (CSRD) and European Sustainability Reporting Standards (ESRS) indicators by European Financial Reporting Advisory Group (EFRAG). However, it is worth noting that there is currently no established methodology that specifically addresses the guidelines for WWTPs in relation to GHG emissions which would give the water bodies a clear instruction to calculate their CF. The obligations of CSRD require adherence to the reporting practise of the Greenhouse Gas Protocol (GHG Protocol) regime, as mandated by the European Union (EU). Consequently, water utilities are obligated to comply with these requirements.

Several studies have been conducted to analyse the GHG emissions associated with different wastewater and sludge treatment technologies. However, these studies have primarily focused on specific aspects of wastewater treatment configurations rather than examining the entire facilities with their technological configuration [34, 35, 57] in order to deliver a simplified CF calculation method. In many cases evaluation of the WWTP's CF was done as the final step of in-situ off-gas measurements to cover direct GHG emissions from BNR treatment stage, sometimes combined with model-based approach [39]. Prior research has indicated that the utilisation of distinct wastewater treatment methodologies may lead to varying levels of direct GHG emissions, as well as differing degrees of energy consumption and sludge generation [10, 24, 41, 42, 51, 58]. Piao et al. (2016) [41] found that the implementation of the Modified Ludzack-Ettinger (MLE) process in wastewater treatment facilities resulted in a 20% increase in the carbon footprint, as compared to facilities utilising the Anaerobic-Anoxic-Oxic (A2/O) process. In addition, it has been found that the implementation of aerobic wastewater treatment methods may result in a significant increase of 105% in direct GHG emissions, as compared to the utilisation of anaerobic wastewater treatment techniques [10].

Nevertheless, there remain uncertainties regarding the comprehension of carbon footprints associated with various configurations of WWTPs. Previous analyses did not take into account several potentially significant sources of GHG emissions, particularly in the context of sludge handling processes focusing only on the chosen emission-related topic rather than on the entire global warming enhancing gases fluxes.

Goal and scope of the work presented in the two-part paper

The overall aim of this work is to provide a valuable resource for researchers, policymakers, and practitioners involved in the assessment and management of the carbon footprint of wastewater treatment plants. By shedding light on the role of evaluating direct GHG emissions in the carbon footprint structure of wastewater treatment facilities and providing guidance on MWWTP's CF estimation, the study can contribute to the development of more accurate and comprehensive carbon footprint assessments and support the efforts to mitigate climate change by delivering the municipal wastewater treatment plant CF calculation algorithm.

Moreover, the research investigates the extent to which facilities data is complete and proposes solutions to address any identified gaps in information regarding the understanding of the carbon footprint associated with WWTPs [52] and their organisational framework. Additionally, a data improvement plan is presented. The analysis also involved a comprehensive investigation into the importance and sources of Scope 1, 2, and 3 emissions (GHG Protocol) within the wider framework of carbon footprint, particularly in relation to the legislative goals of CSRD reporting with its obligations put on waterworks organisations in the near future.

2. CF IN WASTEWATER TREATMENT – EU LEGISLATIVE BACKGROUND

The European Climate Law (Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999) [43], which writes into law the goal set out in the European Green Deal, establishes the overarching structure for the European Union's involvement in the Paris Agreement. This includes both the specific objectives to be achieved and the procedural mechanisms to be employed. The legislation establishes enforceable objectives of a legally binding nature.

The main objective is to achieve a minimum reduction of 55% in GHG emissions relative to the levels recorded in 1990 by the year 2030 (so-called 'Fit for 55' package). Additionally, the aim is to attain net-zero GHG emissions by the year 2050. The achievement of the climate-neutrality objective necessitates the implementation of appropriate measures by the relevant institutions of the European Union and its Member States.

The Corporate Sustainability Reporting Directive, known as CSRD (EU Directive 2022/2464 of the European Parliament and of the Council of 14 December 2022) [23] came into effect on January 5th, 2023, as a part of Green Deal EU legislative tools. This regulation extends the scope and reporting requirements of the already existing Non-Financial Reporting Directive (NFRD; Directive 2014/95/EU of the European Parliament and of the Council of 22 October 2014) [21] – a regulatory framework that mandates sizeable public interest entities to report on their sustainability performance since 2018. The revised CSR directive aims to enhance and update the regulations pertaining to the disclosure of environmental and social data by corporations, thereby enhancing their effectiveness and robustness. A more extensive range of sizable corporations, along with publicly listed small and medium-sized enterprises (SMEs), are mandated to disclose information regarding their sustainability practises. This requirement will encompass approximately 50,000 companies in aggregate, involving waterworks organisations across EU. CSRD will be introduced in three planned phases (Scheme 1). The initial group of companies, including water bodies of the biggest urban areas, will be required to implement the newly established regulations for the inaugural occasion during the fiscal year of 2024, with the corresponding reports being made public in 2025.

CSRD PHASES		
PHASE I	**PHASE II**	**PHASE III**
2024	**2025**	**2026**
only those reporting under the existing NFRD - obligation to use the full ESRS	**report all other large listed and unlisted entities and other large groups (i.e., all sizes of parent companies of large groups) - obligation to use full ESRS**	**small and medium-sized (SME) listed companies and specific types of entities - choice to use either full or simplified ESRS**
Individual reporting - the largest of the large public interest entities that exceed 500 employees and one of the financial thresholds of PLN 85 MLN in total assets or PLN 170 MLN in net revenue **Consolidated reporting** - any public interest entity which is the parent company of a large group that exceeds 500 employees and one of the financial thresholds, i.e: 1) with consolidation exclusions: PLN 85 MLN total assets, PLN 170 MLN net revenue or 2) without consolidation exclusions: PLN 102 MLN total assets, PLN 204 MLN net revenue	**Other large companies** - (i.e., exceeding any two of the three criteria - 250 employees, financial thresholds as in Phase I) **Consolidated reporting** - other companies that are the parent of a large group (i.e., if the group exceeds any two of the three criteria - 250 employees, financial thresholds as in Phase I)	**Individual reporting only** 1) SME listed companies (exceeding two of the three thresholds for micro entities at the same time not exceeding two of the three thresholds for large entities (250 employees, two financial thresholds) 2) small and non-complex institutions or SMEs that are not listed companies 3) captive insurance and captive reinsurance undertakings if they are large entities (listed or not) or small and medium-sized listed companies

Scheme 1. Summary of CSRD implementation phases.
Schemat 1. Podsumowanie faz wprowadzania CSRD w życie.

The implementation of the new regulations will guarantee that investors and other relevant parties are provided with the necessary access to information in order to evaluate investment risks that may arise from climate change, including WWTPs' CF in three scopes, and other matters related to sustainability. Additionally, they will foster a culture that promotes transparency regarding the societal and environmental effects of corporations. In the medium to long term, companies will experience a reduction in reporting costs through the harmonisation of the information required.

Organisations that fall under the jurisdiction of the CSRD will be obligated to adhere to the European Sustainability Reporting Standards (ESRS) when submitting their reports. The draught standards are formulated by the EFRAG, formerly recognised as the European Financial Reporting Advisory Group, an autonomous entity that convenes diverse stakeholders. The proposed standards will be customised to align with the policies of the European Union, while also drawing upon and making contributions to ongoing international standardisation efforts. On the 6th of June, the Commission initiated a four-week period for public feedback regarding the initial set of sustainability reporting standards intended for companies. The draught standards have incorporated technical advice provided by EFRAG in November 2022. The most recent draft of the ESRS [20] necessitates the disclosure of environmental data pertaining to five distinct domains, encompassing climate-related aspects such as adaptation and mitigation. The following examples illustrate CSRD disclosures, specifically focusing on GHG emissions. The numerical values of Scopes 1, 2, and 3, as well as the comprehensive assessment of carbon footprint emissions will be therefore required to present. Additionally, it pertains to the formulation of climate change policy and the development of a strategy aimed at reducing greenhouse gas releases. The ultimate objective of this strategy is to attain a state of net-zero emissions prior to the year 2050.

The evaluation process of carbon footprint, given its comprehensive nature, necessitates extensive data collection efforts across various contexts to identify information gaps. However, the results of CF assessments, which encompass the emission structure of direct activities of wastewater treatment plants (WWTPs), detailed analysis of energy consumption and production schemes, and examination of value chain activities, can also serve as a valuable source of additional knowledge for optimising overall facility operations. Additional European Union legislative instruments related to wastewater treatment may provide the comprehensive data necessary for compliance with CSRD.

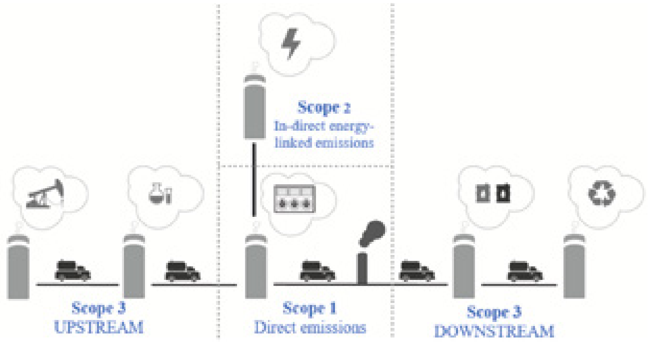
The current regulatory framework, specifically the Urban Waste Water Treatment Directive (UWWTD, 91/271/EEC) and the Sewage Sludge Directive (SSD, 86/278/EEC), does not explicitly consider the matter of GHG emissions, such as nitrous oxide and methane fluxes or, namely, WWTP carbon footprint, in relation to the management and utilisation of wastewater and sewage sludge. The successful implementation of UWWTD over a period of approximately thirty years has resulted in significant reduction of methane emissions through the utilisation of efficient centralised infrastructure for the collection and treatment of wastewater. In contrast to alternative treatment methods, these facilities demonstrate a significant decrease in the release of GHG.

The Sewage Sludge Directive (SSD), which was introduced more than three decades ago, regulates the utilisation of sewage sludge to protect the environment, specifically the soil, from the harmful effects of contaminated sludge when used in agriculture. The ongoing evaluation of the UWWTD is presently in progress. Simultaneously with the assessment of the aforementioned directive, the European Commission commenced a study in the third quarter of 2020 to facilitate the evaluation of regulations pertaining to sewage sludge. Moreover, a supplementary inquiry will be undertaken to assess the feasibility of implementing further actions pertaining to GHG emissions, specifically focusing on methane emissions originating from sewage sludge. Based on the findings of the assessment of the SSD, along with supplementary inquiries and the evaluation of the effects of the amendment to the urban UWWTD, the Commission will consider the adoption of measures aimed at limiting the emission of greenhouse gases derived from sewage sludge.

The proposed Directive of The European Parliament and of The Council, dated October 26th, 2022 (2022/0345) [22], aims to amend the existing UWWTD. According to the proposal, it is crucial for Member States to ensure the regular conduct of energy audits on urban wastewater treatment plants and collecting systems every four years. The audits have a broad range of coverage, which includes the identification of potential avenues for the cost-effective utilisation or production of renewable energy. The primary focus of the audits will be to prioritise the identification and optimal utilisation of biogas production capacity, while simultaneously addressing the reduction of methane emissions. The deadline for compliance with regulations pertaining to urban wastewater treatment plants and their associated collecting systems is contingent upon the specific load of each plant. Wastewater treatment facilities with a capacity of 100,000 population equivalents (p.e.) or higher are required to meet compliance standards by December 31st, 2025. Conversely, facilities treating a load ranging from 10,000 p.e. to 100,000 p.e. are granted an extended compliance deadline until December 31st, 2030.

3. CORPORATE CARBON FOOTPRINT – GHG PROTOCOL GUIDELINESS

The Greenhouse Gas Protocol (GHG Protocol) developed by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) was responsible for the initial step that involves the categorization of GHG emissions according to the three different scopes in 2004 (Scheme 2).



Scheme 2. GHG Protocol emission Scopes 1, 2, 3.
Schemat 2. Zakresy emisji wg GHG Protocol.

Scope 1 encompasses the direct GHG releases originating from facilities that are directly managed by the reporting entity. Therefore, the first scope, is recognised as crucial in the case of the WWT-specific emissions. The compounds generated during the treatment of wastewater and sludge are specifically N_2O and CH_4. Nitrous oxide primarily originates from the BNR procedures employed in the context of wastewater treatment. In contrast to N_2O, CH_4 typically originates within the sewer system and specific areas of the WWTP where anaerobic conditions prevail, such as anaerobic wastewater and sludge treatment processes [16]. According to the IPCC AR6 Report (IPCC, 2021), the greenhouse gases N_2O and CH_4 possess global warming potentials (GWPs) of 273 and up to 29.8 carbon dioxide equivalents (CO_2e), respectively. As a result, even minimal emissions of N_2O and CH_4 from a wastewater treatment process make a substantial contribution to its carbon footprint. According to De Haas and Hartley (2004) [29], it was approximated that a conversion of 1% of nitrogen loading to N_2O could result in a 30% increase in the overall carbon footprint of wastewater treatment plants. Scope 2 covers the emissions linked to the externally purchased streams of energy such as: electricity heat, steam and cooling [4]. Third scope indicates all indirect emissions that can be linked to the reporting entity activities that arise from assets that are not under the ownership or control of the organisation responsible for reporting in their value chains. Scopes 2 and 3 will be further described in the following part two article.

The GHG Protocol methodology is applicable to various industries and is widely acknowledged as a set of principles for calculating the carbon footprint of organisations, particularly for the purpose of external reporting. However, as forementioned, it does not provide specific guidelines for WWTPs. The GHG Protocol acknowledges that there are limitations in its methodology when it comes to reporting entities that own WWT facilities. As a result, it recommends referring to the IPCC (2006 and 2019) as a supplementary resource to address these gaps [30]. The GHG Protocol Scope 3 Calculation Guidance (2013) [55] suggests that for the purpose of emissions calculation, it is advisable for the reporting entity to gather emission data from waste treatment, including wastewater. The Protocol places a significant emphasis on the fact that greenhouse gas emissions originating from wastewater exhibit considerable variability, which is contingent upon the extent of processing required for water treatment. This variability is determined by the levels of nitrogen loads and, as well, biochemical oxygen demand (BOD) and/or chemical oxygen demand (COD) characterising the facility's compresence. In summary, GHG Protocol should be used as an overall CF calculation guidelines package accompanied by detailed methodology.

4. CURRENT STATUS OF CARBON FOOTPRINT METHODOLOGIES IN WWT

Intergovernmental Panel on Climate Change (2006 with 2019 Refinement) [30]

As previously mentioned in the Introduction, the methodology employed by the IPCC for calculating methane emissions is widely recognised as one of the most popular approaches within the field of wastewater treatment. Established originally in 1996, actualised in 2006, then updated in 2019 – mainly with the novel guidelines both for N_2O and CH_4 emissions included based mainly on the full-scale measurements.

The methodology encompasses three distinct tiers, which are utilised for the estimation the greenhouse gas effect, gas fluxes resulting from the treatment process, as well as the discharge of treated wastewater. These tiers are outlined in Table 1. The application of Tier 1 is appropriate in cases where there is a lack of available activity data. Tier 2 is employed when there are some country-specific factors that are present. Finally, Tier 3 is selected when all country-specific factors have been collected. The calculations for all these Tiers are derived from specific methane and nitrous oxide emission rates that are associated with biological oxygen demand (BOD), chemical oxygen demand (COD) or specific N-fraction loads respectively. These often are adjusted using specific corrective factors tailored to each particular situation.

Table 1. Presentation of IPCC (2019) methodology Tiers for assessment of WWT GHG emissions.
Tabela 1. Prezentacja metodologii IPCC (2019) do oceny emisji gazów cieplarnianych z OŚ.

IPCC Tier GHG emissions calculation methodology (2019)	Treatment process	Discharge
Tier 1	Estimate emissions from treatment using default emission factors and methodology.	Estimate emissions from discharge to all aquatic environments using default emission factor and methodology.
Tier 2	Estimate emissions using country-specific emission factors and/or activity data and default methodology.	Estimate emissions from discharge to aquatic environments using default emission factors dedicated to the type of the recipient and methodology
Tier 3	Estimate emissions from treatment using country-specific method based on measured emissions data from facilities.	Estimate emissions from discharge to specific types of aquatic environments using country-specific emissions data and methodology.

The utilisation of default emission factors (Tier 1) is recommended by the IPCC for estimating CH_4 and N_2O emissions from wastewater treatment plants in GHG inventories, particularly in cases where data is scarce, as observed in many developing countries. Nevertheless, the accuracy of these estimations may be significantly imprecise due to the limited availability of dependable data regarding the functioning of the treatment technology itself and the specific environmental factors in the area. There is lack of locally measured methane and nitrous oxide emission factors from MWWTPs still observed, resulting in a low accuracy, especially in the case of the CH_4 emission estimates. Currently, the veracity of the national emission estimations derived from the Tier 1, IPCC Guidelines for wastewater treatment and discharge (Vol. 5, Chapter 6; IPCC, 2019) [30] is constrained by various factors: the exclusion of CH_4 emissions from closed sewer systems and dissolved CH_4 in the influent from WWTP is not accounted for. Furthermore, the appropriate approach for addressing aerobic treatment systems supplemented with anaerobic sludge digesters under Tier 1 is unclear. Additionally, it is imperative to acknowledge the anaerobic-aerobic process for nutrient removal as a novel addition to the repertoire of treatment systems.

Australian National Greenhouse Accounts/ National Greenhouse and Energy Reporting (2023 update) [14, 15]

Australia has implemented two primary protocols, namely the National Greenhouse and Energy Reporting (NGER) and the National Greenhouse Accounts (NGA) guidelines. The NGER framework encompasses corporations that surpass specific emission thresholds to meet Australia's overall international reporting obligations. The emission factors and instructions provided by the NGA are designed specifically for use by corporations and individuals (NGA, 2013). As the result, the methodologies employed by the NGA exhibit a higher level of precision in their definition, as they are designed to be applicable to a narrower scope being tailored to encompass a wider range of emissions and sources. Due to the increased level of sophistication and the corresponding abundance of wastewater-specific methodologies, the NGA and its methodologies are generally more pertinent compared to the NGER standards. Australian methodologies provide three different methods of emission calculations depending on the data access (Table 2).

Table 2. Presentation of NGA/NGER (2023) methodology: Methods for assessment of WWT GHG emissions.

Tabela 2. Prezentacja metodologii NGA/NGER (2023): Metody oceny emisji gazów cieplarnianych z OŚ.

NGER/NGA Calculation methods (2023)	WWT emissions
Method 1	Estimate emissions from using default emission factors – based on national average estimates.
Method 2	Estimate emissions using facility specific method based on industry practices for sampling and Australian or equivalent standards for analysis.
Method 3	Estimate emissions using facility specific method based Australian or equivalent standards for both sampling and analysis.

The topic of methane emissions from wastewater collection systems is not addressed in either the NGER or the NGA. However, it is worth noting that the estimation of methane fluxes from the initial stages of treatment, specifically the mechanical stage, is based on levels of chemical oxygen demand (COD) reduction. There is a lack of guidelines specifically addressing the release of CH4, as the existing methodology assumes that well-managed treatment systems do not emit methane.

The emissions of CH_4 associated with sludge management are extensively debated within the field of biogas production through AD. The biogas production stream can be classified into three distinct categories: captured, flared, and transferred. The accounting of AD fugitive emissions is currently lacking. Default emissions factors are provided for the combustion of biogas on-site.

The calculation of N_2O emissions is conducted using a population-based approach that incorporates the average protein intake and assumes a certain percentage of nitrogen composition. Hence, the emissions originating from the BNR stage exhibit a correlation with the N-removal efficiency. Additionally, in the context of N_2O emissions associated with the effluent, the N-concentration in the treated wastewater stream plays a role, contingent upon the recipient type, as determined by fixed emission factors [54].

California Air Resources Board's Local Government Operations Protocol (2010) [11]

The Local Government Operations Protocol (LGOP) owned by California Air Resources Board (CARB) is designed to establish a standardised protocol for local governments, such as cities and counties, within USA, to accurately report emissions resulting from their own operational activities. This endeavour specifically omits the emissions produced by the general population residing in those identical jurisdictions that are not subject to direct governmental authority.

The protocol developed by the LGOP exclusively addresses the topic of methane emissions in relation to the decomposition of sludge biosolids within landfill management practises. In the context of AD, the methodology consistently operates under the assumption that the entire biogas generated is captured and subsequently combusted with a 99% efficiency rate, thereby preventing any methane emissions.

N_2O emissions, as determined by the LGOP methodology, originate from BNR systems and solids decomposition processes. The calculations are derived from established population-based plant emission factors, which have been categorised separately for nitrification/denitrification and compartments without nitrogen removal.

U.S. Community Protocol for Accounting and Reporting of Greenhouse Gas Emissions by International Council for Local Environmental Initiatives – Local Governments for Sustainability USA (2013) [48]

The International Council for Local Environmental Initiatives (ICLEI) standards pertain to local governments operating within the United States. The protocol's stated objectives encompass informing climate action planning and fostering community engagement, monitoring GHG emissions trends, facilitating comparisons among similar communities, enabling the aggregation of regional GHG emissions data, demonstrating compliance with regulations, agreements, and standards, as well as showcasing accountability and leadership. The U.S. Protocol encompasses government operations such as the LGOP, as well as emissions originating from the general public.

There are 14 basic and 6 alternative methods of both CH_4 and N_2O calculation in the area of wastewater treatment given by the U.S. Protocol. Each dedicated to the different GHG source complied with the treatment technology, type of the gas, emission type and available data. Table 3 summarizes methods dedicated to CH_4 emissions while Table 4 presents N_2O emissions calculation methods. As presented in the Tables, U.S. Protocol considers CH_4 and N_2O emission in the entire value chain of WWT, giving methods to calculate methane fluxes in the lifecycle.

Table 3. Presentation of U.S. Protocol (2013) methodology: Methods for assessment of WWT CH_4 emissions.

Tabela 3. Prezentacja metodologii protokołu amerykańskiego (2013): Metody oceny emisji CH_4 z OŚ.

U.S. Protocol CH4 Calculation methods (2013)	Emission type	CH4 source with data requirements
Method WW.1.a Method WW.1.b	Stationary emissions	Combustion of digester gas at a centralized WWTP with anaerobic digestion of biosolids when process data known
Method WW.1.(alt)	Stationary emissions	Combustion of digester gas at a centralized WWTP with anaerobic digestion of biosolids based on the population served by the facility
Method WW.4	Stationary emissions	Emissions from residuals combustion based on the mass composition of the material sent to the combustion device
Method WW.6	Process emissions	Emissions from anaerobic or facultative lagoons based on the BOD_5 daily load and BOD_5 fraction removal performance
Method WW.6.(alt)	Process emissions	Emissions from anaerobic or facultative lagoons based on population served by the facility
Method WW.11	Fugitive emissions	Emissions from septic systems based on the BOD_5 daily load
Method WW.11.(alt)	Fugitive emissions	Emissions from septic systems based on population served by the facility
Method $WW.13_{CH4}$	Attributed emissions	Process emissions from cluster package systems based on population served by the facility
Method WW.14	Lifecycle emissions associated with water acquisition, distribution and treatment	Upstream indirect emissions resulting from the energy consumption based on the amount of energy purchased and consumed or on the national average energy consumption per unit of water and wastewater and the total annual volume of the water and wastewater passing through the analysed system(s)
Method WW.15	Lifecycle emissions associated with water acquisition, distribution and treatment	Upstream indirect emissions resulting from the energy consumption based on the amount of energy purchased and consumed or on the national average energy consumption per unit of water and wastewater and the population served by the system(s) divided into the groups linked to the type of the wastewater treatment process (e.g., centralized and other modalities)

The protocol does not address the CH_4 emissions originating from sewer collection systems, as well as those resulting from preliminary and primary treatment processes. The omission of methane emissions from BNR technologies is due to their perceived lack of significance and, consequently, they are not addressed. Furthermore, the absence of guidance pertaining to the management of AD or digestate handling, specifically in relation to thickening and dewatering processes, raises concerns regarding the control of CH_4 fugitive emissions. In the context of sludge combustion, specific emission factors have been established to account for methane releases.

N_2O emissions, as quantified using the U.S. Protocol methodology, are generated from two primary sources: biological nutrient removal (BNR) systems and the decomposition of organic waste materials.

Clean Development Mechanism Treatment of wastewater methodology (2014) [12]

The Clean Development Mechanism is a carbon offset initiative administered by the United Nations (UN). It enables countries to finance projects aimed at reducing greenhouse gas emissions in other nations, while attributing the resulting emission reductions to their own endeavours towards meeting global emissions objectives. CDM was designed with two primary aims: firstly, to support primarily developing nations, in their pursuit of sustainable development and the mitigation of their carbon emissions; and secondly, predominantly industrialised nations, in meeting their obligations to reduce GHG and achieve compliance with their emission reduction targets. In order for a proposed CDM project to undergo validation, approval, and registration, it is imperative that it adheres to an authorised baseline and monitoring methodology, which is also available in the area of wastewater treatment.

The CDM methodology primarily centres around AD processes that involve the capture of biogas for the purpose of generating electricity and/or heat. Additionally, it provides guidelines for calculating the dewatering of sludge and its subsequent application to land. CDM does not differentiate between distinct methods for calculating GHG emissions. Instead, it provides equations that must be adhered to when determining the CF components. These equations rely on data obtained from the facility monitoring system, including

Table 4. Presentation of U.S. Protocol (2013) methodology Methods for assessment of WWT N_2O emissions.

Tabela 4. Prezentacja metodologii protokołu amerykańskiego (2013): Metody oceny emisji N_2O z OŚ.

U.S. Protocol Calculation methods (2013)	Emission type	N_2O source with data requirements
Method WW.2.a Method WW.2.b	Stationary emissions	Combustion of digester gas at a centralized WWTP with anaerobic digestion of biosolids when process data known
Method WW.2.(alt)	Stationary emissions	Combustion of digester gas at a centralized WWTP with anaerobic digestion of biosolids based on the population served by the facility
Method WW.5	Stationary emissions	Emissions from residuals combustion based on the mass composition of the material sent to the combustion device
Method WW.7	Process emissions	Centralized WWTP with nitrification/denitrification or aeration basin based on the population served
Method WW.8	Process emissions	Centralized WWTP without nitrification/denitrification or aeration basin based on the population served
Method WW.10	Process emissions	Emissions from cluster package system based on the population served
Method WW.12	Fugitive emissions	Effluent discharge to receiving aquatic environments based on the daily N-load
Method WW.12.(alt)	Fugitive emissions	Effluent discharge to receiving aquatic environments based on the population served
Method $WW.13_{N2O}$	Attributed emissions	Process emissions from cluster package systems based on population served by the facility
Method WW.14	Lifecycle emissions associated with water acquisition, distribution and treatment	Upstream indirect emissions resulting from the energy consumption based on the amount of energy purchased and consumed or on the national average energy consumption per unit of water and wastewater and the total annual volume of the water and wastewater passing through the analysed system(s)
Method WW.15	Lifecycle emissions associated with water acquisition, distribution and treatment	Upstream indirect emissions resulting from the energy consumption based on the amount of energy purchased and consumed or on the national average energy consumption per unit of water and wastewater and the population served by the system(s) divided into the groups linked to the type of the wastewater treatment process (e.g., centralized and other modalities)

parameters such as the volume and COD of the treated wastewater or sludge, the amount of biogas collected and the methane concentration within it, The methodology employed does not take into account the emissions originating from wastewater collection systems, primary or secondary clarifiers, and the biological treatment stage.

5. DIRECT GHG EMISSIONS IN WASTEWATER TREATMENT

According to estimates, the direct emissions originating from the wastewater sector, specifically CH_4 and N_2O, contribute to approximately 5% of global non-CO_2 GHG emissions. Projections indicate that these emissions are expected to increase by 22% by the year 2030. From a CF perspective of WWTPs, the significance of direct gaseous emissions is noteworthy, particularly for facilities that receive influent with elevated concentrations of pollutants.

The literature exhibits inconsistencies in the accounting of direct CO_2 emissions. The IPCC and CDM excluded biogenic carbon dioxide emissions from their analysis, while LGOP and U.S. Protocol are not discussing them at all. L. Li et al. (2022) [33] contend that while it is commonly believed that CO_2 emissions primarily originate from biogenic organic matter found in human excreta or food waste, this perspective overlooks the potential contribution of fossil carbon sources, including pharmaceuticals and personal care products or even external carbon sources for denitrification enhancement, which could potentially augment the overall quantity of direct carbon emissions. The topic of fossil CO_2 emissions from wastewater has garnered increased attention, prompting the IPCC (2019) to revise its 2006 guidelines to include a comprehensive discussion on this matter. However, the majority of the studies that contribute to the advancement of net-zero carbon wastewater treatment primarily focus on N_2O and CH_4, as detailed in this paper and summarized in a simplified Scheme 3.

Methane

During wastewater collection, methane generation conditions reach their optimal levels. Pumping systems can anaerobicize ascending sewers [5, 60]. These circumstances and high organic matter concentrations encourage methanogenesis [28]. At a discharge well, pressure differentials cause CH_4 emissions and an olfactory disturbance that draws nearby residents [44]. Gravitational systems can also measure CH_4 fluxes [59]. Air depletion stratification beneath the free surface can develop oxygen-deprived underground layers, where CH_4 generation occurs. In this scenario, wastewater flow disturbances reveal emission locations.

The mechanical stage of WWTPs emits CH_4 from compensation tanks (aerobic and anaerobic), preliminary oxidation tanks for slurry wastewater, aerated grit chambers, and sludge concentration tanks, in descending order [32, 33].

GHG emissions, including methane fluxes, are observed at several points in bioreactor compartments during BNR operations. Oxygen deficit in anaerobic and anoxic zones promotes methane production, which is released in aerobic chambers during nitrification [3, 26, 33].

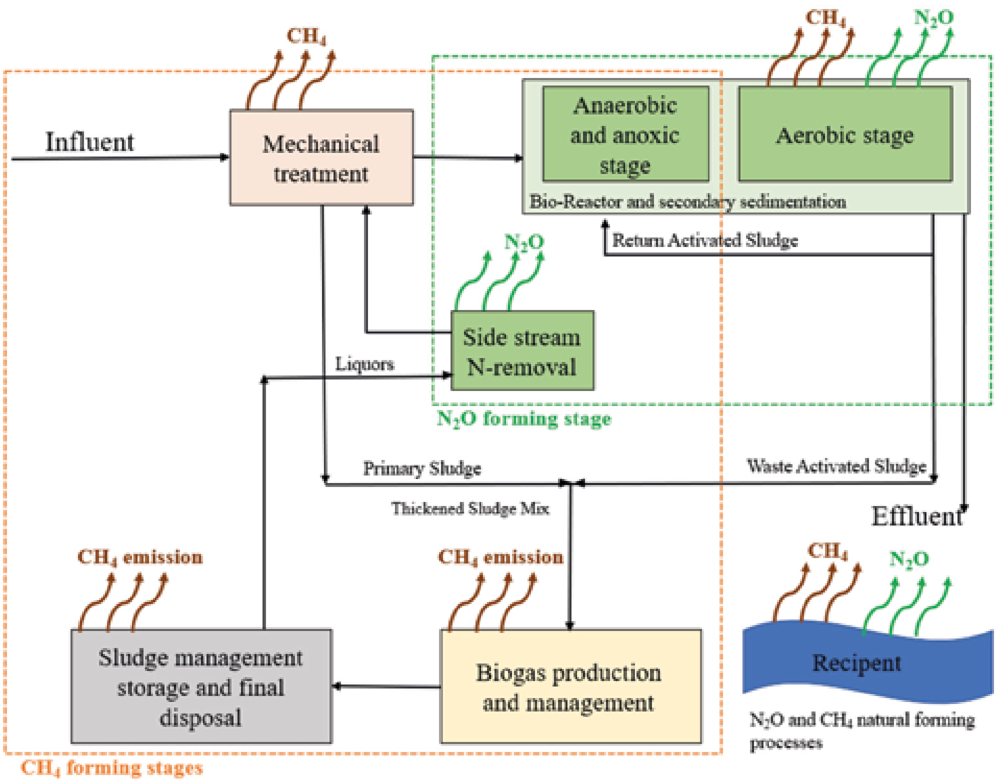
According to Khabiri et al. (2021) [32], the facility emits 75% of its CH_4 via anaerobic digestion of main and secondary sludge. The reported CH_4 emissions mostly come from stripping incoming sewage and anaerobic digesters (Foley et al., 2009). In the event of planned or accidental mechanical disturbances that interrupt pipeline continuity, biogas production, collecting, and transportation systems may emit CH_4 from AD process.

Further digestate or sludge management and disposal is also linked to methane releases, e.g., via long-term storage, in-land application or incineration [25, 59, 62].

Lakes and rivers that receive treated wastewater streams are major methane emitters [61]. When oxygen is scarce, processed wastewater inflows provide organic materials for methanogenesis in aquatic habitats.

Nitrous oxide

While CH_4 emissions can be spotted at different stages of wastewater treatment, N_2O fluxes requires more sophisticated conditions to be released which is particularly observed in BNR compartments. The production of N_2O in the bioreactors encompasses a series of microbiological reactions that necessitate either aerobic or anoxic conditions. Researchers have identified three



Scheme 3. N_2O and CH_4 formation and emission stages/points in a conventional WWTP.

Schemat 3. Tworzenie N_2O i CH_4 oraz etapy/punkty emisji w konwencjonalnej oczyszczalni ścieków.

primary biological pathways in WWT systems with nutrients removal. These involve the N_2O production: (1) as an intermediate product during the oxidation of hydroxylamine (NH_2OH) by ammonia-oxidizing bacteria (AOB), (2) the final product of nitrifier denitrification by AOB, and (2) the intermediate product of denitrifying heterotrophic bacteria (DHET) denitrification.

Drawing upon the existing body of knowledge pertaining to N_2O production pathways, Vasilaki et al. (2019) [50] identified several key operational variables that are responsible for the generation of N_2O, such as the accumulation of low dissolved oxygen (DO), nitrite (NO_2^-), or free nitrous acid (HNO_2), as well as changes in the ammonium (NH_4^+) concentration in the nitrifying compartments or the situation when denitrifying compartments exhibit a low chemical oxygen demand to nitrogen ratio, as well as an accumulation of nitrite ions (NO_2^-) and the alternation of anoxic and aerobic conditions in switching compartments.

The bioreactors emit most of the WWTPs' N_2O, but other elements of the plant release a small amounts of this gas as well, such as partial nitrogen conversion produces N_2O in the effluent receiver [46]. Sludge storage N_2O emissions are estimated based on 12-month uncovered storage. On the other hand, sewer N_2O emission case studies are scarce.

WWT area CF calculation can evaluate GHG emissions from a single facility (centralised WWTP) or develop CF level for many cooperating plants. The reporting organisation shall follow GHG Protocol consolidation requirements in each circumstance. Scheme 4 in the upcoming chapter shows how each criterion differs. Consolidation procedure and organisational boundary requirements guarantee correct CF results.

Hence, it is important to acknowledge that a multitude of diverse factors contribute to and interact within bioreactors in full-scale wastewater treatment plants, and these processes can occur simultaneously in a dynamic manner, often beyond the direct control of operators

6. WWTPs' CARBON FOOTPRINT SCOPE 1 EVALUATION

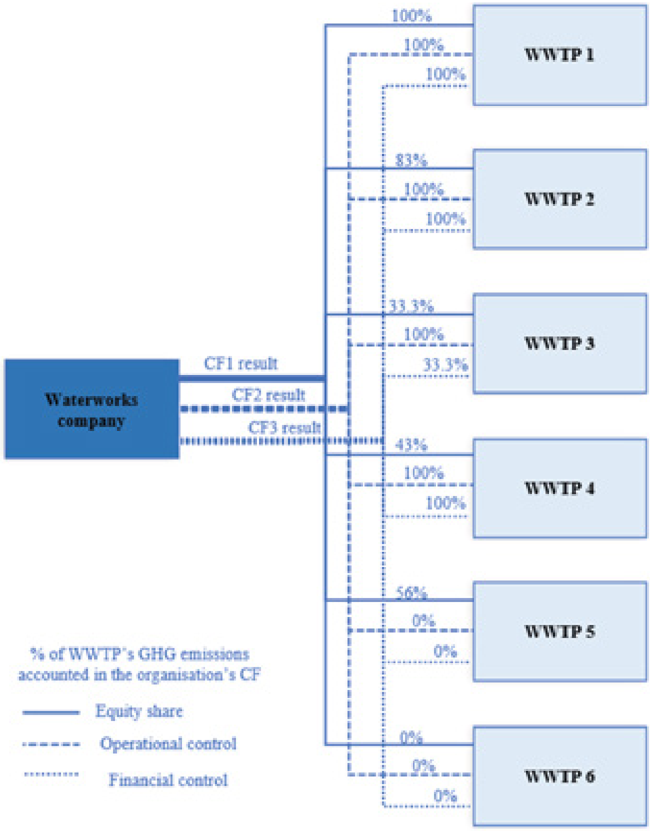
6.1 ESTABLISHING CALCULATION BOUNDARIES – ORGANISATIONAL MATERIALITY ANALYSIS

As per the guidelines provided by the GHG Protocol, the reporting of GHG emissions at the organisational level of CF commences with the fulfilment of the two-stage materiality analysis. Stage one is dedicated to convey the organizational CF calculation boundaries, while the second stage addresses the establishment of operational boundaries.

Organisational boundaries analysis, in a so-called consolidation process, entails determining the responsibility for emissions within the entire structure of the organisation, including subsidiaries, among other factors. The process of ascertaining accountability can be conducted based on either of two criteria: (1) equity share or (2) control: operational or financial control [53].

The concept of equity share pertains to the allocation of ownership in an organisation. Control can be categorized into two main types: operational control, which involves decision-making authority over day-to-day operations, and financial control, which encompasses the ability to influence financial decisions and strategic direction. In the case of consolidation based on financial control, emissions from joint ventures in which the partners share financial control are accounted for on the basis of equity participation. Under the operational control approach, the organisation is responsible for 100% of the emissions from operations over which the organisation or one of its subsidiaries has operational control.

There are two primary scenarios that may arise when calculating the CF in WWT area. The first scenario involves assessing GHG emissions from a single facility, specifically a centralised WWTP. The second scenario involves determining the CF level for a group of collaborating facilities. The consolidation process, as per the requirements of the GHG Protocol, should be undertaken annually in each instance from the standpoint of the reporting organisation. The Scheme 4 effectively demonstrates the distinctions observed in the application of each criterion. The accuracy of CF results can be ensured by providing clear consolidation processes and well-defined criteria for organisational boundaries.



Scheme 4. Defining the organizational boundary of complex waterworks company and 6 WWT facilities.

Schemat 4. Określenie granicy organizacyjnej złożonego przedsiębiorstwa wodociągowego i 6 obiektów OŚ.

Establishing the boundaries for calculating carbon footprint within a specific plant may present challenges. In the scientific investigations, researchers typically direct their attention towards the GHG emission domain of the selected WWTP aspects in order to provide a comprehensive overview of GHG emissions stemming from specific facets of the process, encompassing both direct and fugitive emissions [1, 2, 8, 10, 17, 27, 40, 41, 42, 49, 50, 58] and/or chosen phases of the organisational CF value chain, such as externally sourced energy, transportation, chemical agents usage and waste disposal [19, 24, 34, 35, 36, 39, 56, 57]. As stated before, the GHG Protocol Standard includes the establishment of operational boundaries as the second part of the materiality analysis. This phase is specifically focused on the assessment of indirect GHG emissions, particularly those falling under the purview of Scope 3, as all direct emissions (Scope 1) and energy-related indirect emissions (Scope 2) should be covered by CF calculation. Each Scope 3 category will be discussed further in the article part two.

6.2 SCOPE 1 EMISSIONS

Scope 1 pertains to the direct emissions of greenhouse gases that take place at sites that are either owned or under the control of the organisation, as determined through the analysis of materiality and the process of consolidation [54]. There are two primary categories of direct emissions that can be identified: emissions originating from supporting activities (Table 5), and emissions resulting from process and technological factors (Table 6). These two categories can be further delineated as direct GHG emissions that arise from the combustion of fuels in stationary and mobile combustion sources, as well as from physical or chemical processing and fugitive emissions. The various types mentioned are illustrated with specific examples

Table 5. Summary of direct GHG emission types from a WWTP's supportive activities.

Tabela 5. Podsumowanie bezpośrednich rodzajów emisji gazów cieplarnianych z działań pomocniczych OŚ.

Scope 1 direct emission type	Emission source	Explanation	WWTP example	Minimum data required for calculation
Emissions from supportive activities				
Combustion	Stationary combustion	GHG emissions from combustion of conventional fuel e.g., coal, oil, natural gas in stationary sources owned or controlled by the organisation in order to produce energy	Boilers, turbines, aggregates	Annual usage of fuels collected within the types
Combustion	Mobile combustion	GHG emissions from combustion of conventional fuel e.g., petrol, diesel in the car fleet owned or controlled by the organisation (including leased vehicles)	Passenger vehicle fleet, heavy vehicle fleet, transportation fleet	Annual usage of fuels collected within the types
Fugitive	Mobile	GHG emissions from AdBlue usage in the diesel fleet owned or controlled by the organisation (including leased vehicles)	Diesel vehicle fleet	Annual usage of AdBlue
Fugitive	Refrigerants leaks	GHG emissions from refrigerants leaks (air-conditioning, AC, units/installations)	AC units in administrative buildings and samples storage rooms, probes rooms	Annual amount of the refrigerants refilled (usually in kg) collected within the types (e.g., R407c, R410A)
Fugitive	Welding	GHG emissions from welding procedure done by the organisation itself – usage of GHG-containing shielding gases mixtures	Gases used while the repair process via welding	Annual amount of the welding gases mixtures with its safety data sheets (including weight mass composition)

Table 6. Summary of a WWTP's direct GHG process and technological emission types.

Tabela 6. Podsumowanie bezpośrednich rodzajów emisji gazów cieplarnianych z procesów technologicznych OŚ.

Scope 1 direct emission type	Emission source	Main GHG type	Authors' proposed CF calculation algorithm statement with justification	Emissions included in the algorithm as in methodology
Process and technological emissions				
Fugitive	Collection system	CH_4	Not considered – due to the lack of data, research results and no methodology given. Authors recommend following the updates in the area as fugitive emissions from sewer systems may play crucial role in WWTP's CF structure [18, 31, 45].	IPCC, NGA/NGER, U.S. Protocol, LGOP, CDM
Fugitive	Preliminary and primary treatment	CH_4	Considered – emissions calculated on the basis of EFs (IPCC, 2019 and NGA/NGER, 2023 as complimentary data sources).	IPCC, NGA/NGER
Fugitive	BNR treatment	N_2O, CH_4	Considered – emissions calculated on the basis of EFs (IPCC, 2019, U.S. Protocol, 2013 NGA/NGER, 2023 and LGOP, 2010 as complimentary data sources) depending on the technological process involved.	IPCC, NGA/NGER, U.S. Protocol, LGOP
Fugitive	Denitrification supported by external C-source dosage	Fossil (non-biogenic) CO_2	Considered – emissions calculated on the basis of EFs (IPCC, 2019 – Table 6AP.1) depending on the C-source type	IPCC
Fugitive	Secondary clarification	N_2O	Not considered – authors follow discussed methodologies approach and, on this basis, assume that N_2O emission from secondary clarification process are covered by BNR emissions. Authors recommend following the updates in the area for the probable future supplementary calculation methods.	IPCC, NGA/NGER, U.S. Protocol, LGOP, CDM
Fugitive	Side stream N-removal	N_2O	Considered – emissions calculated on the basis of EFs (IPCC, 2019 and U.S. Protocol, 2013 as complimentary data sources) depending on the technological process involved.	IPCC, U.S. Protocol
Fugitive	Effluent discharge	N_2O, CH_4	Considered – emissions calculated on the basis of EFs (IPCC, 2019 and U.S. Protocol, 2013 as complimentary data sources) depending on the recipient type.	IPCC, NGA/NGER, U.S. Protocol, LGOP, CDM
Fugitive	Anaerobic Digestion	CH_4	Considered – calculated for 4 types of emissions: (1) intended and unintended biogas leaks from digesters, (2) biogas flared, (3) linear biogas transportation leaks, (4) captured biogas combustion (e.g., cogeneration process)	IPCC, NGA/NGER, CDM
Fugitive	Thickening and dewatering	CH_4	Not considered – authors follow discussed methodologies approach delivering no discussion on GHG emissions from thickening or dewatering procedures. Authors recommend following the updates in the area for the probable future supplementary calculation methods.	IPCC, NGA/NGER, U.S. Protocol, LGOP, CDM
Fugitive	Dewatered sludge and digestate management and usage	CH_4, N_2O	Considered depending on materiality analysis and consolidation process results	IPCC, NGA/NGER, U.S. Protocol, LGOP, CDM
Fugitive	Process waste management	CH_4, N_2O	Considered depending on materiality analysis and consolidation process results	IPCC, NGA/NGER, U.S. Protocol, LGOP, CDM

in the Tables with the indication of minimum data required for CF Scope 1 supportive activities' emission calculation.

As stated in the aforementioned article, the primary objective of this study involves the development of comprehensive guidelines for calculating CF in WWTPs. These guidelines aim to address the existing gaps in accounting for both direct process emissions and technological emissions. The Table 6 provided below presents a summary of the authors' work in developing fundamental aspects to enhance the GHG emissions evaluation algorithm, which can be utilised by professionals in the field. Moreover, comprehensive guidelines are provided in subsequent sections of this document.

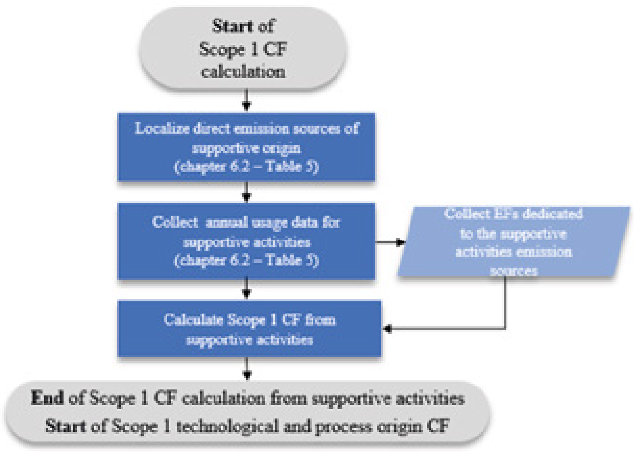
7. CARBON FOOTPRINT ALGORITHM OF MWWTP: SCOPE 1 – STEP BY STEP INSTRUCTION

The algorithm for calculating the carbon Footprint of MWWTP, presented in this study as a two-part article, encompasses seven distinct stages that adhere to the guidelines set forth by the GHG Protocol and meet the requirements of the CSRD. The following steps are:

1. Consolidation process evaluation.
2. Scope 1 emission calculation:
   a. GHG emissions from the supportive activities,
   b. N_2O direct fugitive emissions,
   c. CH_4 direct fugitive emissions from wastewater treatment path,
   d. CH_4 direct fugitive emissions from sludge management, biogas production and utilisation.
3. Scope 2 (location – and market-based methods) calculation.
4. Scope 3 calculation.
5. Results summary, uncertainty discussion and report preparation.
6. Conclusions in the area of data aggregation.
7. Carbon footprint results analysis and GHG emission reduction planning.

In this article, there are guidelines for Scope 1 in the light of steps 1, 2, 5, 6. To enhance the clarity of the proposed calculation approach for CF, we have included seven supplementary decision trees (algorithms) along with corresponding instructions. This part one article includes guidelines, as well as analyses of various GHG calculation methodologies used in WWTP, namely:

- IPCC – 2006 methodology with 2019 Refinement, Guidelines for wastewater treatment and discharge (Vol. 5, Chapter 6) and its default value summary tables,
- NGA/NGER – 2023 methodology and its default value summary tables,
- U.S. Protocol – 2013 methodology and its default value summary tables from Appendix F.

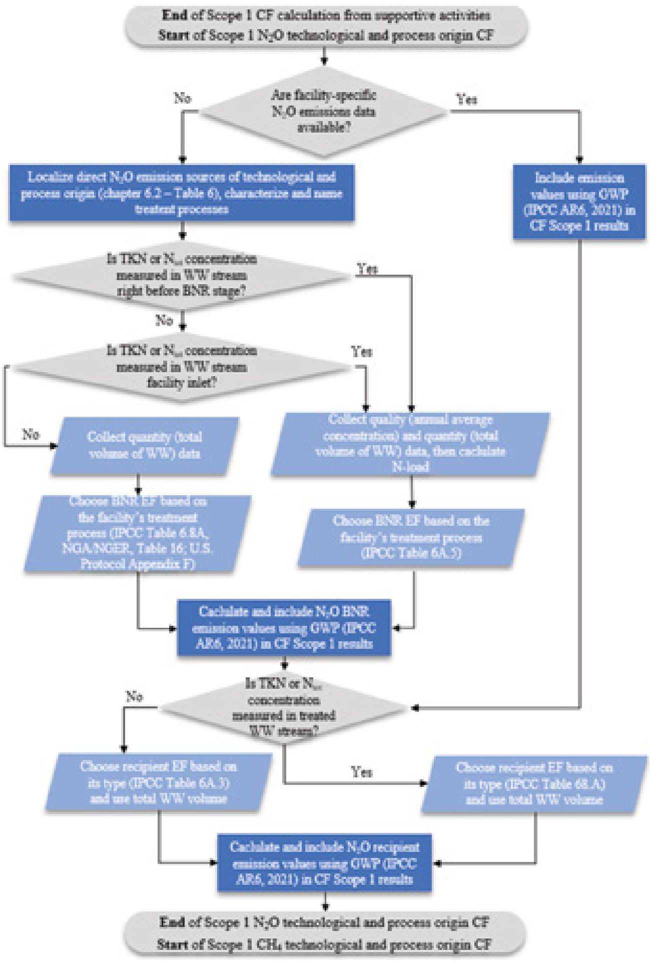


Algorithm 1. Instruction for WTTP Scope 1 carbon footprint calculation.
Algorytm 1. Instrukcja obliczania śladu węglowego dla OŚ w Zakresie 1.

The proposal of the WWTP's CF calculation steps suggests commencing the evaluation of Scope 1 carbon footprint by assessing the greenhouse gas emissions associated with supportive activities, as outlined in Algorithm 2.

Algorithm 2 initiates the phase of fugitive emissions calculations, specifically focusing on the quantification of N_2O fluxes. When implementing side stream N-removal in a WWTP, it is recommended to follow the same steps as previously presented.

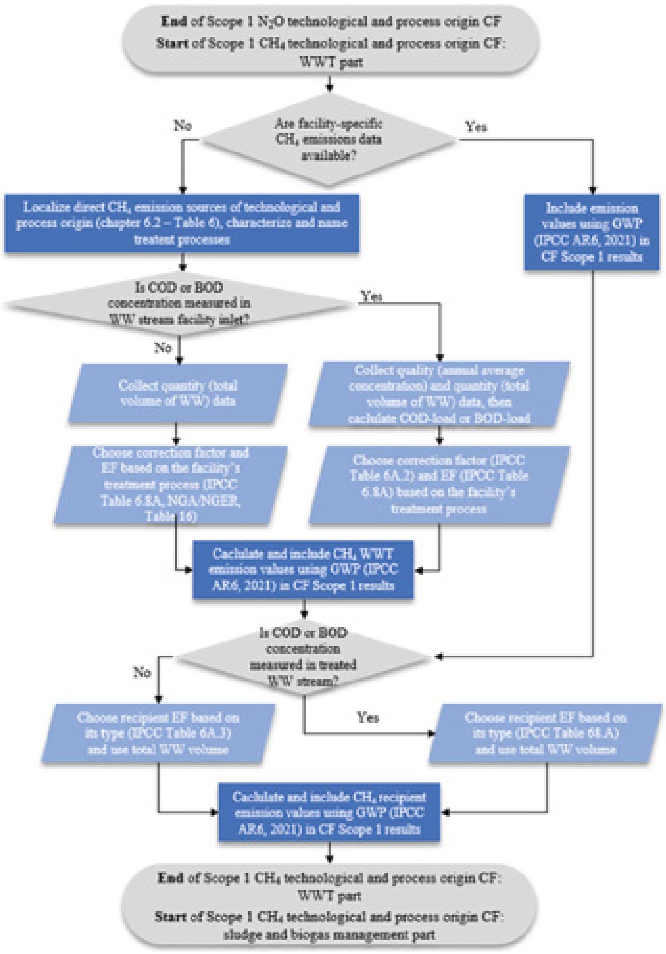
Algorithms 3 and 4 are specifically designed for the calculation of direct fugitive emissions of CH_4. Given the absence of comprehensive biogas quality data pertaining to methane concentration, it is advisable to rely on average information derived from scholarly literature sources, such as reports published by IEA.



Algorithm 2. Decision tree and instructions for N_2O direct fugitive emissions from WWTP.
Algorytm 2. Drzewo decyzyjne i instrukcje dotyczące bezpośrednich emisji niezorganizowanych N_2O z OŚ.

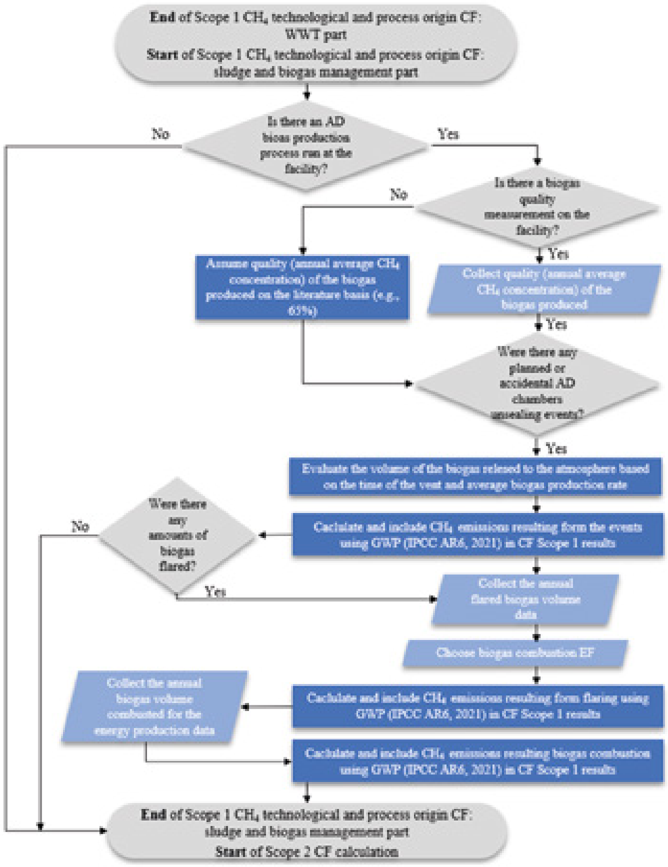
8. UNCERTAINTY DISCUSSION

As per the guidelines outlined by the GHG Protocol, it is imperative to include an analysis of uncertainty or, at the very least, engage in a thorough discussion of it within the calculation procedure. Uncertainty in the context of direct emissions in WTTPs arises from two sources: measurement uncertainties, which pertain to the quality of the data collected, and uncertainties associated with the calculation of emission factors, which relate to the quality of the factors used in estimating emissions. The authors put forth a methodology for ascertaining the level of uncertainty associated with emission factors, denoted as Scheme 5. Further discussion on the uncertainty topic within the authors' recommendation will be presented in the article part two.



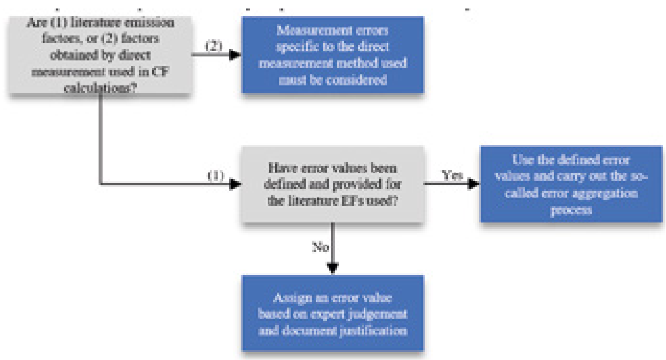
Algorithm 3. Decision tree and instructions for CH_4 direct fugitive emissions from WWTP: wastewater treatment path.

Algorytm 3. Drzewo decyzyjne i instrukcje dotyczące bezpośrednich emisji niezorganizowanych CH_4 z OŚ: ścieżka ściekowa.



Algorithm 4. Decision tree and instructions for CH_4 direct fugitive emissions from WWTP: sludge management and AD part.

Algorytm 4. Drzewo decyzyjne i instrukcje dotyczące bezpośrednich emisji niezorganizowanych CH_4 z OŚ: część osadowa i produkcja biogazu.



Scheme 5. Simplified procedure for emission factors uncertainty assessment.

Schemat 5. Uproszczona procedura oceny niepewności wskaźników emisji.

9. CONSLUSIONS

This paper highlights the need for standardized approaches in calculating GHG emissions from WWTPs to meet the requirements CSRD and ESRS indicators. The developed algorithm for calculating the carbon footprint of WWTPs, provides a comprehensive framework for assessing GHG emissions. Authors address final conclusions described below.

- The calculation of Scope 1 GHG emissions, as outlined by the GHG Protocol, presents a significant challenge in terms of data aggregation for wastewater utilities. As a result, it is recommended that these utilities adopt a best practise approach by establishing a dedicated team or department responsible for the calculation of carbon footprints.
- The calculation of fugitive emissions in Scope 1, which includes N_2O and CH_4 fluxes, necessitates comprehensive technological data, encompassing both quantitative and qualitative aspects. Consequently, it may be necessary to periodically update the measurement schedule on an annual basis to gather data for evaluating carbon footprint.
- WWTPs which employ complete nitrogen removal processes exhibit a higher level of emission in contrast to facilities that do not utilise biological nutrient removal techniques.
- In order to conduct a comprehensive comparison of CF results, especially within Scope 1, it is essential to establish emission intensity ratios (expressed as $kgCO_2e/m^3$ of treated wastewater). Relying solely on total CF levels may lead to inaccurate or incomplete conclusions.
- It is assumed that in the foreseeable future, there will be an implementation of improved on-site GHG emission evaluation campaigns at MWWTPs. The purpose of these campaigns would be to gather precise N_2O and CH_4 emission factors that are specific to each facility. This is necessary because relying solely on literature-based indicators may lead to an overestimation of Scope 1 CF results, as literature-based indicators may overestimate Scope 1 CF results even up to two orders of magnitude [18].

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