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

Algorytm obliczania śladu węglowego miejskiej oczyszczalni ścieków – część druga

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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

Given the increasing concern surrounding the issue of global warming, many countries have made a firm pledge to achieve a state of net-zero emissions by the year 2050 [13], in accordance with the guidelines set forth by the Intergovernmental Panel on Climate Change (IPCC) to prevent exceeding the 1.5°C limit [10]. Wastewater treatment plants (WWTPs) have been recognised as a notable contributor to direct greenhouse gas (GHG) emissions, particularly in the form of N_2O and CH_4. These emissions constitute roughly 3% of worldwide GHG emissions [11, 19]. Furthermore, when examining indirect emissions, it becomes apparent from an energy perspective that WWTPs persist in consuming a substantial quantity of energy, predominantly obtained from fossil fuel origins. In light of the contemporary emphasis on climate change, rising electricity expenses, and the necessity to mitigate carbon footprint emissions in organisational or operational contexts, the wastewater treatment facility is perceived as a complex situation that offers both obstacles and possibilities for improvement. Water utilities are taking a leading role in addressing GHG emissions, as evidenced by several waterworks organisations aiming to achieve net-zero emissions in their operations in the next decades [2, 3, 9]. The initial stage in developing a GHG reduction strategy involves

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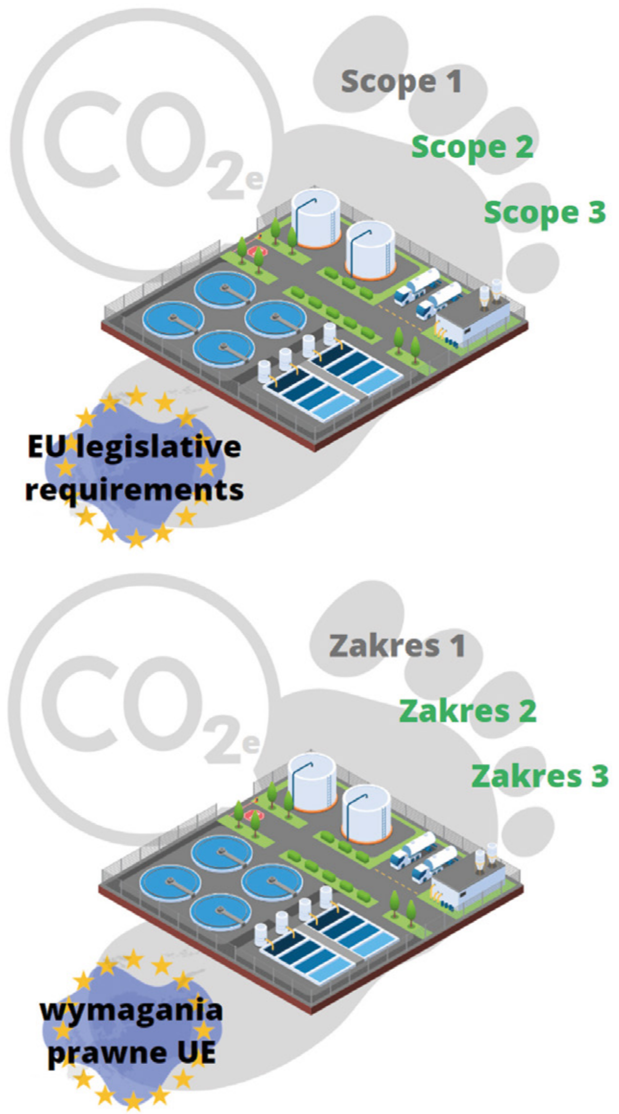


GRAPHICAL ABSTRACT

doing an annual carbon footprint (CF) estimate. This calculation serves to enhance transparency and facilitate the comparison of outcomes across various facilities and economic regions.

In the upcoming year, the primary urban water management utilities will be obligated to conduct CF calculations in compliance with the Corporate Sustainability Reporting Directive (CSRD) and European Sustainability Reporting Standards (ESRS) indicators as stipulated by the European Financial Reporting Advisory Group (EFRAG). Nevertheless, it is important to acknowledge that there is presently no recognised methodology that explicitly deals with the rules for WWTPs in regard to GHG emissions. This lack of a standardised approach hinders water bodies from receiving clear instructions on how to calculate their CF. The compliance with the reporting requirements of the Greenhouse Gas Protocol (GHG Protocol) regime, as legislated by the European Union (EU), is necessary in order to fulfil the duties of CSRD. As a result, water providers have a responsibility to adhere to these stipulations.

Previous studies have demonstrated that the application of different wastewater treatment methods can result in different levels of direct GHG emissions, as well as various degrees of energy usage and sludge production [4, 8, 11, 12, 14, 20]. According to the study conducted by Piao et al. (2016) [11], the introduction of the Modified Ludzack-Ettinger (MLE) process in wastewater treatment plants led to a 20% rise in the carbon footprint when compared to facilities employing the Anaerobic-Anoxic-Oxic (A2/O) process. Furthermore, research has indicated that the adoption of aerobic wastewater treatment methods might lead to a substantial rise of 105% in direct GHG emissions, in contrast to the usage of anaerobic wastewater treatment techniques [4].

However, there are still ambiguities around the understanding of carbon footprints linked to different layouts of WWTPs. Previous studies failed to consider several potentially major sources of greenhouse gas emissions, particularly in relation to sludge handling operations. These studies focused solely on specific emission-related aspects, rather than considering the overall fluxes of gases that contribute to global warming.

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

The primary objective of this study is to offer a helpful resource for academics, policymakers, and practitioners engaged in the evaluation and control of the carbon footprint associated with wastewater treatment facilities. This study aims to enhance our understanding of the carbon footprint composition of wastewater treatment facilities by emphasising the evaluation of direct greenhouse gas emissions. Additionally, it seeks to offer guidance on estimating the carbon footprint of municipal wastewater treatment plants. By doing so, this research can contribute to the advancement of more precise and comprehensive carbon footprint assessments and aid in the mitigation of climate change.

Furthermore, this study examines the degree of completeness of facilities data and suggests potential remedies to resolve any discovered deficiencies in information pertaining to the comprehension of the carbon footprint linked to WWTPs [15] and their organisational structure. Furthermore, a plan for enhancing the quality of data is proposed. The analysis encompassed a thorough examination of the significance and origins of Scope 1, 2, and 3 emissions (as defined by the GHG Protocol) within the broader context of carbon footprint, specifically in relation to the regulatory objectives of CSRD reporting and the imminent responsibilities imposed on waterworks organisations.

2. INDIRECT EMISSIONS IN WASTEWATER TREATMENT – EU LEGISLATION

The Corporate Sustainability Reporting Directive (CSRD), officially referred to as EU Directive 2022/2464 of the European Parliament and of the Council of 14 December 2022 [7], was implemented on January 5th, 2023, as a component of the legislative measures associated with the Green Deal EU initiative. The article's first section presents the regulatory scopes and introductory phases.

Organisations who are subject to the oversight of the CSRD will have a duty to comply with the ESRS when presenting their reports. The disclosure of CSRD reports highlights the significance GHG emissions, with particular emphasis on Scope 2 and Scope 3 indirect emissions. These emissions are of utmost relevance since they arise from the value chain activities of each firm. Furthermore, this pertains to the formulation of climate change policy and the development of a strategy aimed at mitigating greenhouse gas emissions. The primary objective of this strategy is to achieve a state of net-zero emissions by the year 2050, as outlined in the second and third scope reduction goals.

The assessment of CF, due to its complete character, requires significant data collection endeavours in several settings to discover areas lacking information. This will entail the development of data collection schemes in collaboration with the organization's suppliers.

3. WWTPs' SCOPE 2 AND 3 CARBON FOOTPRINT EVALUATION

3.1. ESTABLISHING CALCULATION BOUNDARIES – OPERATIONAL MATERIALITY ANALYSIS

GHG Protocol requires annually provided materiality analysis – organisational and operational. Organisational assessment process has been described in detail in the article part one.

For the purpose of operational boundaries assessment, it is recommended to convey initial Scope 3 emission structure analysis on the basis of spend-based method [18]. The spend-based method is a technique that enables the estimation of emissions by gathering data on the economic value of goods and services acquired, and subsequently multiplying this value by appropriate secondary emission factors, such as industry averages (Equation 1). The emission factors provided herein represent the mean emissions attributed to each unit of monetary value of goods. Typically, the availability of expenditure data surpasses that of detailed mass or relevant units' information. It is imperative to gather economic aggregates for every category. In order to ensure comprehensive reporting, it is recommended that the emission factors necessary for calculating the CF of Scope 3 emissions be collected. The resulting CF values should then be presented individually for each relevant area. This presentation should encompass categories that account for over 90% of the emissions within the value [17].

$$sCF_{Scope\ 3\ category\ i,n}[tCO_2e] = Ec_{i,n}\ [currency] \cdot sEF_{i,n}\ [tCO_2e/currency] \quad (1)$$

$sCF_{Scope\ 3\ category_{i,n}}$ – initial (screening) CF category *i* result of the year *n*, tCO_2e
$Ec_{i,n}$ – economic value of the purchased good or service in category *i*, spent in the year *n*, currency, e.g., PLN, EUR, USD
$sEF_{i,n}$ – initial (screening) CF category i emission factor used for the year *n*, tCO_2e*/currency, e.g.,* tCO_2e */PLN,* tCO_2e */EUR,* tCO_2e */USD*

The selection of emission factors (EFs) may pose a significant challenge in conveying the Scope 3 screening procedure. The utilisation of the Climatiq [5] free database is advised as the primary source of data. It is necessary to update each GHG emissions factor (EF) on an annual basis in order to accurately reflect the evaluation year. For instance, when conducting a materiality analysis for the year 2023, it is imperative to recalculate the EFs if they are outdated – dedicated to previous years (as indicated in Equation 2). For this purpose, the inflation rate is required to be used. It is important to acknowledge that the predominant currencies utilised in EF databases are USD, GBP, and EUR. Consequently, the utilisation of currency exchange rates may also be necessary.

$$sEF_{i,n}\ [tCO_2e/currency] = \frac{sEF_{i,n-x}\ [tCO_2e/currency]}{1 + IR_{n\ vs.n-x}\ [-]} \quad (2)$$

$sEF_{i,n}$ – initial (screening) CF category *i* emission factor used for the year *n*, tCO_2e*/currency, e.g., ,* tCO_2e */PLN,* tCO_2e */EUR,* tCO_2e */USD*
$sEF_{i,n-x}$ – initial (screening) CF category *i* emission factor used for the year *n-x* (outdated), tCO_2e*/currency, e.g.,* tCO_2e */PLN,* tCO_2e */EUR,* tCO_2e */USD*
$IR_{n\ vs.n-x}$ – inflation rate in the year n vs. year *n-x*, –

3.2. SCOPE 2 EMISSIONS

Scope 2 encompasses the energy indirect emissions that are associated with the acquisition and utilisation of electricity, heat, steam, or cooling by the organisation during the specified reporting period [16] reported in the energy consumption points falling under the calculation boundaries established through materiality analysis [17]. The inclusion of energy generated from self-owned renewable energy systems in the calculation provides a comprehensive assessment of the organization's total energy consumption. It is argued that the calculation of carbon footprints should not be applied to energy generated through self-owned renewable energy source (RES) installations.

The GHG Protocol's Scope 2 guidance outlines two methods for calculating emissions from purchased electricity: the location-based (LB) method and the market-based (MB) method [16]. Both methods are essential as the comparison of the results they provide allows for an examination of the influence of the organization's decision-making process on CF. The final result for Scope 2 carbon footprint is presented in the form of market-based method outcomes.

The emissions in the LB method are determined by utilising the country average EFs obtained from the National Centre for Emissions Management (KOBiZE) for Poland, and the European Environment Agency (EEA) or International Energy Agency (IEA) for other countries worldwide. The calculation of MB CF is derived from the residual energy mixes of national EFs, as published by the Association of Issuing Bodies (AIB) in the European Residual Mixes Report on an annual basis. In the event of acquiring energy through a specialised tariff for renewable energy systems (RES) or through a Guarantee of Origin (GO or GoO) supported by an appropriate statement document issued by the national energy-balancing body, the EF for electricity under said tariff or GO is effectively reduced to zero. To account for externally procured heat, process steam, and cold, it is recommended to utilise the average emission factors specific to the country in question.

The concept of a Guarantee of Origin refers to an energy certificate that is explicitly outlined in Article 15 of the European Directive 2009/28/EC [6]. A Green Option programme is designed to certify the origin of electricity derived from renewable sources and furnish customers with pertinent information regarding the energy source. GOs represent the sole established mechanisms that provide evidence regarding the source of electricity derived from renewable energy sources. Therefore, in case of the externally purchased electricity GOs, according to GHG Protocol, proves zero-levelled EF for MB Scope 2 calculation.

The national residual electricity mix (residual mix) represents the composition of the electricity supply that is not accounted for by Guarantees of Origin or other reliable tracking mechanisms. In order to ensure the reliability of the tracking instrument, it is necessary to incorporate a residual mix when not all consumption is accounted for using GO certificates. The residual mix refers to the composition of energy sources used for generation, excluding any tracked energy generation attributes. The existence of a residual mix can be understood as a logical outcome of the implementation of energy attribute tracking. This implementation serves to prevent the inadvertent disclosure of the attributes associated with GOs to multiple consumers through an implicit mix. Without a residual mix, renewable electricity sold with GOs would be double counted because the same electricity would be disclosed to consumers buying "regular" electricity. It is advisable to refrain from utilising uncorrected generation statistics for the purpose of CF disclosure in MB Scope 2 calculation procedure [1].

The inclusion of energy generated by self-owned renewable energy systems in the calculation enables a comprehensive assessment of the organization's total energy consumption. The calculation of carbon footprints should not be applied to energy generated through self-owned renewable energy systems (RES).

When obtaining heat from external sources, such as process steam and cold, it is recommended to utilise the average emission factors provided by the country.

As previously indicated, the GHG Protocol [16] restricts the consideration of Scope 2 emissions to solely encompass the energy procured and utilised by the reporting organisation. Indirect emissions associated with the procurement and subsequent resale of energy are classified under Category 3 of Scope 3 as Well-to-Tank (WTT) emissions pertaining to electricity [18].

Table 1 summarizes possible WWTP's Scope 2 emission sources and indicates minimum data required for the CF calculations.

Table 1. Summary of possible WWTP's Scope 2 emission sources with minimum data required for the CF calculations indicated.

Tabela 1. Podsumowanie możliwych źródeł emisji Zakresu 2 oczyszczalni ścieków ze wskazaniem minimalnych danych wymaganych do obliczeń CF.

Scope 2	Type of externally sourced energy	Energy consumption point	Minimum data required for calculation
LB, MB	Electricity	Pumping wastewater collection system owned or controlled by the reporting organisation	Amount of energy in kWh or MWh purchased and consumed in the reporting year
LB	Heat and cooling		Amount of energy in GJ purchased and consumed in the reporting year
LB, MB	Electricity	Offices, mechanical workshop, warehouses, data centre rooms and other supporting buildings including own electrical car fleet charging points owned or controlled by the reporting organisation	Amount of energy in kWh or MWh purchased and consumed in the reporting year
LB	Heat and cooling		Amount of energy in GJ purchased and consumed in the reporting year
LB, MB	Electricity	WWTP installations with the entire energy-consuming infrastructure	Amount of energy in kWh or MWh purchased and consumed in the reporting year
LB	Heat, steam and cooling		Amount of energy in GJ purchased and consumed in the reporting year

The overall Scope 2 emission equation (3) is given below.

$$CF_{Scope\ 2\ \ LB\ or\ MB,n}[tCO_2e] = E_{Ext,\ n}\ [kWh\ or\ GJ] \cdot EF_{LB\ or\ MB,n}\ \left[\frac{tCO_2e}{kWh}\ or\ \frac{tCO_2e}{GJ}\right] \quad (3)$$

$CF_{Scope\ 2\ LB\ or\ MB}$ – Scope 2 CF (MB or LB) result of the year n, tCO_2e

$E_{Ext,\ n}$ – energy (electricity/heat/steam/cooling) purchased and consumed from external sources in the year n, kWh (electricity) GJ (heat, steam, cooling)

$EF_{LB\ or\ MB,n}$ – EF (LB – country average energy mix, or MB – national residual mix) for the year n, tCO_2e/kWh (electricity) or tCO_2e/GJ (heat, steam, cooling)

3.3. SCOPE 3 EMISSIONS

Scope 3 encompasses indirect GHG emissions that occur indirectly within the value chain of the WWTP. These emissions include those that arise upstream in the supply chain, as well as downstream in the processes of waste disposal or the beneficial reuse of by-products, along with the associated transportation activities. The categorization of GHG emissions, as outlined by the GHG Protocol [18] encompasses a total of 15 distinct categories. In this article, the authors delineate the categories that exhibit the highest likelihood of being of paramount significance for a typical WWTP organisation. As stated, the determination of categories to be included in the calculation of CF is conducted through a materiality analysis using the Scope 3 screening procedure.

The overall Scope 3 emission equation (4) is given below.

$$CF_{Scope\ 3\ \ i,n}[tCO_2e] = C_{i,z,n}\ [usage\ units] \cdot EF_{i,z,n}\ \left[\frac{tCO_2e}{unit}\right] \quad (4)$$

$CF_{Scope\ 3\ i,n}$ – Scope 3, category i CF result of the year n, tCO_2e

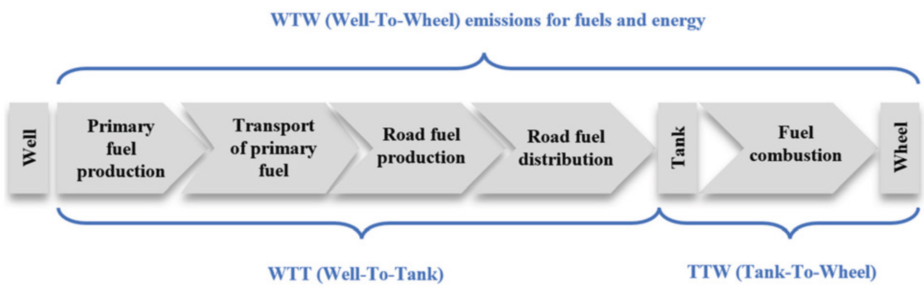
$C_{i,\ n}$ – z-type consumption in the year n, usage units

$EF_{i,z,n}$ – z-type EF for category i emissions for the year n, $tCO_2e/unit$

The Tables (2 – for Scope 3 upstream categories; 3 – for Scope 3 downstream categories) provided, contain a summary of the proposed work for evaluating emissions in the value chain. These include the rationale for selecting specific categories, recommended databases for emission factor data, and the minimum data necessary for calculating CF.

Special explanation should be given in case of the Category 3 od GHG Protocol Scope 3 – fuel – and energy-related activities, not included in Scope 1 or Scope 2. Scope 3 within Category 3 encompasses WTT (Well-To-Tank) emissions, which refers to emissions produced during the fuel production stage and the use of fuels for energy generation, including electricity, heat, steam, and cooling streams [18]. It also includes emissions associated with the energy transmission and distribution losses. The terminology employed within category 3 is derived from the fuel life cycle and pertains to distinct stages, namely extraction (well), fuel storage (tank), and utilization/combustion (wheel). Components of category 3, reflecting as said fuel life cycle, constitute a portion of Well-To-Wheel (WTW) emissions, which are presented in the life cycle phases on the Scheme 1. The residual portion the WTW emissions consists of TTW (Tank-To-Wheel) emissions, which occur when fuels are combusted within the organization's facilities (Scope 1) or during the generation of electricity procured by the organisation (Scope 2).

The provided Tables 2 and 3 present the summarised recommendations of authors regarding the calculation procedure for Scope 3 categories in a 'typical case' municipal wastewater treatment plant (MWWTP): Table 2 – upstream, Table 3 – down-



Scheme 1. Well-To-Wheel life cycle for fuels and energy with characteristic points and stages.

Schemat 1. Cykl życia Well-To-Wheel dla paliw i energii z charakterystycznymi punktami i etapami.

stream. This 'typical scenario' entails the presence of a reporting organisation that possesses both a treatment facility and a sewer collection system. The WWTP under consideration comprises several stages, including the mechanical treatment stage, the BNR removal process, and the production of biogas through anaerobic digestion, which is further utilised for energy co-generation to meet the plant's own energy needs. The organisation under consideration does not possess or exercise authority over sludge or other waste disposal sites. There are also simplified recommendations for each category indicated as well as minimal data required for the calculation in a 'quick-win' scenario which can be only introduced in the case of first year calculation when data gaps are detected. The authors emphasise that the information presented in this paper should be regarded as a mere indication and must be substantiated by additional evidence of consolidation process analysis results and Scope 3 screening procedure conclusions.

Equations dedicated for the upstream indirect emission calculations:

$$CF_{Scope\ 3\ \mathbf{4},m,n}[tCO_2e] = aL_{4,m,n}\ [t] \cdot tD_{\mathbf{4,m},n}\ [km] \cdot EF_{\mathbf{4,m},n}\ \left[\frac{tCO_2e}{tkm}\right] \quad (5)$$

$CF_{Scope\ 3\ 4,m,n}$ – Scope 3, category 4 CF result for m-mode transportation of the year n, tCO_2e

$aL_{4,m,n}$ – average vehicle load in m-mode transportation in the year n, t

$tD_{4,m,n}$ – total distance done by m-mode transportation cargo in the year n, km

$EF_{4,m,n}$ –EF for category 4 emissions and m-mode transportation for the year n, tCO_2e *per tonne-kilometre* (tkm)

Scope 3 Category 4 emissions can be also calculated on the basis of total cargo load in tonnes and average distance made via each transportation mode.

$$CF_{Scope\ 3\ \mathbf{6},m,n}[tCO_2e] = P_{6,m,n}\ [passenger] \cdot D_{\mathbf{6,m},n}\ [km] \cdot EF_{\mathbf{4,m},n}\ \left[\frac{tCO_2e}{pkm}\right] \quad (6)$$

$CF_{Scope\ 3\ 6,m,n}$ – Scope 3, category 6 CF result for m-mode transportation of the year n, tCO_2e

$P_{6,m,n}$ – number of the employees taking par in a journey via m-mode transportation in the year n, *passenger* (p)

$D_{6,m,n}$ – total distance done by m-mode transportation during the journey (two way) in the year n, km

$EF_{6,m,n}$ – EF for category 6 emissions and m-mode transportation during for the year n, tCO_2e *per passenger-kilometre* (pkm)

Table 2. Summary of recommendations for Scope 3 calculation – upstream categories.

Tabela 2. Podsumowanie zaleceń dotyczących obliczania zakresu 3 – kategorie upstream.

Cat. No.	Scope 3 emission Category name	Authors' proposed CF calculation algorithm statement for a typical MWWTP with justification	First year CF calculation method proposed as 'quick-win' scenario	EF data base potential sources *commercial
		Upstream indirect emissions		
1	Purchased goods and services	Relevant – cradle-to-gate emissions of the crucial materials purchased and used in the reporting year by the facility such as at least chemical agents should be enclosed	Purchased goods: calculation on the basis of site-specific data in kg, t or L, m^3 (Equation 3 and 4) Services: calculation via spend-based method (Equation 1 and 2) and then in the following years on the basis of actual materials and electricity usage of services	EcoInvent* Climatiq DEFRA Scientific papers
2	Capital goods	Relevant – emissions resulting from construction services (linear and cubature installations) purchased and done in the reporting year	Calculation via spend-based method (Equation 1 and 2) and then in the following years on the basis of actual materials and electricity usage of services (Equation 3 and 4)	EcoInvent* Climatiq Scientific papers
3	Fuel – and Energy-Related Activities, Not Included in Scope 1 or Scope 2	Relevant – emissions resulting from fuels generation and transportation services (WTT) as well as WTT of energy purchased and used with transmission and distribution (T&D) losses emission; all fuels (given in Scope 1) and energy (included in Scope 2) should be covered by WTT calculation	Calculation via actual energy consumption values in kWh or GJ (Equation 4)	EcoInvent* KOBiZE EEA IEA DEFRA
4	Upstream transportation services	Relevant – emissions resulting from external transportation services of the purchased goods covered in Category 1 calculation	Calculation on the annual basis of: average transportation mode type load in tonnes and total distance of each cargo in kilometres (Equation 5); transportation modes include wheel, rail, ferry, air	EcoInvent* Climatiq DEFRA
5	Waste generated in operations	Relevant – emissions resulting from process waste transportation via external services and its final disposal (excluding potential recycling procedures)	Calculation on the basis of the total mass (tonnes) of each type of waste generated with the final disposal method information provided for each waste stream (Equation 4)	EcoInvent* Climatiq DEFRA
6	Business travel	Irrelevant yet recommended for calculation on the basis of GHG Protocol good practice – emissions resulting from work-related journeys taken by the employees during the reporting year via vehicle not owned or controlled by organisation	Calculation on the annual basis of: number of employees travelling and total distance of business journey in kilometres (Equation 6) for each mode of transport (taxi, coach, train, ferry, aeroplane)	EcoInvent* Climatiq DEFRA
7	Employee commuting and remote working	Irrelevant – in comparison to other emission types, Category 7 may not play a relevant contribution to WWTP's CF structure	-	-
8	Upstream leased assets	Irrelevant – in comparison to other emission types, Category 8 may not play a relevant contribution to the WWTP's CF structure due to rare situation when the WWTP rents/leases its assets (e.g., offices, warehouses) for external entities	-	-

Table 3. Summary of recommendations for Scope 3 calculation – downstream categories.
Tabela 3. Podsumowanie zaleceń dotyczących obliczania zakresu 3 – kategorie downstream.

Cat. No.	Scope 3 emission Category name	Authors' proposed CF calculation algorithm statement for a typical MWWTP with justification	First year CF calculation method proposed as 'quick-win' scenario	EF data base potential sources *commercial
		Downstream indirect emissions		
9	Downstream transportation services	Irrelevant – Category 9 may not appear at all in the WWTP's CF structure due to rare situation when the WWTP releases final products to the market	When WWTP releases final products (e.g., struvite granulates or fertilizers, sand recovered from the grit), the transportation services (collection of goods) should be included as in Category 4	EcoInvent* Climatiq DEFRA
10	Processing of sold products	Irrelevant – Category 11 may not appear at all in the WWTP's CF structure due to rare situation when the WWTP releases intermediate products to the market	When WWTP releases intermediate products requiring further processing, emissions should be calculated via Equation 4	EcoInvent* Climatiq DEFRA Scientific papers
11	Use of sold products	Irrelevant – Category 10 may not appear at all in the WWTP's CF structure due to rare situation when the WWTP releases final products to the market	Category 11 emissions should be calculated only when Category 12 is included in the CF; usually emissions included in this category result from fertilizers usage	EcoInvent* Climatiq DEFRA Scientific papers
12	End-of-Life (EoL) of sold products (intermediate product, if relevant)	Irrelevant – Category 12 may not appear at all in the WWTP's CF structure due the fact that all possible products do not possess EoL stage; there can be a rare situation of biopolymers and bioplastic released by WWTP to the market which requires Category 12 calculation	-	-
13	Downstream leased assets	Irrelevant – in comparison to other emission types, Category 13 may not play a relevant contribution to the WWTP's CF structure due to rare situation when the WWTP rents/leases assets (e.g., offices, warehouses) from external entities	-	-
14	Franchises	Irrelevant – franchise mechanism rarely present in WWTP area	-	-
15	Investments	Irrelevant – WWTP rarely plays a Financial Market Participant (FMP) role	-	-

3.4. DOUBLE COUNTING ELIMINATION

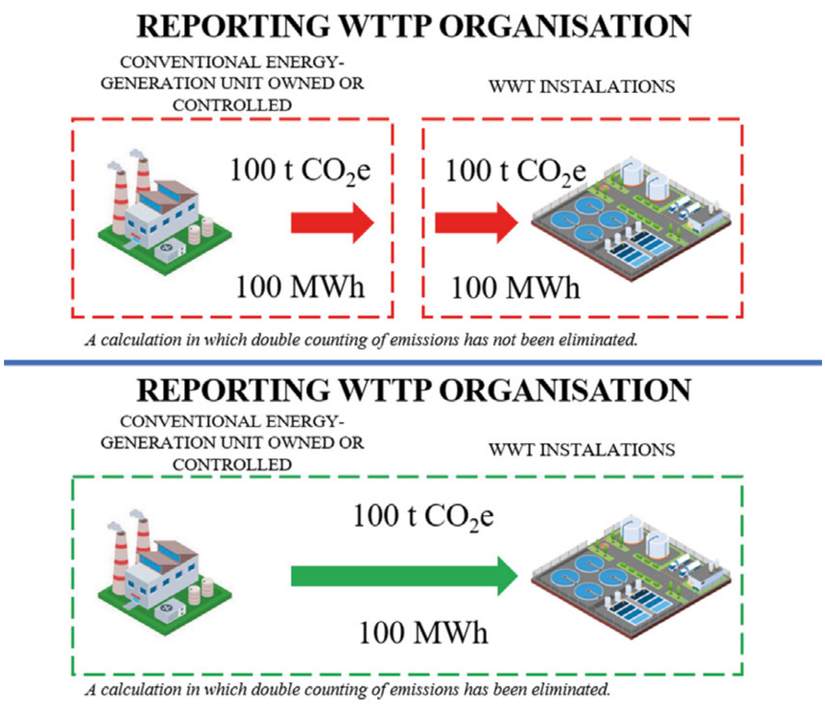
When performing carbon footprint calculations, it is crucial to exercise prudence in order to prevent the potential occurrence of duplicating greenhouse gas emissions. There are two distinct occurrences of double counting that can be discerned: (1) those that emerge as a result of organisational structure, and (2) those that manifest due to errors in operational structure.

One instance of double counting arises when an internally generated good or energy flow is erroneously considered as an external input (Scheme 2).

Second type of double counting mistakes occurs as result or wrong type or Scope emission assignment within the CF structure given by GHG Protocol guidelines. Common mistakes are summarized by the authors in the Table 4.

4. CARBON FOOTPRINT ALGORITHM OF MWWTP. SCOPES 2 AND 3 – STEP BY STEP INSTRUCTION

The methodology employed in this study to compute the carbon footprint of MWWTP is provided as a two-part article. It comprises seven distinct stages that align with the rules established by the GHG Protocol and fulfil the criteria outlined in the CSRD. The subsequent procedures are as follows:



Scheme 2. Organisational cause double counting case – CF calculation without its elimination (upper part) and with its elimination (bottom part).
Schemat 2. Przypadek podwójnego liczenia przyczyny organizacyjnej – obliczenie CF bez jej eliminacji (górna część) i z jej eliminacją (dolna część).

Table 4. Summary of common operational cause mistakes committed during WWTP's CF calculation.

Tabela 4. Podsumowanie typowych błędów operacyjnych popełnianych podczas obliczania CF dla OŚ.

Sc. No.	Scope and or Category involved in the scenario	Scenario description	Justification
1	Scope 1 vs. Scope 2	Emissions linked to energy produced in the facilities owned or controlled by the organisation calculated both in Scope 1 (stationery fuels combustion) and Scope 2 (energy purchase)	Scope 1 – direct GHG emissions from energy-production units Scope 2 – indirect GHG emissions from generation of externally purchased energy streams (CF calculation done via both LB and MB method)
2	Scope 1 vs. Scope 3, Category 4 and 9	Emissions linked to transportation of purchased goods and distribution of the products done by owned or controlled vehicles calculated both on the basis of fuel consumption (Scope 1) and tonne-kilometres (Scope 3, Category 4 or 9)	Scope 1 – direct GHG emissions from fuels combustion in vehicles owned or controlled by the organisation Scope 3 – indirect GHG emissions from transportation services acquired externally
3	Scope 1 vs. Scope 3, Category 5	Emissions linked to waste transportation done by owned or controlled vehicles calculated both on the basis of fuel consumption (Scope 1) and tonne-kilometres (Scope 3, Category 5)	Scope 1 – direct GHG emissions from fuels combustion in vehicles owned or controlled by the organisation Scope 5 – indirect GHG emissions from transportation and final waste disposal
4	Scope 1 vs. Scope 3, Category 6	Emissions linked to business travel done by owned or controlled vehicles calculated both on the basis of fuel consumption (Scope 1) and tonne-kilometres (Scope 3, Category 6)	Scope 1 – direct GHG emissions from fuels combustion in vehicles owned or controlled by the organisation Scope 6 – indirect GHG emissions from transportation services acquired externally (taxi, uber)
5	Scope 3, Category 4 vs. Scope 3, Category 3	Emissions linked to the transportation of fuels (e.g., coal, burning oil) via external services calculated in Scope 3, Category 4 instead of Scope 3, Category 3	Scope 3, Category 3 – indirect GHG emissions related to the lifecycle of fuels, including its transportation services stage Scope 3, Category 4 – indirect GHG emissions related to transportation services of purchased goods

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.

This part two article presents rules pertaining to Scope 2 and 3, with a focus on steps 1, 3, 4, 5, 6, and 7. In order to improve the comprehensibility of the suggested computational methodology for CF, we have incorporated seven additional decision trees (referred algorithms) accompanied by appropriate guidelines. This article provides a comprehensive analysis of greenhouse gas calculation methodologies employed in wastewater treatment plants. Specifically, it references specific chapters and equations from various guidelines, including:

- 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.

The implementation of Algorithm 1 procedure, as mandated by the GHG Protocol, is an annual requirement. Ensuring the completion of the consolidation process is of utmost importance, particularly in instances involving the acquisition of new facilities. It is advisable to initiate the collection of specific data for Scope 3 promptly following the acquisition of screening outcomes, as the data collection procedure is notably laborious and time intensive.

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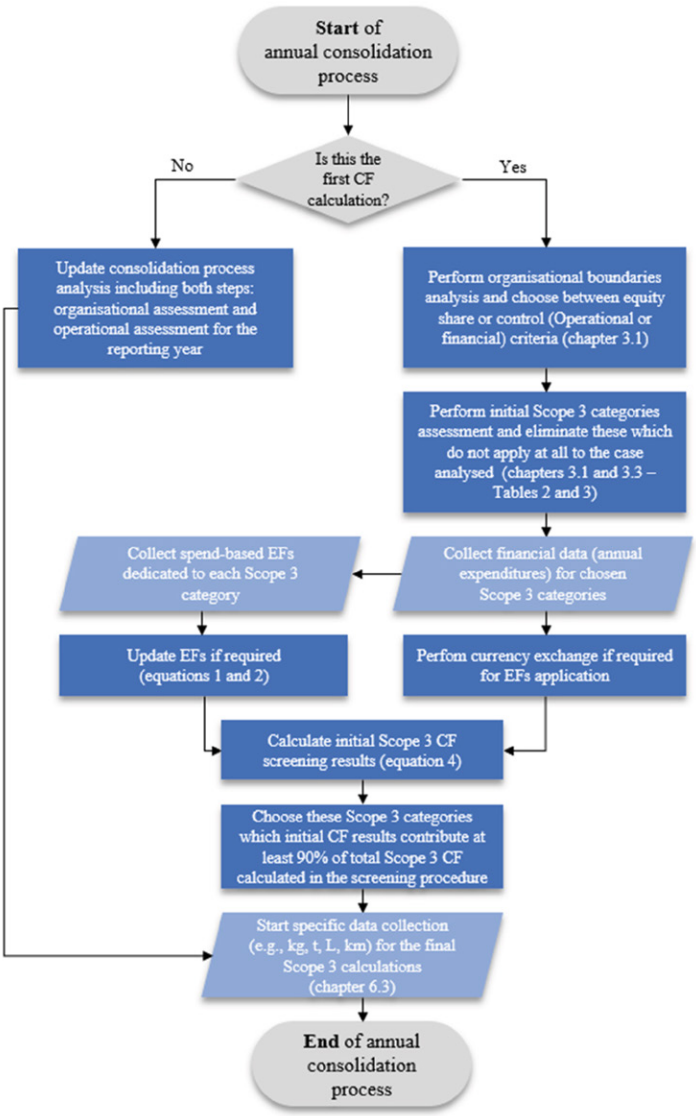
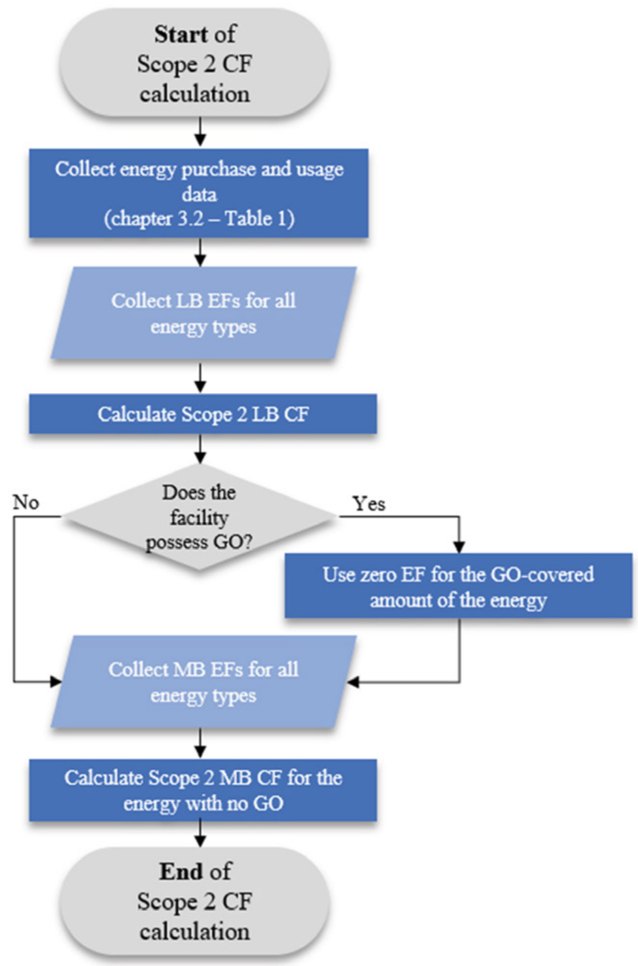


Algorithm 1. Decision tree and instruction for consolidation process procedure – WWTP case.

Algorytm 1. Drzewo decyzyjne i instrukcja postępowania w procesie konsolidacji – dla OŚ.



Algorithm 2. Instruction for WWTP Scope 2 (location-based and market-based methods) carbon footprint calculation.
Algorytm 2. Instrukcja obliczania śladu węglowego OŚ w Zakresie 2 (metody location – i market-based).

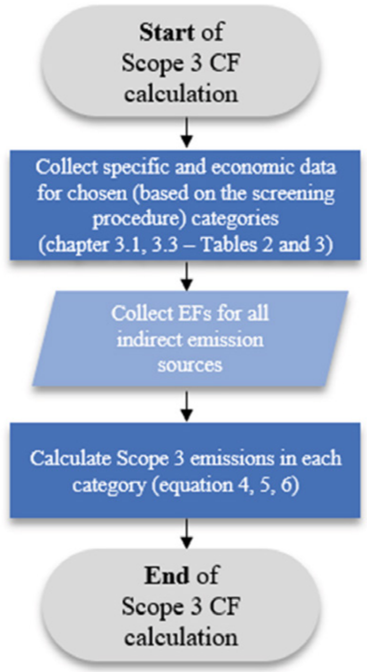
The instructions for calculating Scope 2 carbon footprint are provided in Algorithm 2, which includes both the location-based and market-based methods. This phase necessitates the preparation of the wastewater treatment plant's energy framework, encompassing both quantitative and qualitative data. In the event that the organisation procured GOs or energy through a specialised green tariff during the reporting year, it is necessary to include this information (in addition to the certificates themselves) in order to apply a zero emission factor for the corresponding amount of energy covered in the MB method.

The data gathered during this phase is additionally utilised for the calculation of Scope 3 Category 3 emissions, specifically for energy-related indirect emissions, such as WTT and T&D losses.

The seventh algorithm is a streamlined set of instructions for conducting Scope 3 calculations, as outlined in chapter 6.4 of this paper.

When CF calculation procedure is done and the results are obtained in each of the three Scopes, it is crucial to present the Cf structure in a proper way required by GHG Protocol guidelines. Example of the CF results submission is presented in the Table 5.

Given the intricate nature of the data collection process involved in CF calculation, it is advisable to generate an internal report within the organisation subsequent to the finalisation of CF calculation. This report should encompass data aggregation conclusions, with the aim of identifying any existing data gaps and proposing potential solutions for future data acquisition. Additionally, the report should address issues pertaining to low data quality and document pertinent information regarding the team responsible for the data collection procedures.



Algorithm 3. Instruction for WWTP Scope 3 carbon footprint calculation.
Algorytm 3. Instrukcja obliczania śladu węglowego OŚ w Zakresie 3.

Table 5. An example of the final WWTP's CF results.
Tabela 5. Przykład prezentacji finalnych wyników CF dla OŚ.

Scope	Total GHG emission [t CO_2e]	CO_2 emission [t CO_2e]	CH_4 emission [t CO_2e]	N_2O emission [t CO_2e]
Scope 1				
Scope 2 LB				
Scope 2 MB				
Scope 3 – TOTAL (MB)				
Category 1				
Category…				
Category n				
TOTAL CF				

The calculation of carbon footprint is deemed comprehensive only when it is accompanied by an analysis of the carbon footprint structure, in which the planning procedure for greenhouse gas reduction is outlined or prepared as a strategy for limiting emissions.

5. 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. The selected methods for validating uncertainty are outlined in Table 6, accompanied by the authors' rationale for assessing the level of difficulty in implementing these methods. A three-tiered rating system is provided, consisting of low, medium, and high levels. Authors recommend providing at least uncertainty qualitative discussion with the usage of one method given below to finalize CF calculation.

Uncertainty in the context of WWTPs 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 assessment of data quality in WWT processes can be straightforward when it comes to qualitative discussions. However, evaluating EF may present certain challenges. Hence, the authors put forth a methodology for ascertaining the level of uncertainty associated with emission factors, denoted as Scheme 5 presented in the first part of the article.

6. 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, 2, and 3 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 consolidation process plays a crucial role in obtaining accurate CF results by establishing calculation boundaries. Errors made during this stage can significantly magnify the values of GHG emissions.

The levels of energy consumption and the energy structure of a WWTP, specifically the proportion of renewable energy sources in the mix, can pose a significant impact on the facility's CF results. The proposed calculation algorithm allows for the assessment of the influence of stakeholders' decisions in this area on the indirect emissions levels in Scope 2, through a comparison of the LB and MB methods.

In order to conduct a comprehensive comparison of CF results, 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.

The emissions associated with the value chain of rapidly expanding WWTP utilities are likely to be higher due to the dynamic development of infrastructure. ■

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Table 6. Summary of chosen uncertainty assessment methods.

Tabela 6. Podsumowanie wybranych metod oceny niepewności.

Uncertainty assessment method	Short description	Difficulty of implementation
Qualitative discussion	• Sources of uncertainty are listed and discussed. • The relative value of the imprecision may be given if known.	Low
Expert evaluation of data quality	• The assessment is based on expert judgement; it may be combined with a qualitative discussion. • This method is also present in IPCC (2019) methodology where uncertainty range given by the expert judgment by lead methodology authors are given	Low
Data Attribute Rating System – DARS	• The numerical values representing the relative uncertainty are assigned using objective methods.	Medium
Expert estimation method	• Experts estimate the parameters of the emission distribution (i.e., mean, standard deviation and type of distribution). • Simple analytical and graphical techniques are then used to estimate confidence limits based on the assumed distribution data. • Delphi or Pedigree Matrix methods are used.	Medium
Error propagation method	• The means and standard deviations for the emission design parameters are estimated using expert judgement, measurements or other methods. • Standard error propagation statistical techniques are used, typically based on Taylor series expansions, which are then used to estimate the compound uncertainty.	Medium
Direct simulation method	• The Monte Carlo method and other numerical methods are used to directly estimate confidence intervals of individual emission components. In the Monte Carlo method, expert judgment is used to estimate the values of the distribution parameters before the Monte Carlo simulation is performed. Other methods do not require such assumptions.	High
Direct or indirect measurement (validation) method	• Direct or indirect measurements of the Organisation's emissions are made; these are then used for direct emission calculations and uncertainty analysis. • These methods include direct measurements such as stack sampling, Fourier-Transform Infrared Spectroscopy (FTIR) analyses and indirect measurements such as tracer tests. • These methods also provide data for validation of emission estimates and emission uncertainties.	High