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Proposals for regulatory methods to reduce nitrous oxide emissions from treatment facilities

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1. Summary and Recommendations

One of the goals set in the “Climate Plan for a Green Waste Sector and Circular Economy” is to reduce nitrous oxide emissions from treatment plants with a capacity of 30,000 PE or more. Analysis work has therefore been initiated to determine how such regulation could be designed and implemented so as to achieve a 50 per cent reduction in nitrous oxide emissions from Danish treatment plants.

This report examines various *types* of limit values (regulatory methods) that could all be used to regulate nitrous oxide emissions from treatment facilities (Section 3). These different limit values are evaluated against several criteria that jointly highlight incentive structures, environmental impact and socioeconomic considerations. On the basis of this assessment, it is recommended to adopt a relative limit value. A “relative limit value” is taken to mean a threshold for nitrous oxide in relation to the nitrogen content at the plant’s intake. In addition, it is recommended that the limit value be tailored to the specific characteristics of each plant – and at least to the plant’s most recent discharge baseline.

The proposed relative limit value is not intended to be static, but should be a dynamic tool where annual evaluations and continuous revisions are *necessary* to ensure the limit value remains relevant and effective.

In order to enforce a relative limit value, precise measurements of the plant’s nitrous oxide emissions are essential. This requires both valid, accurate measurement technology and a reliable method for calculating total nitrous oxide emissions from the plant. An assessment of various available measurement technologies has therefore been conducted (Section 4). It is recommended to implement process-specific online measurements that provide the necessary insights into the treatment plant’s emission factors, as well as the dynamics of nitrous oxide production and discharge from these processes. Moreover, process-specific online measurements can be used as a management tool with a view to reducing nitrous oxide emissions from treatment plants.

To ensure sufficient quality of the nitrous oxide measurements and for regulatory purposes, it is recommended to create a list of approved measurement technologies for emissions (a positive list). This will ensure that the measurements are accurate, reliable and in accordance with regulatory requirements.

Furthermore, it is suggested that an accredited method be developed long-term so as to allow companies to become accredited under DANAK in the future. Until this has been established, regulation must rely on a *valid* and *uniform* method for measuring and calculating nitrous oxide emissions from Danish treatment plants (proposals for this are presented in Section 6).

It is essential to reach consensus regarding the historical nitrous oxide emissions from treatment plants (baseline). A literature review has been conducted as part of this report, and this clearly shows that numerous measurements and calculations of nitrous oxide emissions have been performed both in Denmark and internationally

(Section 5). These measurements were conducted with a view to acquiring new knowledge – not to set a baseline. As a result, the measurement methods used have been diverse and typically applied during short periods or campaigns. Precisely due to the absence of certified measurement technologies (a positive list) and standardised measurement methods and emissions calculations, the available data, as analysed in the literature review, cannot be used as baseline data since they are not considered to be uniform and comparable.

This report and the economic analyses it contains (presented in section 7) are thus based on two potential baselines:

- 0.84% N_2O-N/TN-in is used given that this baseline is founded on in the best-validated Danish measurement campaigns to date.
- 1.6% N_2O-N/TN-in is used given that this is the IPCC's key figure for nitrous oxide emissions. It is the baseline utilised internationally for calculating such emissions from treatment plants.

Implementing regulation of nitrous oxide emissions from Danish treatment plants requires a *valid* and *uniform* method so as to ensure precise measurement, calculation and extrapolation of these emissions. This report therefore contains a *guideline* for utilities and industries that can be applied universally, irrespective of plant size and setup (Section 6).

Introducing regulation through a *differentiated measurement method* at treatment plants is recommended. This would allow for swift implementation, enhanced understanding and an expanded data basis for ensuring accurate and valid baseline emissions, with the potential for revising the limit values as more information becomes available (Section 6). To this end, a phase-in period is suggested, during which all treatment plants involved should measure nitrous oxide emissions using a straightforward measurement approach with limited data points (*the BASIS method*). If a plant's emissions factor exceeds the set limit after this initial screening phase, it is recommended that the plant expand the measurement programme to include additional data points (*EXTENDED method*), as this would ensure more comprehensive documentation of emissions and serve as a means to reduce emissions.

Besides the suggestion for a *differentiated measurement method*, this report presents various emission reduction strategies, including operational improvements (Option A) and capacity enhancements (Option B) (Section 6). These form the basis for evaluating the economic implications – including shadow pricing – of deploying measurement methods and limits values (section 7).

Introducing a limit value for nitrous oxide emissions from Danish treatment plants with a certified capacity of 30,000 PE or more will involve a variety of costs which should be balanced against the potential benefits (see Section 7). The principal benefit of establishing a limit value is likewise its core purpose: To reduce the climate impact of the treatment plants from nitrous oxide emissions. Costs for compliance with the limit value consist not only of costs for measuring and monitoring nitrous oxide emissions at the treatment plants, but also of the expenses associated with implementing measures to reduce nitrous oxide emissions. These costs can be evaluated against the anticipated reduction in climate impact, and a reduction cost for $CO_{2,}$ – also known as a shadow price – can be calculated.

There are considerable uncertainties linked to the calculations of these shadow prices. For instance, limited knowledge is available about the current baseline level of nitrous oxide emissions from treatment plants, which influences the expected achievable reduction. Uncertainty also exists with regard to the costs of the possible reduction initiatives as these are defined by specific conditions at the individual treatment plants.

Given these uncertainties, the shadow prices are calculated and presented as a range – from “the lowest possible shadow price expected ” to “the highest possible shadow price expected ”– and results should thus be interpreted as indicators of size rather than precise figures.

Based on the goal of achieving a 50 per cent reduction in nitrous oxide emissions from Danish treatment plants, the necessary limit values are established on the assumption that all plants start with the same emission factor (baseline). If all treatment plants are assumed to have an emission factor of 0.84% N_2O-N/TN in, they need to lower it to 0.42% N_2O-N/TN in, and likewise for a starting point where the emission factor is 1.60% N_2O-N/TN in. By introducing a single limit value applicable to all treatment plants, those plants that are already below the limit need not implement reduction measures, as plants with the highest emission factors must achieve reductions in excess of 50%.

Introducing a “BASIS method” for measuring nitrous oxide emissions at treatment plants implies that 89 plants with an approved capacity of at least 30,000 PE will initially be required to install a single sensor per plant. The estimated investment costs for installing a single sensor per facility range between DKK 7.2 million and DKK 13.8 million for the 89 plants, depending on whether liquid or gas sensors are used. The calculated average annual costs are similarly DKK 1.7–2.3 million for off-gas sensors and liquid-phase sensors, respectively. In the same way, for treatment plants with an approved capacity of 10,000 to 29,999 PE, the estimated investment costs are between DKK 6.6 million and DKK 12.6 million, with the calculated average annual costs being DKK 1.5–2.1 million per year for this group of facilities.

If the “EXPANDED method” were to be adopted rather than the “BASE method”, the plants would be required to install one measuring point (one sensor) per aerated tank, which corresponds to approximately one sensor per 40,000 PE of approved capacity. This would increase the estimated investment to DKK 17.0–45.8 million for the 89 plants, depending on whether liquid or gas sensors are used. The calculated average annual costs would correspondingly increase to DKK 5.5–7.0 million per year for off-gas sensors and liquid-phase sensors, respectively.

Regarding measures to reduce nitrous oxide emissions, generally speaking there are two options: “Option A”, which involves operational optimisation (management), and “Option B”, which involves measures to expand capacity. If it is feasible to achieve the entire desired 50 per cent reduction using measures under “Option A”, and if the costs of these reduction measures are at the lower end of the assessed costs, the total estimated investment is around DKK 40 million. For the 84 treatment plants with an approved capacity of 10–29,999 PE, the estimated investment is correspondingly DKK 21 million.

However, investments could be up to 100 times higher if the reduction measures under “Option B” and the upper end of the estimated investment come into play: Total investments would then amount to 4.7 billion DKK if a 50 per cent reduction is to be achieved through the most capital-intensive capacity expansions. The additional investment for the 84 treatment plants with an approved capacity of 10,000–29,999 PE amounts to approximately DKK 1.3 billion.

The calculated average costs are estimated to lie between DKK 6 and 423 million per year for the 89 treatment plants with an approved capacity exceeding 30,000 PE. There is potentially a difference by a factor of more than 70 in the average annual costs, depending on whether the lowest estimated costs or the highest expected ones are achieved. For the 84 treatment plants with an approved capacity of 10,000–29,999 PE, the interval is DKK 3–114 million per year.

The variation in estimated costs and the uncertainty about the scale of reductions in nitrous oxide emissions from the treatment plants have the following implications for the calculated shadow prices:

- With regard to the reduction of nitrous oxide emissions, the greatest reduction in total volume would be achieved assuming the highest emissions factor.
- The lowest shadow price is achieved when the costs for measurements and reduction measures are minimal, while the reduction in nitrous oxide emissions is maximised.
- The highest shadow price is achieved when the costs for measurements and reduction measures are the highest possible, while the reduction in nitrous oxide emissions is minimised.

The range of calculated shadow prices for CO_2-e reduction through nitrous oxide reductions stretches from DKK 49 per tonne CO_2-e to DKK 10,217 per tonne CO_2-e, which corresponds to a factor of more than 200, and the following observations are made:

- The lowest shadow prices are typically calculated for the treatment plants with the largest capacity. This results from the lower marginal costs associated with both measurements and mitigation efforts, alongside the higher relative nitrogen loading (N) seen in several of the treatment facilities with larger approved capacities.
- Reducing nitrous oxide emissions from Danish treatment plants through straightforward measurements and operational optimisation is typically a cost-effective method for most plant sizes to reduce the climate impact, especially when comparing the calculated shadow prices with other non-quota sector measures.
- Reducing emissions of nitrous oxide from Danish treatment plants via capacity extensions is a relatively costly approach to reducing climate impact.

Similarly, the overall tariff impact on the wastewater sector is estimated to range between DKK 0.04 and 1.95 DKK/m^3 of debited water.

Taken together, the conclusions and recommendations of the report could provide grounds for the Ministry of the Environment and the Danish Environmental Protection Agency to introduce regulations on nitrous oxide emissions from Danish treatment plants in 2025, employing a relative limit value based on existing baseline emissions from these facilities. Future regulation should be anchored in a *valid* and *uniform* approach to measurement using existing measurement technology, which would enhance collective understanding of the baseline emissions from treatment plants prior to determining the *final* target group for regulation and the level of the *final* limit value.

2. Background

In connection with wastewater purification at Danish sewage treatment plants, varying quantities of nitrous oxide are released into the atmosphere. This is problematic, given that nitrous oxide is a potent greenhouse gas with a long atmospheric lifespan, and that emissions of same contribute significantly to global warming.

To reduce the contribution of treatment plants to global warming, a political majority has decided to introduce a limit value for the volume of nitrous oxide these plants emit into the atmosphere. The “Climate Plan for a Green Waste Sector and Circular Economy” outlines this objective:

Limit values are to be established for emissions of nitrous oxide from treatment plants that manage wastewater corresponding to the emissions of 30,000 people (PE) [or more]. As a result, the limit values encompass approximately 65 per cent of wastewater volume and 75 per cent of nitrous oxide emissions from the process. Based on experiences, discussions will be held with the parties to the agreement by 2025 at the latest to determine whether the emission limit should be reduced from 30,000 PE (Person Equivalents) to a lower level.

Between 2018 and 2020, an MUDP pool has been in place for measuring and quantifying the nitrous oxide emissions from Danish sewage treatment plants, which has significantly improved the data foundation for ongoing efforts to implement a limit value for these emissions.

The objective of introducing a limit value is achieve a 50 per cent reduction in nitrous oxide emissions from Danish sewage treatment facilities.

This report puts forward proposals for regulatory methods to decrease nitrous oxide emissions from Danish treatment plants. The report examines how a limit value for nitrous oxide emissions at treatment plants can be established and structured (Section 3), how these emissions can be measured effectively (Section 4), and the historical levels of these emissions (Section 5).

To ensure nitrous oxide emissions from treatment plants are measured and calculated in a *valid* and uniform manner, guidelines for using proposed measurement methods have also been presented (Section 6). Introducing a limit value for nitrous oxide emissions is certain to generate costs relating to the measurement of these emissions, as well as expenses for implementing emission-reducing measures at treatment plants in order to ensure compliance with the set limit (Section 7) and thereby reduce the total nitrous oxide emissions from Danish treatment plants.

3. Regulating nitrous oxide emissions through emission limit values

3.1 Potential regulatory methods

There are fundamentally two types of environmental regulation: administrative instruments and financial instruments.

Administrative instruments, also known as legal instruments, include requirements for the use of specific technologies to meet emission limit values (e.g. BAT – Best Available Techniques[1]). Provisions may also exist regarding the location of noisy or odorous activities (e.g. requirements pertaining to the location of livestock facilities[2]), or – as in environmental approvals – conditions for ensuring compliance with limit values for air pollutants emitted from company chimneys and exhausts[3].

Financial management tools can include taxes, quotas and subsidies, etc. One example of this is the CO_2 quota system (the EU CO_2 quota scheme[4]), where CO_2 allowances can be traded between enterprises. Another example is taxes levied on emissions from polluting activities (such as the tax on industrial wastewater[5]).

Generally speaking, the socioeconomic costs linked to financial management tools are lower than those associated with administrative management tools, as the reduction initiatives are usually come to apply to those enterprises that can implement them most economically. For a comprehensive overview of management tools, including financial ones, refer to the article "Choosing Management Instruments in Environmental and Nature Policy" by Jørgen Birk Mortensen, former advisor to the Danish Economic Councils[6].

Compared to financial management tools, administrative management tools are better suited to complex regulations, such as the implementation of various limit values over different time intervals, or to emissions of acutely hazardous substances, where specific concentrations must never be exceeded to prevent serious harm to people, animals or the broader environment. One example of this is the emission limit values for waste gas and diffuse emissions from organic solvents[7].

The responsibility for financial management tools falls under the Ministry of Taxation (and, occasionally, the Ministry of Climate, Energy and Utilities), whereas the Ministry

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[1] The Danish Environmental Protection Agency's Guide to Environmental Approvals, Section 5.8: More about BAT.

[2] The Danish Environmental Protection Agency's Guidelines for Livestock and Requirements regarding the Location of Facilities on Livestock Farms in Relation to Surroundings.

[3] The Danish Environmental Protection Agency, Air Pollution from Enterprises.

[4] Danish Energy Agency, The EU CO_2 Quota Scheme.

[5] Danish Tax Agency, Tax Rates for Wastewater.

[6] The Danish Economic Councils (DØRS), Choosing Management Instruments in Environmental and Nature Policy.

[7] Executive Order No. 1491 of 07/12/2015, Regulation Concerning Facilities and Activities That Use Organic Solvents.

for the Environment oversees administrative management tools in the context of the environment.

This report solely evaluates the feasibility of using administrative management tools, with a particular focus on limit values for regulating emissions of nitrous oxide from Danish treatment facilities.

3.2 Design and Establishment of Emission Limit Values

Limit values can be designed in a variety of ways. They are usually set for a specific timeframe – for example, as the permitted quantity of a substance in flue gas that may be released into the atmosphere during that period. One example of this is the emission limit values for large combustion plants, as detailed in the "Regulation Concerning the Restriction of Certain Air Polluting Emissions from Large Combustion Plants", where "validated mean values per hour and day are derived from the accurately measured mean hourly values, after deducting the confidence interval specified in Section 10" [8]. In theory, these values can be established for a year, for example, the total tonnes of nitrous oxide emitted annually.

Finally, these values can be expressed as an absolute quantity (e.g. number of kg) that may be emitted, or as a relative value calculated as a percentage of an input factor, such as nitrous oxide emissions relative to the nitrogen content in inflow wastewater at a treatment plant.

The most appropriate design of the emission limit value depends on the emission(s) being targeted for reduction. That said, the limit can be designed so as to differentiate within the target group that is subject to the limit. For instance, while the same threshold might apply universally, it is often adjusted according to the type or size of different enterprises and the like. This approach is utilised in the "Regulation Concerning the Restriction of Certain Air Pollutant Emissions from Large Combustion Plants", which differentiates between various types of gas-fired plants, each of which is subjected to different emission limits for substances such as NO_x and CO[9].

In theory, individual limit values can also be established, an approach that may be relevant if the framework conditions to which enterprises are subject vary significantly.

3.3 Enforcing Limit Values

An emission limit value under the Environmental Protection Act is implemented through environmental approval and enforced via the options stipulated in said Act. This means that different measures are applied to different types of breach, depending on their frequency or severity. For example, recommendations, orders and warnings can be issued. For further details, refer to "Guidelines Concerning Enforcement of the Environmental Protection Act"[10]. These guidelines include examples such as when a supervisory authority finds that a limit value has been exceeded, it is considered a "verifying decision" and an injunction may be issued to adhere more strictly to

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[8] Executive Order No. 1940 of 04/10/2021, Regulation Concerning the Restriction of Certain Air Pollutant Emissions from Large Combustion Plants. The limit value may also be established relative to production – for instance, as the aggregate limit values for emissions of solvents during the coating of cars, trucks, etc. – as outlined in the "Regulation Concerning Installations and Activities That Involve the Use of Organic Solvents". Here, the limit stated is a maximum limit that must not be exceeded.

[9] Executive Order No. 1940 of 04/10/2021, Regulation Concerning the Restriction of Certain Air Pollutant Emissions from Large Combustion Plants

[10] Ministry of the Environment, "Guidelines Concerning Enforcement of the Environmental Protection Act".

the limit value. If the injunction is not complied with, this could result in a police report and under aggravated circumstances, the authority could prohibit further operation or demand the removal of the enterprise in question. Prohibition and removal are both noted in the guidelines as “far-reaching enforcement measures”.

3.4 Emission limit values in relation to nitrous oxide

While nitrous oxide emissions from sewage treatment plants do not have an immediate toxicological effect on people, flora and fauna, the emissions of same vary depending on factors such as the supply of nitrogen to the treatment plant. These emissions occur in several locations within sewage plants – often in association with aeration tanks, for instance. It is already possible to regulate emissions of nitrous oxide into the atmosphere through “B-values”, as described in the B-value Guidelines issued by the Environmental Protection Agency[11]. However, the aim of these guidelines is to regulate air quality rather than reduce greenhouse gas emissions. The B-value Guidelines are therefore not relevant in this context.

Nitrous oxide emissions from treatment plants are problematic, as nitrous oxide is a potent greenhouse gas – approximately 298 times more powerful than CO_2. The reduction of nitrous oxide emissions from treatment plants would thus make a significant contribution to achieving the currently applicable national climate targets. Nitrous oxide is thus distinct from emissions typically regulated by limit values, which are generally set because the emissions themselves are harmful either to people or to the local environment into which they are released.

Unlike other emissions, nitrous oxide and similar greenhouse gases have the same harmful effect irrespective of where on the planet they are released. The focus should therefore be on reducing the total amount of greenhouse gases. This being the case it is, in principle, not important how the concentration of nitrous oxide is distributed over a day or a year.

Since the cost associated with the damage remains unchanged regardless of the emission location, making nitrous oxide quotas tradable has the potential to lower socioeconomic costs. Enterprises that succeed in reducing emissions at the lowest cost would thus be able to sell their residual quotas to those operating with higher reduction costs. This is precisely the mechanism utilised in the CO_2 quota system. In this report, however, we have chosen not to explore tradable quotas in more depth because this type of regulation is not otherwise applied under the Environmental Protection Act.

3.5 Limit values for emissions of nitrous oxide at treatment facilities

Based on the information presented above, a series of limit values considered relevant have been established, and these have therefore been analysed in detail with a view to assessing their suitability for regulating emissions of nitrous oxide from treatment facilities. These limit values present a broad scope of solutions and the assessments of same may therefore underpin the final choice of one or more limit values.

In the following sections, an “absolute limit value” is taken to mean the total volume of nitrous oxide discharged from a treatment facility, assessed over a given period such as a year. Similarly, a “relative limit value” is taken to mean the volume of nitrous oxide emitted relative to the nitrogen content in the wastewater that enters the

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[11] Guidelines on B-values. Guidelines No. 20. August 2016. The Danish Environmental Protection Agency.

facility, as this is typically how the emission factor for nitrous oxide emissions from treatment plants is determined. The relative limit value takes into account that treatment plants operate under differing conditions on account of differences in the nitrogen content in the wastewater. This is a critical factor with regard to nitrous oxide emissions and thus affects the capabilities of treatment plants to mitigate these emissions.

For each of the two types of limits – absolute and relative – a detailed analysis is conducted on four specific configurations of these limit values:

- Uniform limit value for all treatment plants: All treatment plants are required to adhere to the same emission limit value for nitrous oxide.
- Differentiated limit value depending on the size/capacity of the treatment plant: Treatment plants are categorised by size, capacity (expressed in PE – Person Equivalents), or by type of plant.
- Limit value based on existing discharge at the treatment plant (baseline): The emission limit value is set for each individual treatment plant, taking into consideration historical nitrous oxide emissions presented as baseline emissions.
- Individualised limit value determined by the specific conditions at each individual treatment plant: An individual limit value is established for each treatment plant. This involves taking into account factors such as nitrogen content in the inflow water, plant type and processes, previously implemented measures to reduce nitrous oxide emissions, and (the current) potential for further reductions in emissions.

There are benefits and drawbacks to each limit value configuration, and these will be revealed through evaluations based on a range of specific criteria established for this purpose.

3.6 Establishing criteria for assessing emission limit values

The criteria presented in the following sections are considered key when selecting the most appropriate limit value. The evaluations of the limit values in relation to the established criteria will clarify which limit values perform best and thereby contribute to the decision-making framework for selecting a specific limit value.

3.6.1 Validity and precision

What is the degree of **measurement uncertainty** when compliance with the emission limit value for nitrous oxide is to be documented through measurements? Are the available **measurement methods** and **measurement technologies** sufficiently valid and precise for performing these measurements, thus forming a basis for setting and enforcing the limit?

3.6.2 Incentives for reduction and ongoing improvements

Does the emission limit value provide **no, few, many or all** treatment plants with an incentive to reduce nitrous oxide emissions? Does the limit value sufficiently encourage treatment plants towards **continuous improvements**, as well as the development and introduction of better and cleaner technologies and practices?

3.6.3 Distribution effects

What are the distributional consequences of the limit value? Are some (types of) treatment plants affected more (or less) than others? Are **no, few, many or all** treatment plants affected?

3.6.4 Fairness

Is the emission limit value **unfair** or **fair**? For example, does it take into account the fact that some treatment plants have already acted to reduce nitrous oxide emissions, while others have not?

3.6.5 Implementation costs at treatment plants

How manageable is the limit value for treatment plants, and what is the approximate **cost level** for measuring nitrous oxide emissions and implementing reduction measures to comply with the limit?

3.6.6 Implementation by the authorities

How **easy** is it for the authorities to implement the emission limit value? For instance, is a large amount of administrative preparatory work required to implement the emission limit, along with annual administration?

3.6.7 Probability of achieving goals

How likely is it that treatment plants will meet the limit value? Does this apply to **no, few, many or all** treatment plants?

3.6.8 Socioeconomic considerations

What is the approximate **level of the socioeconomic shadow price** for reducing nitrous oxide emissions from treatment plants using the limit value in question? The assessment is based on evaluating the likelihood of goal achievement, combined with assessments of the costs for the treatment plants and the administrative demands on authorities.

3.6.9 Additional criteria

The following supplementary criteria have also been evaluated but omitted, either because there is no variation among the different types of limit values, or because they cannot be operationalised at this more generic level:

- Reduction potential: What is the assessed impact of the emission limit value?
- Scalability and export potential (e.g. system export of accredited measurements)?
- Efficiency: Is the threshold value robust under all conditions, including extreme scenarios? (Omitted, as the variation in the compliance of limit values with criteria is demonstrated through case studies instead).
- Legal certainty: Is the legal certainty adequate? (Omitted, as it depends to a significant extent on the authorities' implementation and enforcement of the regulation, and it is not inherently reliant on the type of limit value itself).

3.7 Evaluation of designs for emission limit values

The following table presents evaluations of different potential designs of limit values for emissions of nitrous oxide from treatment facilities. Please note that the text within the table has been condensed for clarity, and that more detailed explanations of the table content follow.

TABLE 3.1: Evaluations of potential designs for limit values for emissions of nitrous oxide from treatment facilities

	Absolute limit value				**Relative limit value**			
Criteria/Types of limit value	**Uniform for all treatment facilities**	**Dependent on factors such as capacity**	**Relative to the treatment facility's baseline emissions**	**Individually set for each treatment facility**	**Uniform for all treatment facilities**	**Dependent on factors such as capacity**	**Relative to the treatment facility's baseline emissions**	**Individually set for each treatment facility**
Validity and precision (1)	Same	Same	Same	Same	Same	Same	Same	Same
Incentives for reduction (2)	Few to many	Few to many	All	All	Few to many	Few to many	All	All
Distribution effects (3)	Few to many	Few to many	All	All	Few to many	Few to many	All	All
Fairness (4)	Unfair	Unfair	Unfair	Fair	Unfair	Unfair	Unfair	Fair
Implementation costs for treatment facilities, including reduction initiatives (5)	None to high	Low to high	Low to high	Lowest possible	None to high	Low to high	Low to high	Lowest possible
Implementation by the authorities (admin.) (6)	Less comprehensive	Comprehensive	Comprehensive	Highly comprehensive	Less comprehensive	Comprehensive	Comprehensive	Highly comprehensive
Probability of achieving goals (7)	Variable	Variable	Variable	High likelihood of achievement	Variable	Variable	Variable	High likelihood of achievement
Socioeconomic shadow price (8)	High	High	High	Lowest possible	High	High	High	Lowest possible

(re 1) Validity and precision:
Measurement technologies, methods and associated uncertainties are considered independent of the design of the limit values examined. Therefore, all types of limit values are rated as “Same”.

(re 2) Incentives for reduction:
For both absolute and relative limit values, incentives for treatment facilities to reduce nitrous oxide emissions are considered to vary depending on whether the limit is uniform or linked to factors such as capacity and size. Conversely, all treatment facilities have a reduction incentive if the limit value is set relative to the facility’s baseline emissions, or if it is set individually on the basis of baseline emissions such as nitrogen content in the inflow wastewater, plant type and processes, implemented reduction initiatives and (current) reduction potential for emissions of nitrous oxide. This naturally presupposes that a genuine reduction requirement is established with a limit value.

(re 3) Distribution effects:
A pattern similar to “Incentives for reduction” is observed with regard to distribution effects, where it is assessed that treatment facilities may perceive uniform limit values as more or less restrictive. This assessment applies equally to limit values that are dependent on the capacity and size of the treatment plant and other similar factors. When limit values are set relative to the baseline emissions of the treatment plant, or set individually on the basis of these emissions, the nitrogen content in the inflow wastewater and other specific conditions, it is anticipated that all treatment plants will perceive their limit values as restrictive.

(re 4) Fairness:
The initial assessment is that only an individually established limit value, whether absolute or relative, would generally be perceived as fair by treatment plants. This approach essentially considers factors such as the nitrogen content in the inflow wastewater, plant type and processes, previously implemented measures to reduce nitrous oxide emissions and the (current) potential for reducing these emissions at the treatment plant. It is likewise assessed that other forms of limit values (be they uniformly applied, dependent on factors such as capacity, or relative to the plant’s baseline emissions), would all be perceived as unfair to some degree.

(re 5) Implementation costs for treatment facilities, including reduction initiatives:
While an individually determined limit value, whether absolute or relative, makes it feasible to consider the treatment plant’s potential for reduction, possible reduction measures and the associated costs, it is estimated that this approach would generally result in the lowest costs for implementing and complying with the limit value. In contrast, other configurations of the limit value would carry a significant variation in the costs that each treatment plant is likely to encounter, which, overall, is anticipated to result in the highest expenses.

(re 6) Implementation by the authorities:
It is estimated that a uniform limit value for all treatment plants would allow the simplest form of implementation by the authorities, thereby placing the least administrative burden on them. However, the more individual the circumstances to be taken into account when setting the limit value, the more challenging the implementation and administration for the authorities is likely to become.

(re 7) Probability of achieving goals:
With regard to the likelihood of the individual treatment plants achieving their goals, it estimated that individually set limit values would generate the highest probability of their doing so. In scenarios where limit values are designed without taking individual conditions into consideration to the same extent, the number of treatment facilities complying with the limit is expected to vary.

(re 8) Socioeconomic shadow price:
Based on assessments of the likelihood of goal achievement, cost evaluations at treatment facilities and administrative demands on authorities, it is estimated that the socioeconomic shadow price for

reducing nitrous oxide emissions would be significantly high were a uniform limit to be applied across all treatment plants. It is assessed that shadow price would be elevated in particular by treatment plants with limited reduction capacities but correspondingly high reduction expenses. In this context, it is estimated that the limited administrative burden on the authorities of applying the same limit value to all treatment plants would not be sufficiently low to counterbalance the high reduction costs. It is assessed that the lowest shadow price could be achieved through individually set limit values, although this would make administration by the authorities more challenging and potentially more expensive.

The assessments of the two broad categories of limit values (absolute and relative) indicate no immediate differences, as shown in the table above. However, with respect to the criteria of “Fairness” and “Distributive effects” in particular, a relative limit value offers significant advantages over an absolute one: The major benefit of a relative limit value lies in its capacity to accommodate variations in a key factor outside the control of the treatment plants – specifically the nitrogen content in the inflow water. For this reason, a relative limit value will be analysed in the following cases, even though it could be argued that setting an absolute limit value in the form of the total emitted quantity would provide a more direct relationship between the limit value and its goal, which is to reduce absolute nitrous oxide emissions.

3.7.1 Cases

The following section presents two cases to illustrate the potential consequences of different designs of limit values for two treatment plants, each subject to different framework conditions:

Case 1

Small treatment plant, low nitrogen level at inflow, minor annual variation in nitrogen (= Low expected nitrous oxide emissions, showing slight variation over the year). Has not yet introduced reduction measures but is in a position to implement minor initiatives leading to limited reduction (= Limited potential for reduction).

Case 2

Large treatment plant, high nitrogen level at inflow, significant annual variation in nitrogen (= High expected nitrous oxide emissions with significant variation over the year). Has already implemented several reduction measures and has the opportunity to introduce more, although this would require substantial facility changes (= Greater potential for reduction).

Case 1. Relative limit value, small treatment plant

	Same relative limit value for all	Relative limit value based on plant size/capacity	Relative limit value based on plant's baseline	Individually determined relative limit value
Incentives for reduction	(Low expected nitrous oxide emissions with slight annual variation) MINIMAL	(Low expected nitrous oxide emissions with slight annual variation) MINIMAL–AVERAGE	(Low expected nitrous oxide emissions and limited reduction potential) SIGNIFICANT	(Low expected nitrous oxide emissions and limited reduction potential) SIGNIFICANT
Distribution effects	(Low expected nitrous oxide emissions) PROBABLY UNAFFECTED	(Low expected nitrous oxide emissions) PROBABLY UNAFFECTED	(Low expected nitrous oxide emissions with slight annual variation) MUST REDUCE	(Low expected nitrous oxide emissions with slight annual variation) MUST REDUCE
Implementation costs for treatment facilities, including reduction initiatives	(Low expected nitrous oxide emissions, thus probably no need for reduction measures) LIKELY LOW	(Low expected nitrous oxide emissions, thus probably no need for reduction measures) LIKELY LOW	(Low expected nitrous oxide emissions and limited reduction potential) LOW–AVERAGE	(Low expected nitrous oxide emissions and limited reduction potential) LOW
Probability of achieving goals	(Low expected nitrous oxide emissions, thus probably no need for reduction) HIGH	(Low expected nitrous oxide emissions, thus probably no need for reduction) HIGH	(Limited reduction potential) HIGH	(Limited reduction potential) HIGH
Socioeconomic shadow price	(No or very minor reductions and low costs at treatment facilities and in authority administration) HIGH	(No or very minor reductions and low costs at treatment facilities and in authority administration) HIGH	(Low expected nitrous oxide emissions and limited reduction potential) MEDIUM–HIGH	(Low expected nitrous oxide emissions and limited reduction potential) LOW

As the table shows, implementing the same relative limit value for all treatment plants would be unlikely to require a plant with low expected nitrous oxide emissions to reduce them. The same also applies to implementing a relative limit value based on size or capacity, which, alongside the costs of measuring emissions at the treatment plant, would lead to a high socioeconomic shadow cost for achieving no – or only limited – reduction in nitrous oxide emissions. The most cost-effective socioeconomic shadow price for reducing nitrous oxide emissions at the plant in this scenario is obtained when a limit is set individually. In this case, the plant would be required to reduce a smaller amount of nitrous oxide due to a lower reduction potential, although it is estimated that this could be achieved cost-effectively because the individual setting takes into account both the specific reduction potential and the conditions particular to the treatment facility.

Case 2. Relative limit value, large treatment plant

	Same relative limit value for all	Relative limit value based on plant size/capacity	Relative limit value based on plant's baseline	Individually determined relative limit value
Incentives for reduction	(High expected nitrous oxide emissions with significant annual variation) SIGNIFICANT	(High expected nitrous oxide emissions with significant annual variation) MEDIUM–SIGNIFICANT	(High expected nitrous oxide emissions and major reduction potential) SIGNIFICANT	(High expected nitrous oxide emissions and major reduction potential) SIGNIFICANT
Distribution effects	(High expected nitrous oxide emissions) MUST REDUCE	(High expected nitrous oxide emissions) MUST REDUCE	(High expected nitrous oxide emissions with significant annual variation) MUST REDUCE	(High expected nitrous oxide emissions with significant annual variation) MUST REDUCE
Implementation costs for treatment facilities, including reduction initiatives	(High expected nitrous oxide emissions, thus probably a need for reduction measures) PROBABLY HIGH	(High expected nitrous oxide emissions, thus probably a need for reduction measures) PROBABLY HIGH	(High expected nitrous oxide emissions and major reduction potential) PROBABLY HIGH	(High expected nitrous oxide emissions and major reduction potential) PROBABLY LOW–AVERAGE
Probability of achieving goals	(High expected nitrous oxide emissions, thus probably a need for reduction) LOW	(High expected nitrous oxide emissions, thus probably a need for reduction) LOW–AVERAGE	(Significant reduction potential, although several measures already implemented, further actions would demand extensive changes to the plant) LOW	(Considerable reduction potential, and additional reduction measures could be limited to avoid extensive facility modifications) HIGH
Socioeconomic shadow price	(High expected nitrous oxide emissions, thus reduction probably needed, along with further measures that entail extensive facility modifications) HIGH	(High expected nitrous oxide emissions, thus reduction probably needed, along with further measures that entail extensive facility modifications) HIGH	(High expected nitrous oxide emissions, thus reduction probably needed, along with further measures that entail extensive facility modifications) HIGH	(High expected nitrous oxide emissions and major reduction potential. Additional reduction measures could likely be limited to avoiding extensive changes at the facility) LOW

As the table shows, implementing the same relative limit value for all treatment plants would be likely to require a plant with high expected nitrous oxide emissions to reduce them. This similarly holds true for a relative limit set by size or capacity, which, combined with the potentially extensive changes to the plant – if further reduction potential is to be significantly realised – would result in a high socioeconomic shadow cost for cutting nitrous oxide emissions. In this case, too, it is assessed that the most cost-effective socioeconomic shadow price for reducing nitrous oxide emissions at the plant in this scenario would be obtained when a limit is set individually. Here, the treatment plant must reduce an individually specified amount of nitrous oxide on the basis of greater reduction potential. However, achieving the full potential is likely to necessitate extensive and costly modifications to the treatment facility. Nonetheless, it is estimated that when setting an individual limit value for the treatment plant, potential exists to achieve considerable cost-effectiveness by taking into account not only the plant's individual reduction potential, but also the specific conditions governing its operations.

3.8 Conclusions and Recommendations

The following conclusions and recommendations are presented on the basis of the analyses and evaluations above:

1) Given that nitrous oxide is a greenhouse gas and that emissions of it from Danish treatment plants are primarily damaging to the climate, it is considered inappropriate to establish a limit value based on maximum emission intensity per minute, hour or day. Conversely, it is deemed more suitable to establish a limit value as either an absolute annual volume of nitrous oxide emissions from the treatment plant, or as an annual quantity correlated with the volume of nitrogen in the wastewater entering the treatment plant.

2) The options for developing an absolute or a relative limit value for nitrous oxide emissions from treatment plants have been evaluated on the basis of a variety of criteria including incentive structure, likelihood of achieving (environmental) goals and socioeconomic factors. The conclusion drawn is that a significant benefit of a relative limit value is that it takes into account variations in a factor beyond the control of treatment facilities – specifically, the nitrogen content in the inflow water. For this reason, the recommendation is that going forward, the focus should solely be on devising limit values that are relative to the volume of nitrogen in the wastewater entering the treatment plant.

3) Four distinct types of relative limit values have been evaluated:
    a. Same relative limit value for all plants;
    b. Multiple relative limit values based on the size or capacity of the treatment plants;
    c. A relative limit value tailored for each treatment facility, based on specific baseline nitrous oxide emissions; or
    d. An individually set relative limit value for each facility, taking into account the specific baseline and the plant's reduction potential and costs.

These evaluations led to the following conclusions:

a. Implementing the same relative limit value for all treatment facilities might prove inappropriate, as the plants' incentive to reduce emissions would be defined by their current emissions; moreover, it is not certain that this approach would prove effective given that it is not necessarily the plants with the greatest reduction potential and the lowest reduction costs that currently operate with nitrous oxide emissions superior to the limit value. Consequently, it is unlikely that such a limit would be universally accepted as "fair", and the associated costs to the plants of meeting the limit could vary significantly. The overall likelihood of compliance with the limit value across all treatment plants could be low, due to the variation in reduction potentials and associated costs. One argument for implementing a uniform relative limit value across all treatment plants is the belief that the administrative costs for authorities related to setting and enforcing this limit would be low. From an economic perspective, however, it is not anticipated that these low administrative costs would outweigh the perceived drawbacks, leading to a potentially high overall socioeconomic shadow price for reducing nitrous oxide emissions from the treatment plants.

b. Setting a relative limit based on the size or capacity of treatment plants could also be problematic, given that their incentive to reduce emissions would depend on their current emission levels. Were such a limit value to be applied, its effect might apply disproportionately, because those plants with the greatest potential for reduction and lowest costs might not necessarily be the ones that currently exceed the limit. Applying limit values determined by treatment plants' size or capacity could thus be perceived as "unfair". Finally, the costs to treatment plants of complying with such limits would vary, and the administrative processes for the authorities would be more comprehensive compared to working with a uniform relative limit value. From a socioeconomic perspective, therefore, it is estimated that this would ultimately lead to a high shadow price for reducing nitrous oxide emissions from the treatment facilities.

c. Setting relative limit values based on each facility's emissions against a predetermined baseline is considered an effective approach. In principle, such a limit incentivises all facilities to reduce their nitrous oxide emissions even though their capacities for reduction might still differ. However, this methodology would also affect plants with less reduction capacity and high costs, were a uniform reduction target to be for all plants imposed relative to their baseline emissions. It is estimated that this could be perceived as "unfair". The likelihood of achieving the objective, i.e. all facilities meeting the same reduction goals, is estimated to depend on how the reduction target is set in relation to their reduction potential. This would also determine the costs of facilities meeting the limit value, which are thus predicted to range from low to high: Low because all plants are obliged to achieve a relative reduction in their nitrous oxide emissions compared to their baseline; high in scenarios where the reduction potential is minimal costly to achieve. It is also anticipated that implementing this type of limit value would require more comprehensive administration by the authorities than managing a uniform relative limit value for all treatment facilities, or one that varies according to their size or capacity. From a socioeconomic perspective, the shadow price for reducing emissions of nitrous oxide from these facilities is projected to be high, although it is expected to be less skewed than the other limit value models presented above, as this approach takes into account the historical nitrous oxide emission levels specific to each facility. It is important to emphasise that establishing a baseline for the nitrous oxide emissions of each treatment plant necessitates the introduction and enforcement of an annual measurement programme across all facilities. These measurements could, however, also be utilised for ongoing monitoring of the nitrous oxide emissions from the treatment plants and facilitate the reassessment and adjustment, where necessary, of the overall reduction targets. Given that baseline measurements are not currently available for all treatment plants, it will be necessary to establish them before it is possible to implement the limit value.

d. Based on the criteria applied, individually tailored relative limit values for each treatment plant are therefore deemed appropriate. This type of limit value incentivises all treatment plants to reduce their nitrous oxide emissions, and the precision of this limit is maximised when it is individually set, taking into account the baseline of each treatment plant, as well as their reduction potential and costs. This limit value will likely be perceived as the "fairest", and it is estimated that the associated costs for treatment plants would be the lowest possible, provided the reduction goal has been determined in relation to the reduction potentials and costs. The likelihood of achieving the reduction goal would depend on how the goal is actually established in relation to potential reductions and their associated costs. However, it is likely that administering the limit value would be a comprehensive and complex task for the authorities. In all, it is estimated that this approach would minimise the shadow price for reducing nitrous oxide emissions from treatment facilities. Nevertheless, it is not considered to be currently feasible – from an administrative perspective – to define relative limit values for each facility. This is because baseline nitrous oxide emissions for the individual plants have not yet been established and the reduction potential likewise remains unidentified.

4. Measurement of Nitrous Oxide Emissions

The following section reviews the available methods for measuring nitrous oxide emissions from treatment facilities, including how each method works, as well as their respective advantages and disadvantages in practical use (see the technology review in Bilag 1).

The review concludes with a recommendation for the most suitable measurement method for estimating nitrous oxide emissions from treatment facilities. In addition, it presents suggestions for a straightforward method of implementing regulation (Section 5).

It is important to note that the most recent update of the “2019 Refinement of the Intergovernmental Panel on Climate Change” (IPCC) (Bartram, D. 2019) does not contain a standard method for the direct measurement of nitrous oxide emissions or for calculating the emission factor from treatment facilities using Tier 3. The IPCC Tier 3 approach is considered the optimal monitoring level and is utilised in countries with robust data and advanced treatment facilities. It makes use of country-specific emission factors that are derived from measurements at either the national or facility level.

4.1 Dynamics of Nitrous Oxide

It is widely acknowledged that nitrous oxide emissions from treatment facilities are the result of complex processes. The emissions vary from the perspectives of both time and location, and they exhibit seasonal and daily fluctuations. Some facilities generate higher emissions in summer than in winter, and daily variations can also occur on account of flow to and load at the treatment plant. The aeration of the biological processes likewise affects nitrous oxide emissions, causing variations even over brief periods.

It has not yet been established how frequently spot measurements should be taken in order to obtain a representative emission factor for nitrous oxide from treatment facilities. The typical profile of nitrous oxide emissions from a treatment plant indicates periods of low emissions, occasionally interrupted by brief periods of high emissions.

Measuring nitrous oxide emissions is crucial; in practice, however, an emission factor relative to the nitrogen supplied or removed serves as a benchmark. Because the nitrogen content in the inflow is frequently measured through daily samples, it is essential to calculate nitrous oxide emissions from these samples in order to determine total daily nitrous oxide emissions.

The mandatory self-monitoring programme for treatment plants includes a relatively small number of test days for nitrogen in the inflow. The number of test days is defined on the basis of the capacity of the specific treatment plant. This limited dataset regarding the inflow of nitrogen to treatment plants results in significant uncertainty in calculating the emission factor for nitrous oxide.

4.2 Approaches for measuring nitrous oxide emissions from treatment plants

Measuring nitrous oxide emissions from treatment plants is directly connected to the loss – or flux – of nitrous oxide into the atmosphere and comprises two components:

I. The concentration of nitrous oxide in the discharged air
II. The volume of air emitted into the atmosphere

This flux can be measured either through plant-wide methods, which assess the total emissions from the treatment plant, or through process-specific methods that assess emissions from individual units or processes (FIGURE 4.1).

A method for detecting nitrous oxide emissions from treatment plants thus comprises both the measurement technology itself and an associated emissions calculation, such that nitrous oxide emissions from the plant can be estimated either specific to processes or plant-wide.

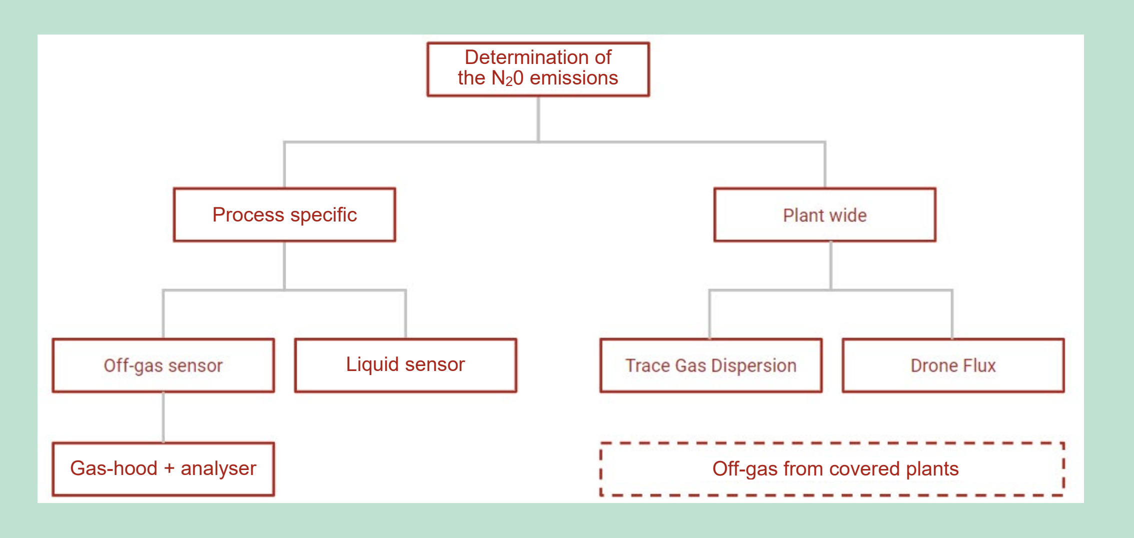


FIGURE 4.1. Plant-wide and process-specific techniques for measuring nitrous oxide emissions from treatment plants

4.2.1 Plant-wide measurements

A variety of plant-wide measurement techniques are available for assessing the overall N_2O flux from a treatment plant. Most methods rely on spot measurements, although ECM (see the section below) does offer continuous measurement options. A non-exhaustive list of methods for calculating emission rates from specific areas (e.g. a process tank at a sewage treatment facility or an area of land) is provided in Ye et al. (2022):

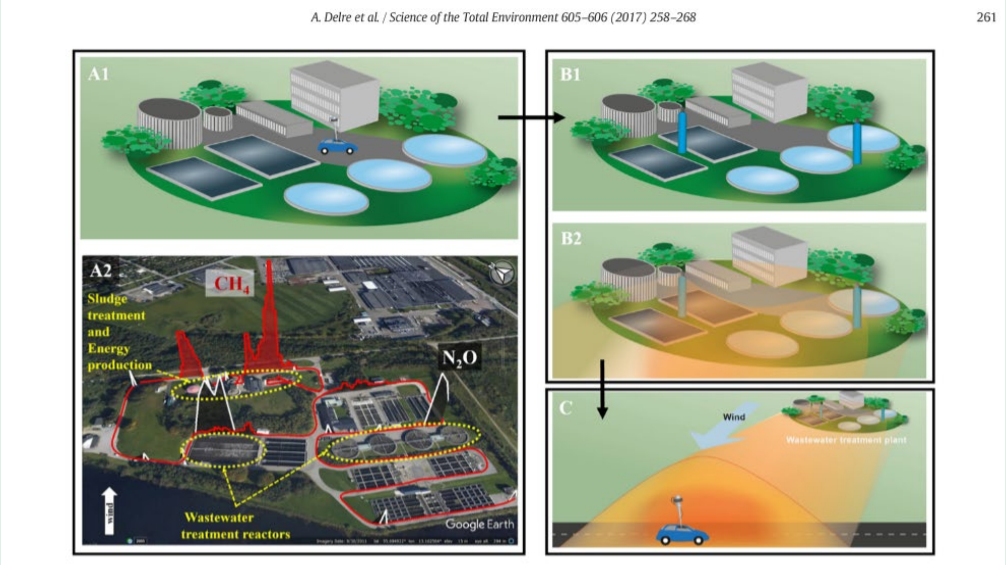
- Mobile tracer gas dispersion method (MTDM)
- Inverse dispersion modelling method (IDMM)
- Solar occultation flux (SOF)
- Differential absorption light detecting and ranging (DIAL)
- Radial plume mapping (RPM)

The following can also be mentioned:

- Drone Flux Method (DFM)
- Eddy Covariance Method (ECM)

Several methods, including MTDM, IDMM, SOF, DIAL, RPM, DFM, and ECM, can calculate emission rates for areas such as process tanks or stretches of land using a description of the *gas plume* (of nitrous oxide, for example) moving downwind of the treatment plant (FIGURE 4.2). With the exception of DFM, all methods are “terrestrial” and therefore rely to some extent on plume measurement, whereas DFM may potentially measure the full transverse spread of the plume – on account of the use of drones (see the technology review in Bilag 1).

MTDM compensates for this partial measurement by using a tracer gas, whereas the other methods rely exclusively on local atmospheric models to calculate the dispersion or dilution of gases (in this case, nitrous oxide).



Source: Copied from Delre et al. (2017)

FIGURE 4.2. Illustration of the tracer gas dispersion method as applied in wastewater treatment plants

The initial screening phase A1 displays on-site measurements of atmospheric concentrations of target and trace gases, while A2 presents an example of on-site screening conducted in Källby (SE), visualised on a Google Earth © image. Concentrations of CH_4 *(red) and* N_2O *(white) are shown above the background level. The white arrow illustrates the wind direction. B) B1 shows tracer gas location for source simulation while B2 illustrates tracer gas release into the atmosphere. C) The quantification phase demonstrates the downstream gas concentration measurement along a plume transect.*

MTDM and DFM are the only methods that have been employed so far to quantify nitrous oxide emissions from treatment plants. ECM is still considered to be at a Technology Readiness Level (TRL) of 5 and is therefore not deemed suitable for regulatory purposes.

The Mobile Tracer Gas Dispersion Method (MTDM) involves measuring a tracer gas (acetylene) with a known concentration in order to calculate nitrous oxide emissions. It is well-suited to measuring overall emissions at a given time, but it has limitations in the event of interfering sources and requires favourable wind conditions (Bilag 1).

The Drone Flux Method (DFM) uses a remote-controlled drone to measure the wind plume downstream of the emission source. DFM likewise provides a snapshot of emissions and shares similar benefits and limitations with MTDM. Specific weather conditions and specialised personnel are required (Bilag 1).

Both methods (MTDM and DFM) are evaluated at a TRL of 8–9, which indicates that they are ready for commercial application. Measurement campaigns have been conducted at several treatment plants, but uncertainty remains regarding their capacity to assess the plant's emission factor accurately. Measurement uncertainties have been estimated for both methods, with known suppliers including DTU and FORCE Technology for MTDM and Explicit ApS for DFM (Bilag 1).

4.2.2 Process-specific measurements

There are essentially two process-specific approaches to measuring nitrous oxide emissions from treatment facilities, each based on different principles:

- A principle that involves direct measurement of N_2O dissolved in the liquid phase and a subsequent estimation of N_2O in the released air, thus allowing calculation of the emissions.
- A principle that involves direct measurement of N_2O in the gas phase along with measuring the volume of the emitted air, thus allowing calculation of the emissions (off-gas measurement).

Both principles rely on the precise and accurate determination of the volume of air released due to aeration during the biological treatment processes. Both principles likewise depend on extrapolating from the actual (process-specific) measurement points to the total emissions from the treatment plant as a whole.

FIGURE 4.3 illustrates the fundamental distinction between process-specific measurements in the gas phase and liquid phase. The critical difference is that liquid phase measurements require an additional calculation step to estimate mass transport from liquid to gas, whereas this is not necessary with gas phase measurements, which measure *directly* in the gas phase. Both methods necessitate subsequently extrapolating nitrous oxide emissions from individual (process-specific) measurement locations to the emissions from the entire facility.

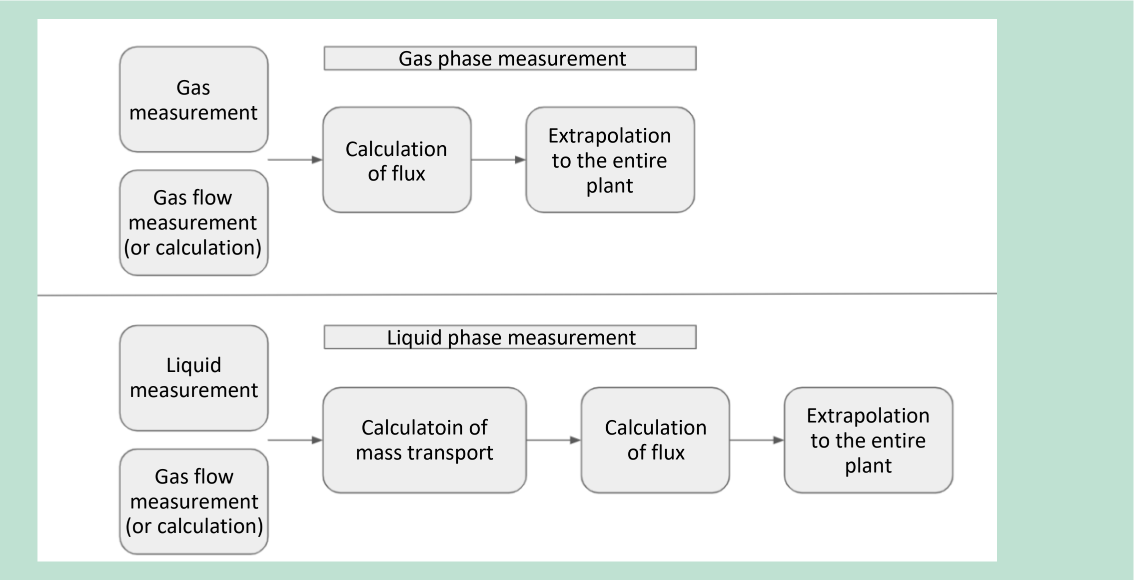


FIGURE 4.3. Schematic illustrating the various steps from measuring N_2O in liquid and gas, respectively, to estimating total emissions from the entire facility

Technologies are available within both principles that allow for online or continuous monitoring of nitrous oxide emissions. This technology is widely applied in treatment facilities both in Denmark and worldwide, having obtained a high TRL of 9.

Limitations on the measurement of nitrous oxide in the liquid phase include the need to convert the measurements taken to gas phase concentrations in order to estimate emissions. This conversion hinges on an empirical formula, which carries uncertainties. Measurement uncertainties can pose challenges and are particularly attributable to temperature sensitivity, sensor head wear and emission model uncertainties. While suppliers report varying degrees of measurement uncertainty, overall they are estimated at less than 20%.

4.2.3 Overview of existing measurement technologies

TABLE 4.1 below summarises the review of suppliers and the corresponding nitrous oxide measurement technologies at treatment plants. Detailed descriptions of the underlying technologies can be found in Bilag 1.

TABLE 4.1. Summary of suppliers and the associated technologies for measuring nitrous oxide emissions from treatment plants

Parameter	Unisense A/S	Duotech	VarioLytics	Upwater	Explicit	DTU
Measurement method	Liquid phase measurement	Gas phase measurement	Combined gas and liquid phase measurement	Gas phase measurement	Drone-based measurement	Tracer gas measurement
Sensor type	Amperometric	Proprietary float chamber and compensated NDIR measurement technology provided by Novasis innovazione	Analytical tool: Mass spectrometry	NDIR analyser from German Witec paired with a flux chamber developed at Eawag	MIRA Strato N_2O/CO_2 sensor (Aeris Technologies)	Laser-based
Sensor medium	Water	Air	Air: Floating chamber placed on aeration tank, which transfers collected gas to a mass spectrometer. Liquid: Direct measurement in the liquid phase using membrane inlet mass spectrometry.	Air	Air	Air
Measurement level	Process-specific	Process-specific	Process-specific	Process-specific	Plant-wide + process-specific	Plant-wide + process-specific
Measurement uncertainty	5% (+/-)	Unknown	3% (+/-)	1%	20%	20%
Cost type	One-time investment + consumption of calibration fluid and sensor heads	One-time investment + cost of service and maintenance	One-time investment + maintenance (5% of the purchase price annually). Can also be rented/leased, where maintenance is included in the price.	One-time investment + consumption of gas and use for calibration.	Cost per measurement	Cost per measurement
Advantages	Continuous real-time measurement. Integratable with other online sensor data (link between operating parameters and process dynamics).	Continuous real-time measurement	Continuous real-time measurement. Auto-calibration, eliminating the need for manual calibration. Daily validation of measured values using reference gases (consistent measurement quality). Measurement of both nitrous oxide and methane.	Continuous real-time measurement. Detects low concentrations of N_2O, making it suitable for applications that require precise measurements. (0–2000 ppm). Uniform and accurate measurements over extended periods.	Direct gas measurement. Plant-wide quantification without the need for extrapolation. Can measure other greenhouse gases.	Direct gas measurement. Plant-wide quantification without the need for extrapolation. Validated method.

	Measuring nitrous oxide production during both nitrification and denitrification.		Measurement of up to 8 aeration tanks with a single analyser. Simultaneous measurement of air and liquid phases.	Quick response times, which enables real-time monitoring and rapid detection of changes in N_2O concentrations.		
Drawbacks	Indirect quantification of emission (via calculation). Uncertainties with input parameters, including airflow. Requires calibration (potential source of error). Requires cleaning (potential source of error). Repeated replacement of sensor heads. Deterioration of measurement quality over time (potential source of error). Temperature sensitivity (potential source of error). There must be no high concentrations of hydrogen sulphides or H_2S.	Can only be used in a bottom-aerated process tank. The sensor is sensitive to CO_2, which means that CO_2 must be measured separately and corrected for in results.	Maintenance and parts replacement, as well as calibration (annual visit by service team). The size of the float chamber is crucial. Large chambers ensure better averaged emissions, while smaller chambers are easier to relocate and facilitate multiple measurement points. Emissions may vary based on the design and configuration of the tank, which the measurements may not account for. Not suitable for systems involving surface aeration.	Measurements can typically only be taken in aerated zones or phases, as the design lacks a sweep gas or gas recirculation. Requires periodic calibration to maintain accuracy. May be affected by some disrupting gases with overlapping absorption spectra. This can lead to inaccuracies in measurements if appropriate compensation or correction methods are not employed. May be more expensive compared to some other gas detection methods.	Sensitive to interfering sources upstream of the emission source. Sensitive to weather conditions. Adequate space is required, and there may be obstacles within the measurement zone. The wind plume must be mapped in its entirety. Spot measurement.	Requires specific weather conditions. There may be obstacles in the measurement zone. The wind plume must be mapped in its entirety. Spot measurement.
Technological maturity	9	7	9	9	8–9	8–9

4.2.4 Optimal method for measuring nitrous oxide emissions from treatment facilities

It is estimated that plant-wide measurements do not determine the nitrous oxide emission factor of treatment facilities accurately, as they only provide a snapshot of emissions which may not be representative. The dynamics of emissions display significant fluctuations over even short periods of time. Therefore, plant-wide measurement methods are not relevant in the context of a relative limit value for nitrous oxide emissions from treatment plants. Nevertheless, they can be used effectively to validate process-specific measurement methods, with the associated calculations and extrapolation, to ascertain total nitrous oxide emissions from the entire facility.

For regulatory purposes, it is recommended to utilise continuous online measurements (process-specific) and perform extrapolation to calculate or estimate the total emissions of nitrous oxide from the treatment facility.

4.3 Uncertainty in estimating the emission factor

The analysis in the following section focuses solely on process-specific measurement methods for estimating nitrous oxide emissions.

As mentioned previously, nitrous oxide emissions from treatment facilities vary considerably, with several factors influencing this variation. At the same time, there are a number of uncertainties involved in estimating nitrous oxide emissions, over and above the measurement uncertainty of each technology (which varies depending on the technology and supplier). Moreover, the calculations of emission factors rely on a relatively limited dataset for nitrogen in the inflow, where self-monitoring (dependent on the size of the facility) is performed only 6 to 12 times annually.

For the purposes of regulation, it is important to give careful consideration to the frequency of measurement and reporting of nitrous oxide emissions is appropriate, taking into account the dynamics of the emissions, existing uncertainties and current self-monitoring at the treatment facilities.

The greatest uncertainties assessed in relation to estimating the emission factor are examined in the following section.

4.3.1 Placement of measurement point

A key uncertainty in estimating the emission factor is linked to the placement of sensors. This uncertainty arises from changing conditions at treatment plants, which complicate the determination of the most representative point for measurement. This challenge can be mitigated in part by conducting preliminary surveys on sensor placement, obtaining prior knowledge of the facility, utilising CFD modelling and employing multiple sensors for verification and validation.

4.3.2 Accurate measurement of airflow

For both gas and liquid phase measurements, it is crucial to determine the total gas flow from the biological process accurately. This can be achieved by measuring the flow in an open flow chamber or within the aeration system, or by calculating the airflow from a fan station or rotor immersion, for example When surface rotors are utilised – and a controlled air measurement is therefore not available – the airflow is often estimated based on rotor immersion and key performance metrics. This conversion carries significant uncertainties and may result in substantial errors in estimating nitrous oxide emissions; moreover, it may complicate gas phase measurements on account of the lack of controlled degassing.

In liquid phase measurements, the concentration of nitrous oxide in the off-gas must be deduced from its concentration in the liquid. Different models for this exist, but the use of an empirical formula to calculate the mass transport coefficient is recommended.

4.3.3 Calculation of mass transport (specifically for liquid-phase sensors)

As liquid-phase sensors measure within the liquid phase and not the off-gas, it is necessary to estimate the mass transport of nitrous oxide. This can be accomplished in several ways; however, the supplier recommends using an empirical formula. An initial (and regular) calibration of the emission model for mass transport may be necessary (Myers *et al.* 2021, Baresel *et al.* 2016 and Baeten *et al.* 2020) to ensure the calculations are representative.

4.3.4 Extrapolation from a limited number of measurement locations to the entire plant

If measurements are not carried out in all tanks and processes, it is necessary to extrapolate from a limited number of measurement points to the entire treatment plant, which involves a degree of uncertainty.

4.3.5 Conclusion on the estimation of nitrous oxide emissions

In order to estimate nitrous oxide emissions, it is recommended to use process-specific measurements that are converted using the mass coefficient transport and airflow to the emission. The main challenges in calculating and estimating nitrous oxide emissions based on process-specific measurements lie in ensuring valid airflow and nitrous oxide measurements, where it is essential to include location in the tank and an understanding of the tank's dynamics in making the decision. Moreover, for liquid-phase sensors, mass transport calculation presents an uncertainty that can be mitigated by periodically recalculating the empirical formula.

Current suppliers of flux chambers (for gas-phase measurement) provide only a solution where nitrous oxide emissions are quantified solely during the nitrification process, i.e. excluding measurements/estimations during the denitrification process. This leads to considerable uncertainty and variation compared to liquid-phase sensors.

4.4 Recommendations for measurement method and determination of nitrous oxide emissions from treatment plants

At present, it would be appropriate to implement process-specific, continuous online measurements to estimate nitrous oxide emissions from treatment plants. There are currently two types of technology available for these measurements (sensors in the liquid phase and off-gas meters), and they are available from several suppliers (Section 4.2.3 and Appendix 1). Using a process-specific online measurement method makes it possible to determine nitrous oxide emissions from the biological processes at treatment plants, as well as to make the necessary extrapolations to assess the total emissions from the facility. At the same time, this provides wastewater utilities with a crucial tool for planning, executing and assessing operational strategies to decrease emissions, thereby ensuring a general reduction in nitrous oxide emissions from treatment plants.

Given the significant fluctuations in process conditions at individual facilities, it is recommended to measure nitrous oxide emissions from at least every *type* of aerated biological process at treatment plants (refer to section 6). Most nitrous oxide emissions from a sewage treatment plant result from the aeration of wastewater, which releases dissolved nitrous oxide produced during the biological processes.

Measuring nitrous oxide emissions and calculating the emission factor from treatment plants can be effectively supported by existing accredited analyses of the nitrogen content of the wastewater supplied to these plants – analyses that are taken in accordance with their discharge permits (see Section 6).

It is also recommended that, in combination with the implementation of regulations, a *positive list* be compiled of technology providers for measuring nitrous oxide emissions from treatment plants. The criteria for technology selection should naturally be scrutinised in greater depth, but could potentially draw on CE marking or DANAK accreditation for the measuring technology itself. The list should include suppliers, their technologies and related emission calculations that the Danish Environmental Protection Agency deems adequate for ensuring the necessary quality of nitrous oxide emission measurements for regulatory purposes. This positive list will assist wastewater utilities and industries with treatment plants in navigating the available technologies.

Finally, it is recommended that in the long term, an *accredited method* be established such that companies can eventually be accredited under DANAK for the measurement, calculation and data validation of nitrous oxide emissions from the *entire* treatment facility. Until such a method is developed, regulation must rely on a valid and uniform method for measuring and calculating nitrous oxide emissions from Danish treatment facilities (see Section 6).

5. Baseline for Nitrous Oxide Emissions

5.1 Background for establishing baseline nitrous oxide emissions

Nitrous oxide emissions can be measured either as a relative or an absolute amount.

A relative measurement describes the percentage of nitrogen emitted as nitrous oxide compared to the total volume of nitrogen supplied to the treatment facility or its biological processes. This is expressed as $\%N_2O/TN$-in. This value is proportional and not absolute. The key metric is the average of the days on which both nitrous oxide emissions and the TN inflow have been measured. The same calculation applies to the standard deviation.

An absolute measurement details the total amount of nitrous oxide-nitrogen emitted from the treatment plant annually, measured in kg N_2O emitted/year. This figure is derived from the average of the daily mean nitrous oxide emissions multiplied by 365 days/year. This volume is absolute and not relative to the operational load or size of the treatment plant. The term nitrous oxide-nitrogen (N_2O-N) is regularly used in academic literature as it simplifies the tracking of nitrogen through the various biological transformation processes that involve different nitrogen compounds.

When establishing a baseline, it is relevant to evaluate existing documented baselines, as well as a new, revised baseline – if any – based on the expanded review of existing literature that takes into account the size of the facility (Appendix 2).

There are currently three acknowledged baselines: 0.32% N_2O-N/TN-in (DK before 2020), 0.84% N_2O-N/TN-in (DK after 2020), and 1.6% N_2O-N/TN-in (IPCC). To determine a baseline emission accurately, it is important to assess the data quality upon which the baseline is based. In this literature review, data have been meticulously gathered from published sources (compiled in a spreadsheet in Appendix 2). In addition, data have been sourced from unpublished sources (nitrous oxide ERFA group).

When the introduction of a limit value for nitrous oxide at treatment plants greater than 30,000 PE was announced in 2020, many utilities opted to purchase measuring equipment to ascertain their standing with regard to nitrous oxide emissions.

Another key factor in 2020 was the “Paris Model”, in which the CO_2 assessments (scope 1 and scope 2) clearly identified nitrous oxide as the largest single contributor, based on a standard emission factor applied of 0.84% N_2O-N/N in the inflow.

The Paris Model dictated that a physical measurement of nitrous oxide necessitated the use of the measured value instead of the standard emission factor, which prompted several utilities to conduct measurements at both small and large plants better to illuminate the actual emissions and thus to obtain a more accurate (and reduced) CO_2 footprint.

5.1.1 Existing measurements of nitrous oxide emissions

Since there is currently no *standard* or accredited method for determining baseline emissions, it should be expected that existing data on nitrous oxide emissions (both published and unpublished) might not necessarily have been calculated consistently.

Experience from Denmark makes it clear that not only are various methods used, but also that there significant uncertainties may exist in the data and the quality of same. The uncertainties that originate from the measurement method (measurement technology plus emission calculation) are detailed in Section 3 , as well as in Appendix 1.

The following section summarises the findings of the underlying work to evaluate the baseline for nitrous oxide emissions from Danish treatment plants (data available in Appendix 2).
In evaluating the baseline, insights have been sought from several datasets on Danish nitrous oxide measurements. These data are categorised into three groups (TABLE 5.1).

TABLE 5.1. Literature review and additional data collection concerning nitrous oxide emissions from treatment plants (background data can be found in Appendix 2).

Colour coding	Dataset	Description
▨	ERFA Group	Krüger A/S facilitates a nitrous oxide ERFA group, which has been holding meetings sinc 2020. During these meetings, several utilities have shared their treatment plants' emissio factors. The data pertain to the period from 2020 to 2022. The data may comprise spot measurements and may not represent an entire year's data. Details regarding data quality, etc. ar not known.
▩	MUDP 2020	Measurements and emission factors from MUDP 2020. Includes datasets from seven bottom-aerated treatment plants. Not all data cover a full year. The data are considered validated and of high quality.
▧	Other projects	Additional treatment plants conducted measurements between 2013 and 2023. The data may comprise spot measurements and may not represent an entire year's data. Details regarding data quality, etc. are not known.

The three datasets are presented below for comparison of the correlation between emission factors and the approved capacity/PE of the treatment plants (FIGURE 5.1).

A correlation between approved capacity and the emission factor for treatment plants is evident, based on data reported from the Danish Environmental Protection Agency (MUDP 2020) and other previously documented emission results (from the ERFA group and other projects). This correlation suggests that the emission factor rises as plant load increases, meaning the larger the treatment plant, the higher the emission factor.

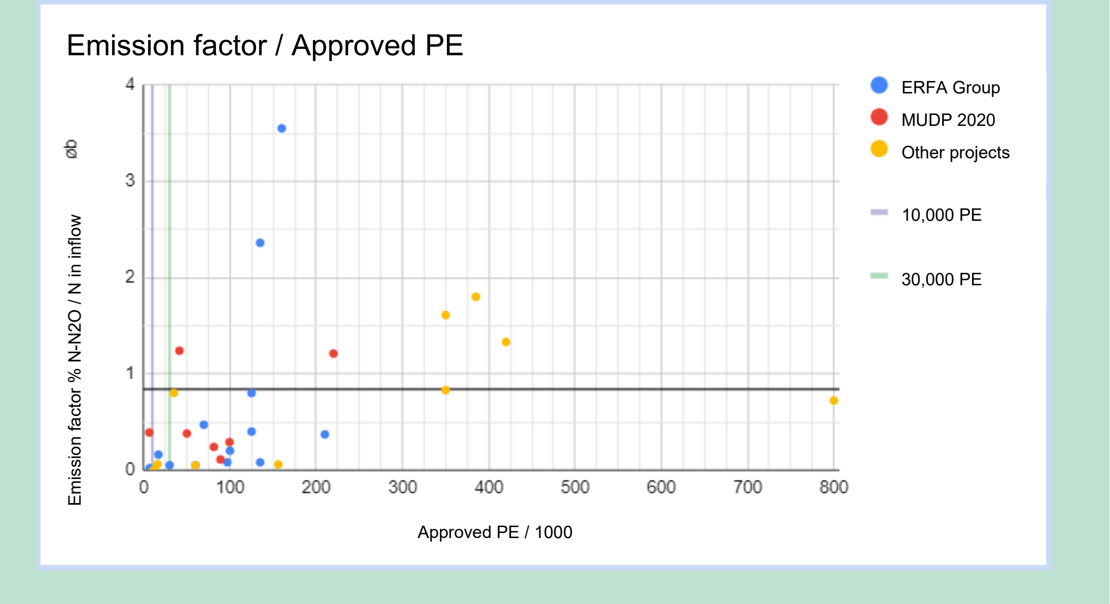


FIGURE 5.1. Emission factor (% N_2O-N/N $_{inflow}$) relative to plant size (approved PE)

Larger sewage treatment plants are generally equipped with digestion tanks and therefore produce reject water containing high concentrations of ammonium. An increased emission factor for large treatment plants (compared to small ones), can *potentially* be attributed to autotrophic aerobic ammonium oxidising bacteria (AOB) along with high ammonium oxidation rates (AOR) due to reject water input into the biological processes. Consequently, the elevated nitrous oxide production and emission from large treatment plants can *potentially* be mitigated by operating digesters at these plants. Increased attention has likewise led to optimisation of the primary treatment stages – thereby also reducing carbon input to biological processes – and created conditions conducive to nitrous oxide production and emission.

5.1.2 Statistical variation in data quality

The literature study and data analysis for this report includes a total of 37 *Danish* datasets, categorised by the facilities' approved capacity and whether emission measurements were taken from the primary or secondary streams (TABLE 5.2). "Secondary streams" are steps in the purification process that treat an internal reject stream or similar, while primary streams comprise the biological treatment of incoming wastewater from the catchment area of the treatment plant.

TABLE 5.2. Distribution of nitrous oxide measurements at Danish treatment plants, as analysed in literature studies and other data collections.

Categorised by plant size (37 in total)	Number of measurements.
PE ≥ 30,000	32
30,000 > PE >= 10000	3
PE < 10,000	2

Categorised by process (37 in total)	Number of measurements.
Primary Stream	34
Secondary Stream	3

In order to reflect real conditions accurately and to consider the treatment plants' load, the average emission factor is determined as a weighted average across the three plant sizes. Consequently, the emission factor of each plant is weighted according to its load, proportional to the plant's size – i.e. the approved capacity. Due to this weighting, figures from larger treatment plants have a greater influence on the resulting weighted average than those from smaller plants. This approach ensures that unusually high or low emission factors at the largest and smallest plants do not lead to an over- or underestimation of the total volume of nitrous oxide emitted from Danish treatment plants.

(FIGURE 5.2) below presents the weighted average and the distribution for the three groupings, as well as for all datasets combined (all). A significant variance is observed in the unvalidated dataset groupings (ERFA group and other projects), whereas the variance is less in uniformly conducted and validated campaigns (MUDP 2020). The visualisation of the variance is intended to demonstrate the extent of measurement variations across different datasets. There is a negative variance for the ERFA group. This naturally does not imply a negative emission factor, but rather a variance that exceeds the weighted average.

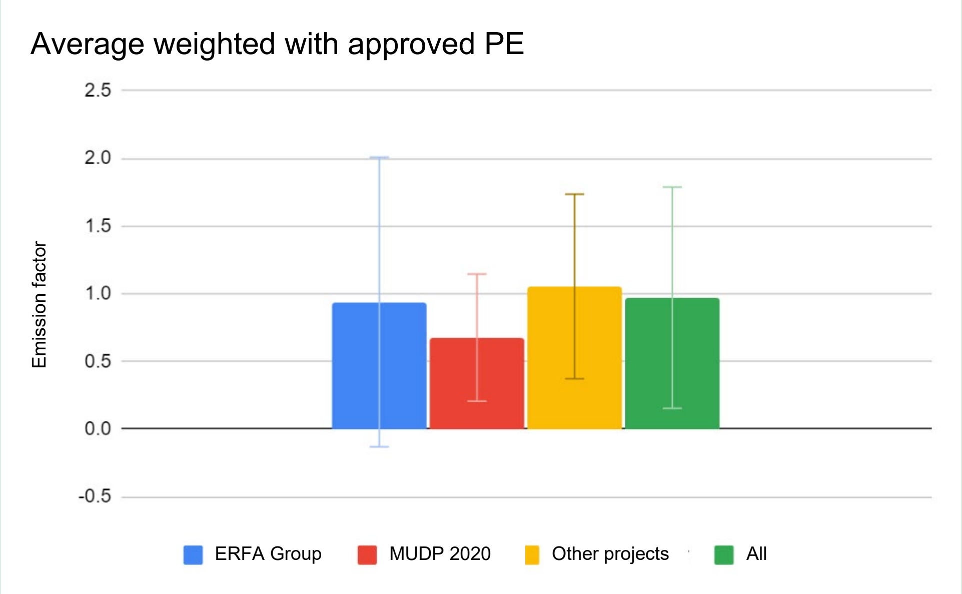


FIGURE 5.2. Weighted average and its distribution across the three dataset groupings: ERFA group, MUDP 2020, and Other projects

Since there is no "standard" or "accredited" measurement method nor baseline calculation, there is a significant likelihood that the data presented (see Appendix 2) are neither valid nor comparable.

Given the current measurements at various Danish treatment plants, inadequate data validation is of concern – perhaps particularly with regard to the airflow measurements used to convert liquid phase measurements into emissions.

Although the literature review compiles a great deal of emission data, many of the data points identified cannot be directly utilised for statistical calculation of a new baseline discharge for Danish facilities due to:

- Significant variation in the measurement methods and measurement periods utilised.

- Numerous data are based on spot measurements over short periods.
- Limited insight into the data quality from different sources (e.g. airflow).
- Limited insight into the extrapolation methods applied.
- Limited insight into the emission calculation formulae/methods used.

The only dataset that meets an acceptable quality standard is MUDP 2020, which comprises validated and documented data, unlike the others mentioned.

Implementing measurement programmes to facilitate the establishment of more valid data sets from Danish treatment plants would be invaluable in further regulating nitrous oxide emissions. Progressively, as more measurements are validated and recorded, this will enhance our knowledge and improve the quality of the overall baseline for nitrous oxide emissions from Danish treatment plants.

5.1.3 Baseline emissions of nitrous oxide for Danish treatment plants

In order to ensure a sound foundation for future regulation, it has been necessary to evaluate whether the three data sets can be considered valid. As noted above, the assessment is that two of the three groupings do not possess sufficiently valid information. Moreover, *metadata* (process data associated with emission data), such as process condition variations, emission calculations and extrapolation, remain ambiguous in the non-validated data, rendering the uncertainty too significant with regard to establishing a reliable baseline for future regulation. These data sets are therefore considered too uncertain for establishing a baseline emission for future regulation.

The baseline emission for Danish treatment plants should, for the time being, be based on the MUDP 2020 dataset, corresponding to 0.84% N_2O-N / TN-in.

The Danish baseline emission factor (MUDP 2020) is derived from the volume of nitrogen supplied to the biological processes at the treatment plants, established using data from plants both with and without primary treatment.

In a single-stage system (without a clarification tank, for example), the nitrogen content in the inflow will roughly correspond to the amount supplied to the biological processes. This is not the case for two-stage plants (with a clarification tank, for instance), where a small fraction of the nitrogen in the wastewater is removed before it reaches the biological process because it is bound to suspended matter that settles and is removed in the primary treatment step. The difference between the volume of nitrogen supplied to the treatment plant and the volume delivered the biological processes in two-stage plants will inevitably depend on how the primary treatment phase is operated.

Due to limited accessibility of MUDP data, this project was unable to adjust the Danish emission factor established for discrepancies between the volume of nitrogen supplied to the inflow and the biological processes at two-stage plants. Moreover, the MUDP dataset is considered to provide an insufficient data basis (limited number of measurement campaigns and treatment plants) to allow a precise correction of the emission factor to be made.

It is nevertheless anticipated that using a primary treatment step (such as a clarification tank) will not have a *significant* impact on the emission factor – compared to other uncertainties in measuring and calculating nitrous oxide emissions. A primary treatment step reduces the amount of particulate matter entering the biological treatment process. Chen et al. (2020) suggest that around one-sixth of the total nitrogen content in wastewater is found as particulate-bound nitrogen. Pre-treatment can typically remove 50–80% of the particulate matter. This means that at least one-twelfth of the nitrogen content is removed through pre-treatment, with a reduction assumed

to be between 10–12%. This uncertainty must *for now* (and until a new and revised baseline emission is determined) be considered negligible in relation to other uncertainties concerning the current baseline emission.
Thus, the baseline emission of 0.84% N_2O-N / TN-in *is currently* considered a representative average for Danish sewage treatment facilities and can be used as a baseline emission across different plant types (one and two-stage plants) until a larger data set for a re-evaluated baseline emission for Danish facilities is available (see section 6).

5.1.4 Industrial treatment facilities

It is expected that the regulation of nitrous oxide emissions will come into effect for municipally owned wastewater treatment facilities with a capacity of 30,000 PE or more. However, it is also *likely* that a significant volume of nitrous oxide emissions will stem from other treatment facilities with nitrogen removal capabilities, including industry-owned facilities (such as pre-treatment plants).

Given the lack of available data on nitrous oxide emissions from industrial treatment facilities, their baseline emissions are unknown. This made it impossible to take industrial treatment facilities into account in the above-mentioned assessment of baseline emissions from Danish treatment facilities.

The baseline emission from industrial treatment facilities must be expected to exhibit even greater variability than that of municipally owned treatment plants. The reason for this is that the composition of industrial wastewater can vary *considerably* and can appear significantly different from typical household wastewater, which otherwise accounts for an appreciable portion of the inflow at municipal facilities. Several industrial treatment facilities handle large volumes or highly concentrated, nitrogen-rich wastewater, potentially leading to elevated emissions. Other industrial facilities primarily deal with wastewater rich in COD rather than nitrogen, likely resulting in only limited emissions.

In order to avoid overlooking a significant source of Danish nitrous oxide emissions, it might be relevant to roll out a measurement campaign, for example, at industrial treatment facilities corresponding to an approved/dimensioned capacity of 30,000 PE. The measurement technologies (Section 4), methods and guidelines (Section 6) outlined above would also be applicable to industrial treatment facilities.

5.1.5 Recommendation for baseline

The literature review (see also Bilag 2) has clearly demonstrated that numerous measurements and calculations of nitrous oxide emissions have been performed both in Denmark and internationally.

These measurements were undertaken to acquire new knowledge, rather than due to any existing requirement or the like. The methods of measurement have varied greatly and were typically conducted over short periods or campaigns.

Consequently, the literature review cannot be used to generate specific baseline data as the data are not considered to be uniform or comparable.

Based on this, it is recommended to continue using the existing baselines to analyse the socioeconomic impacts of implementing limit values:

- 0.84% N_2O-N/TN-in, as this baseline is founded on in the best-validated Danish measurement campaigns to date.

- 1.6% N_2O-N/TN-in, as this is the IPCC’s key figure for nitrous oxide emissions, and it is the baseline utilised internationally for calculating such emissions from treatment plants.

6. Measurement and regulation of nitrous oxide emissions from treatment plants as from 2025

In principle, the measurement and regulation of nitrous oxide emissions from Danish treatment plants will come into effect as from 2025, cf. the “Climate plan for a green waste sector and circular economy”. The following section outlines proposals for a measurement and regulation method applicable to all plant sizes. This method has been created as “*the best possible option*” on the basis of current knowledge and therefore encompasses standard plant types and measurement methods, even though some of these feature significant or undefined uncertainty.

The suggested approach for measuring and regulating nitrous oxide emissions from Danish treatment plants is intended to document the annual nitrous oxide emissions from these plants by expressing the percentage of nitrogen in the inflow to the plant that is emitted into the atmosphere as nitrous oxide.

The method requires measurements and subsequent calculations to be performed in a *valid* and *uniform* manner across all facilities, irrespective of size. In this way, the measurement can be considered valid and serve as a tool for documenting that the treatment facilities are adhering to a specified limit for nitrous oxide emissions.

The method can advantageously be differentiated such that treatment plants emitting below the predetermined limit can have fewer measurement points compared to those exceeding the limit. Additional details are presented in the following sections.

6.1 Formation of nitrous oxide in N and DN zones

The most significant *causes and mechanisms for nitrous oxide emissions* have been taken into account in developing a feasible and viable method for measuring nitrous oxide emissions from Danish treatment facilities:

- It is estimated that approximately 90% of nitrous oxide emissions stem from the aerated zone due to stripping (Unisense Case 1, Chandran, 2010), while 10% originate from diffusion during non-aerated periods.
- Nitrous oxide emissions are typically highest where the ammonium oxidation rate (AOR) is at its peak (Chandran et al. 2011, Law et al. 2012). Given that the oxidation of ammonium (NH_4) to nitrite (NO_2) by nitrifiers can result in the generation of nitrous oxide as a by-product, this is a critical aspect to take into account when selecting sensor placement.
- Generally speaking, there is a tendency for nitrous oxide emissions to rise with increased aeration, since the supply of oxygen initiates nitrogen turnover (AOR) (Chandran et al. 2011, Law et al. 2012) and facilitates the stripping of nitrous oxide from the water column. Accurate measurement during this phase is therefore essential. The volume of air supplied and the size of the aerated zone are crucial factors in the calculation of nitrous oxide emissions, so a representative measurement in the aerated zone would provide an accurate estimate of these emissions.

- Nitrous oxide emissions are generally higher from intensively loaded aeration tanks than from those with lighter loads. For this reason, unevenly loaded tank sets at treatment plants can lead to variable nitrous oxide emissions. There may additionally be variations in nitrous oxide emissions from tank sets if they operate with significantly different sludge concentrations (SS concentration). In this respect, it is recommended to measure emissions in the most heavily loaded tank to ensure coverage of the majority of nitrous oxide emissions from the biological process.

Given the causes and mechanisms of nitrous oxide emissions, measurements in aerated zones are crucial for obtaining a valid reading of the emissions.

Non-aerated zones that are expected to contribute only around 10% of nitrous oxide emissions can be *extrapolated* to avoid the need to install and maintain sensors for detecting this small emission fraction from treatment plants.

Plants that may measure in the DN zones (e.g. BioDenitro) can calculate the current diffusion instead.

The most accurate measurements can thus be achieved by monitoring emissions in all aerated tanks. For treatment facilities with emission factors that exceed the limit value, it would be beneficial to measure in all aerated biological tanks as this would ensure precision and serve as a management tool to reduce emissions (EXPANDED method). If additional control and validation of the measured and calculated emission factor for the facility are desired, it is possible to supplement the method with spot measurements such as plant-wide measurements and trials measuring multiple locations in aerated zones.

Treatment plants with emission factors below the established limit value can effectively measure nitrous oxide emissions from each *type* of aerated biological tank and extrapolate the findings to estimate the total nitrous oxide emissions from the aerated biological processes (BASE method).

This section provides **general guidelines** to assist treatment plants in performing measurements and calculating nitrous oxide emissions. At the same time, the guidelines aim to ensure the calculation of a *valid* emission factor that can be used to support enforcing compliance with the future limit value.

6.2 Differentiated measurement method

Based on the advantages listed below, it is recommended to utilise **differentiated measurement methods** (FIGURE 6.1 *BASE method* and *EXPANDED method*), as this offers the following benefits:

- Rapid and simple implementation of the measurement programme.
- A measurement method that is readily accessible to the treatment plants.
- The measurement method allows all treatment plants above the specified size limit to begin measuring and calculating their nitrous oxide emission factor from as early as 2025.
- This measurement method will provide the Danish Environmental Protection Agency with enhanced knowledge and a more extensive data basis to ensure accurate and validated baseline emissions from Danish treatment plants. It will also support any potential revision of the established limit value as additional information becomes available.

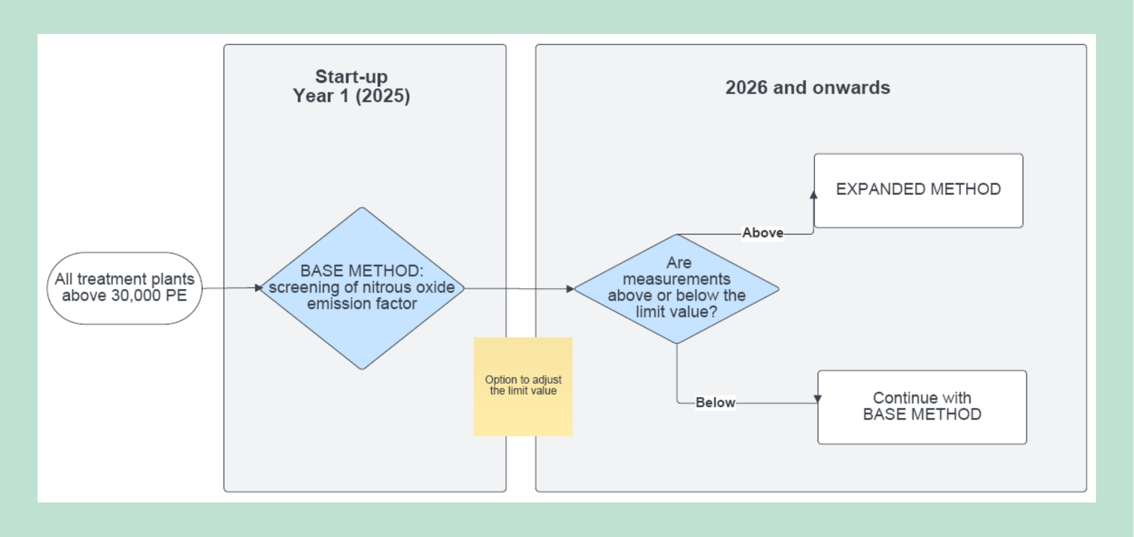


FIGURE 6.1. Differentiated measurement methods for the BASE and EXPANDED methods for regulating nitrous oxide emissions from Danish treatment plants

It is proposed that the regulation of nitrous oxide emissions from Danish treatment plants be implemented through a “light” version called the **BASE METHOD**, which is suitable for screening and monitoring emissions. The BASE method is ideal for an initial implementation phase of the regulation as it would be relatively simple to deploy and operate, while providing a *relatively* accurate measure of nitrous oxide emissions from Danish treatment plants.

With a minimal number of sensors, measurements and calculations, the BASE method is a pragmatic approach to implementing regulation across all treatment plants simultaneously. Nitrous oxide sensors are currently installed at approximately 20–30 treatment plants across Denmark. This means that there are approximately 50–60 treatment plants with a capacity superior to 30,000 PE that lack measuring equipment. Including smaller treatment plants in the regulation (10,000 PE and above) would necessitate more extensive procurement and installation of sensors for measuring nitrous oxide emissions.

Following the initial phase with one year of measurement data, a *valid* emission factor will be established for all treatment plants, along with a *valid* baseline emission, which can be used to reassess the current baseline emission (cf. Section 5) and potentially revise the established limit value.

That said, the limitation of the BASE method lies in its reliance on minimal measurement points, which will likely result in greater extrapolation for estimating nitrous oxide emissions. The method is therefore susceptible to inaccuracies if it is assumed that multiple process tanks/lines produce and emit nitrous oxide at identical levels. While for numerous treatment plants, the nitrous oxide emissions from the different processing lines are generally similar, variations do arise at some treatment plants on account of uneven loading, irregular aeration and slight differences in sludge concentrations – which naturally affects both the production and the emission of nitrous oxide. If assumptions and extrapolations are used instead of physical measurements, there is a risk that the emission factor may become inaccurate.

All facilities identified in the screening (BASE method) as having an emission factor that exceeds the established limit value should transition to a more precise measurement approach, known as the **EXTPADED METHOD**, which entails utilising additional meters and analyses in order to refine the emission factor and enhance understanding of the nitrous oxide issue at the plant.

It is crucial for plants with emission factors that exceed the limit value to obtained more detailed insight into how and where nitrous oxide is generated so as to enable the implementation of effective measures to reduce emissions.

6.2.1 BASE method

Nitrous oxide to be measured from each *type* (TABLE 6.1) of aerated biological process/tank at the treatment plants. Tanks with identical conditions (loading, SS, and control) are regarded as one and the same type.

If there are multiple types of aerated biological processes (types I-III), measurements should be taken at one location within each type.

The total nitrous oxide emission factor for the facility is calculated from one measuring point per type through extrapolation.

If a treatment plant’s nitrous oxide emissions exceed the limit value, additional investigations are necessary to assess the complete extent of these emissions. It will therefore be essential to measure nitrous oxide emissions from each aerated biological process/tank at the treatment plant in question (see EXPANDED method).

6.2.2 EXPANDED method

Measurements of nitrous oxide to be taken from *every single* aerated biological process/tank at the treatment plants.

This requirement applies to all treatment plants that exceed the prescribed limit value and must therefore initiate additional measurements to map emissions across all biological tanks.

The most precise measurement is achieved by taking readings from all tank sets. This approach minimises both known and unknown variables among process lines of the same type that give rise to different nitrous oxide emissions from two “identical” process tanks, for example – where issues may include variations in SS concentration, unequal distribution of wastewater flow in distribution structures and differing set point adjustments in aeration control.

The emission factor of the sewage treatment plant can thus be calculated from measurements in all the aerated tanks and by extrapolating the data from the DN tanks.

TABLE 6.1. Types of biological processes at treatment plants which may cause nitrous oxide production and emission

TYPE I a: Common activated sludge main processes with uniform conditions (load, SS and control)	BioDenitro Recirculation plant Plug flow Step-feed
TYPE I b: Tank sets that significantly differ from others	> 3 kg SS difference Other load conditions Other control/operation

TYPE I a: Common activated sludge main processes with uniform conditions (load, SS and control)	BioDenitro Recirculation plant Plug flow Step-feed
TYPE II: Biofilm and hybrid plant main processes	Biocontrol Membrane Aerated Bioreactor (MABR) Membrane Bioreactor (MBR) Activated Return sludge Process (ARP) Integrated Fixed Film Activated Sludge (IFAS)
TYPE III: Secondary stream processes (reject water treatment)	Anammox Activated Return sludge Process (ARP)

6.3 Valid and consistent method for measuring nitrous oxide emissions from various plant types

The following section describes how valid and consistent measurements can be performed, depending on the plant configuration and type of aeration in the treatment plants. In order to provide the most accurate representation of the nitrous oxide emissions, sensors must be positioned in those places where emissions are predicted to be most representative. Drawing on literature and case studies, several recommendations have been developed regarding measurements in the aerated zones of different plant types.

It should be noted that the number of studies focused on nitrous oxide dynamics in relation to sensor placement is relatively limited, and there is currently no definitive *most valid* placement for nitrous oxide sensors across treatment plants. The optimal sensor placement depends on the type of treatment plant it is to be installed in, as well as specific plant conditions.

Nevertheless, guidelines do exist for positioning sensors both generally across different plant types and specifically tailored to certain types of plants. These guidelines aim to ensure the most precise and representative measurement of nitrous oxide emissions, drawing on past experience from development projects, recommendations from N_2O sensor suppliers and literature reviews.

General recommendations applicable across various plant types (Unisense Case, Unisense Manual):

- The sensor should be installed in the aerated zone of the biological process where nitrogen removal occurs.
- It is essential to measure in that part of the treatment plant where most nitrogen conversion occurs – typically where aeration takes place, resulting in nitrous oxide being released into the atmosphere.
- The most accurate reading of nitrous oxide emissions is usually taken one-third to halfway into the aerated zone (Unisense Case 1, Unisense Case 2, Unisense Manual).
- Sensor placement in the water column must adhere to the instructions provided by the chosen technology supplier. For example, when using Unisense liquid-phase sensors, they should be positioned approximately 30 cm below the water surface and be continuously submerged, while off-gas sensors should be installed above the water surface.
- The sensor should be placed at a distance from the edge of the process tank, within a well-mixed area of the water column.
- It is a good idea to place the sensor in the same tank as other sensors, such as NH_4, NO_3, NO_2, dissolved oxygen (DO) and SS. This facilitates analysis of the

relationship between nitrous oxide production and the operational conditions in the tank and makes it possible to use the sensor as a control tool to reduce nitrous oxide emission.

- For treatment plants with multiple lines or tanks, it is recommended to prioritise purchasing additional sensors. One sensor should then be placed in the aerated zone of each tank in order to achieve simultaneous measurements across tanks, rather than measuring in both aerated and non-aerated zones of a single tank.

Depending on where in the aerated zone the nitrous oxide sensor is positioned, the process conditions (oxygen saturation, underlying currents, load, etc.) will have a crucial impact on the measurement of nitrous oxide emissions (Andreasen, 2013). It is therefore essential to select a position in the aerated area that represents the mean nitrous oxide concentration in order to achieve an accurate measurement of the emissions from the treatment plant.

Placing the nitrous oxide sensor between one-third of the way and halfway into the aerated zone is an excellent location for obtaining a representative value of the nitrous oxide emissions from the entire zone. However, the specific location depends on the type of plant and the type of aeration system. *Specific recommendations* for this can be found in TABLE 6.2 below.

Several *cases* with representative sensor placements have been prepared as examples and for guidance, as shown in Appendix 4.

TABLE 6.2. Optimal sensor placement in relation to plant type and aeration type

	Type of aeration	
Plant type	**Bottom aeration**	**Surface aeration**
Regardless of plant type: **Liquid sensor:** A direct measurement of N_2O dissolved in the liquid phase followed by an estimation of N_2O in the exhaust air, resulting in the calculated emissions. **Off-gas sensor**: Gas-hood + analyser: a direct measurement of N_2O in the gas phase, along with a measurement of released air volume for off-gas emissions calculations. (Bellandi et al. 2017)	In systems where aeration occurs in sections of the tanks, it is recommended to place the sensor approximately one-third to halfway downstream within the aeration zone. Several facilities have achieved most success in positioning the liquid-phase sensors before the rotors so as to prevent detachment or damage from the high turbulence after the rotors.	In systems with surface aeration, the sensor should be positioned at a representative point with good oxygenation in the aerated zone where the rotors are active and operational. Choose the rotor with the most operating hours (if there is any difference), ideally near the inlet where NH_4 concentrations are high.
Recirculating	Both the liquid phase and off-gas sensors should be placed approximately one-third to halfway downstream in the nitrification tank within the area covered by diffusers. See Appendix 4, case A.	
Biodenitro/Biodenipho	It is recommended to place both the liquid phase and off-gas sensors about one-third to halfway downstream within the oxygenated zone.	
Plug flow	Both the liquid phase and off-gas sensors should be placed approximately one-third to halfway downstream within the area covered by diffusers.	

	Type of aeration
Biofilm (Uri-Carreño et al. 2024)	Position sensors in areas with the highest nitrogen turnover and where placement is feasible.
Reject water processes	It is recommended to position one sensor in each reject water container. Place sensors in areas where nitrogen turnover is elevated.
Sequence Batch Reactor (Unisense Instructions)	It is recommended to place both the liquid phase and off-gas sensors wherever feasible within the tank.

6.4 Guidelines for measuring nitrous oxide emissions from treatment plants

This section outlines general guidelines for measuring nitrous oxide and calculating an annual emission factor for nitrous oxide. The guidelines are comprehensively applicable to all types of plants and are designed to ensure treatment plants comply with designated emission limits.

Previous measurement campaigns in Denmark and internationally did not featured a “standard” for measurements, extrapolations and calculations (see Section 5).

Such as standard is, however, crucial when introducing a limit value, as this ensures adherence to *good practice* for measurement technology, calculations and extrapolations, including:

- Set-up, commissioning, and maintenance of measuring equipment
- Overview of necessary data sources, including validation and data cleaning
- Self-monitoring
- “BAT” measurement method – valid and aligned with current measurement technology
- Emission calculations covering both baseline, current figures and reductions

Emission factor determined by nitrogen supply

As mentioned earlier (Section 5), the emission factor is calculated based on nitrogen load and a corresponding factor. In the MUDP project, the factor (baseline of 0.84% $N_2O\text{-}N$ / $TN_{\text{inflow, biology}}$) is calculated using the specific nitrogen load in biological processes:

- Single-stage treatment plant: Nitrogen received via inflow to the treatment plant (post grate and post sand and grease traps).
- Two-stage treatment plant: Nitrogen in the inflow to the process tank (i.e. post primary tank/clarification/pre-filtration).
- Secondary stream processes: Nitrogen in the inflow to the secondary stream process (typically reject water treatment).

For many treatment plants, however, taking flow-proportional 24-hour samples is challenging unless performed at the inflow to the treatment plant, where accredited samples – in accordance with the plant’s discharge permits – are already collected. For this reason, it would be pragmatic and less onerous and costly for treatment plants to use existing accredited nitrogen analyses from the inflow to calculate the emission factor.

Annual emission factor

Significant seasonal variation is often observed in nitrous oxide emissions from treatment plants. The most representative emission factor is therefore derived from an average annual discharge, with data collected continuously over an entire calendar year. Measurements are conducted continuously from January through December, and the emission factor is determined once a year based on the average annual nitrous oxide emission relative to the average nitrogen load applied during the year (FIGURE 6.2).

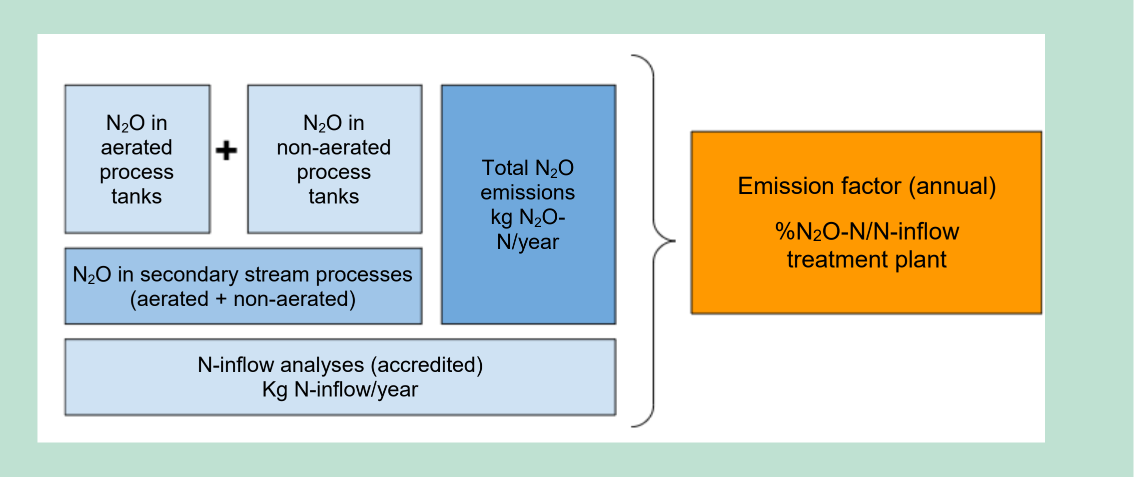


FIGURE 6.2. Illustration of elements utilised in calculating the average annual emission factor

6.4.1 Description of the different elements involved in calculating the emission factor

The emission factor is calculated based on measurements and extrapolations.

Emissions from aerated process tanks, including both primary process and any secondary stream processes, must be included.

Measuring equipment must be installed in the aerated process tanks in order to allow determination of the nitrous oxide emissions from them.

If the plant operates aerated secondary stream processes, measuring equipment must be installed in them as well.

If not all tank sets/process lines are measured, an extrapolation must be performed corresponding to for the total number of aerated process tanks at the treatment plant.

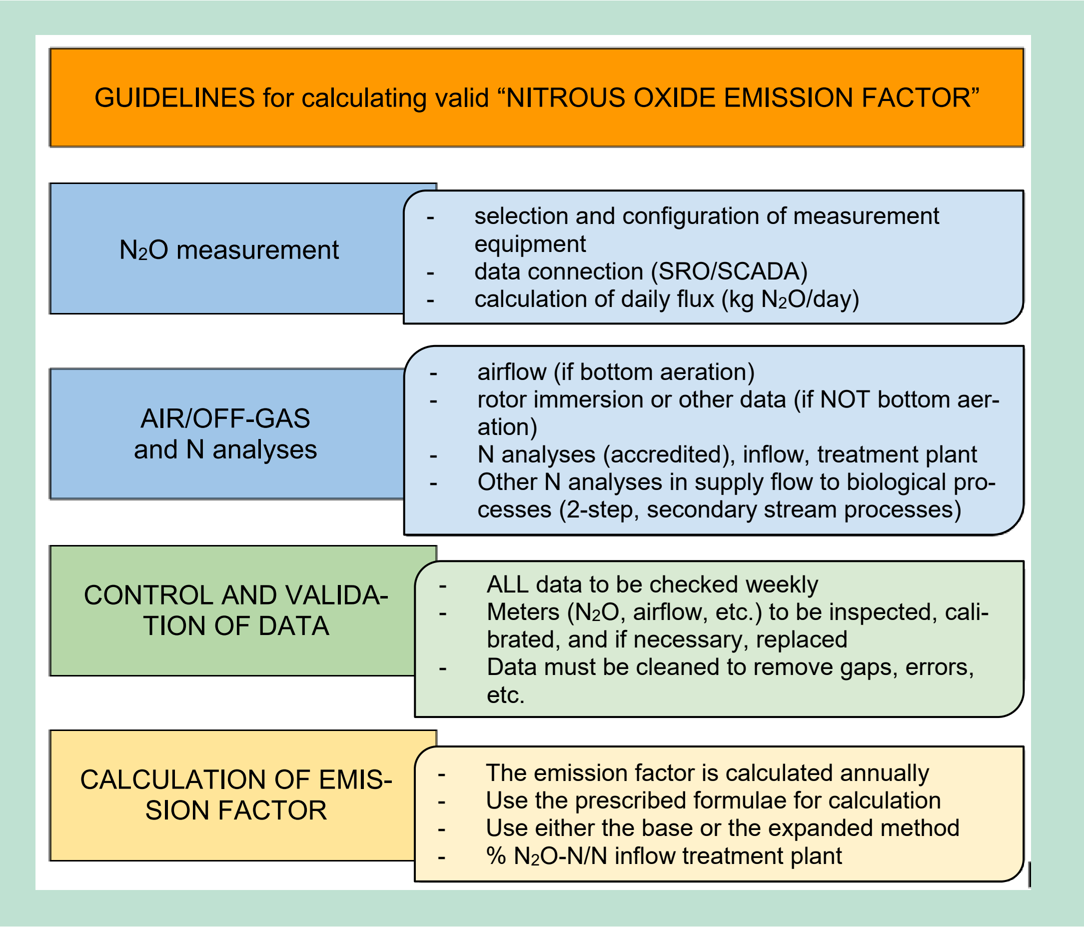
Emissions from non-aerated process tanks:
It is not considered necessary to install measuring equipment in non-aerated process tanks (DN tanks). Any such emissions are calculated by extrapolation as 10% of the emissions in aerated areas.

6.4.2 Guidelines for treatment plants

A set of guidelines has been developed for staff at treatment plants (utilities and industry) to serve as a checklist to ensure *valid and uniform* measurement and emission calculations.

The guidelines below outline the key points (FIGURE 6.3):

- Nitrous oxide measurement
- Other relevant measurements and analyses (air/off-gas and nitrogen analyses)
- Data control and validation
- Calculation of the emission factor



GUIDELINES for calculating valid "NITROUS OXIDE EMISSION FACTOR"

N_2O measurement
- selection and configuration of measurement equipment
- data connection (SRO/SCADA)
- calculation of daily flux (kg N_2O/day)

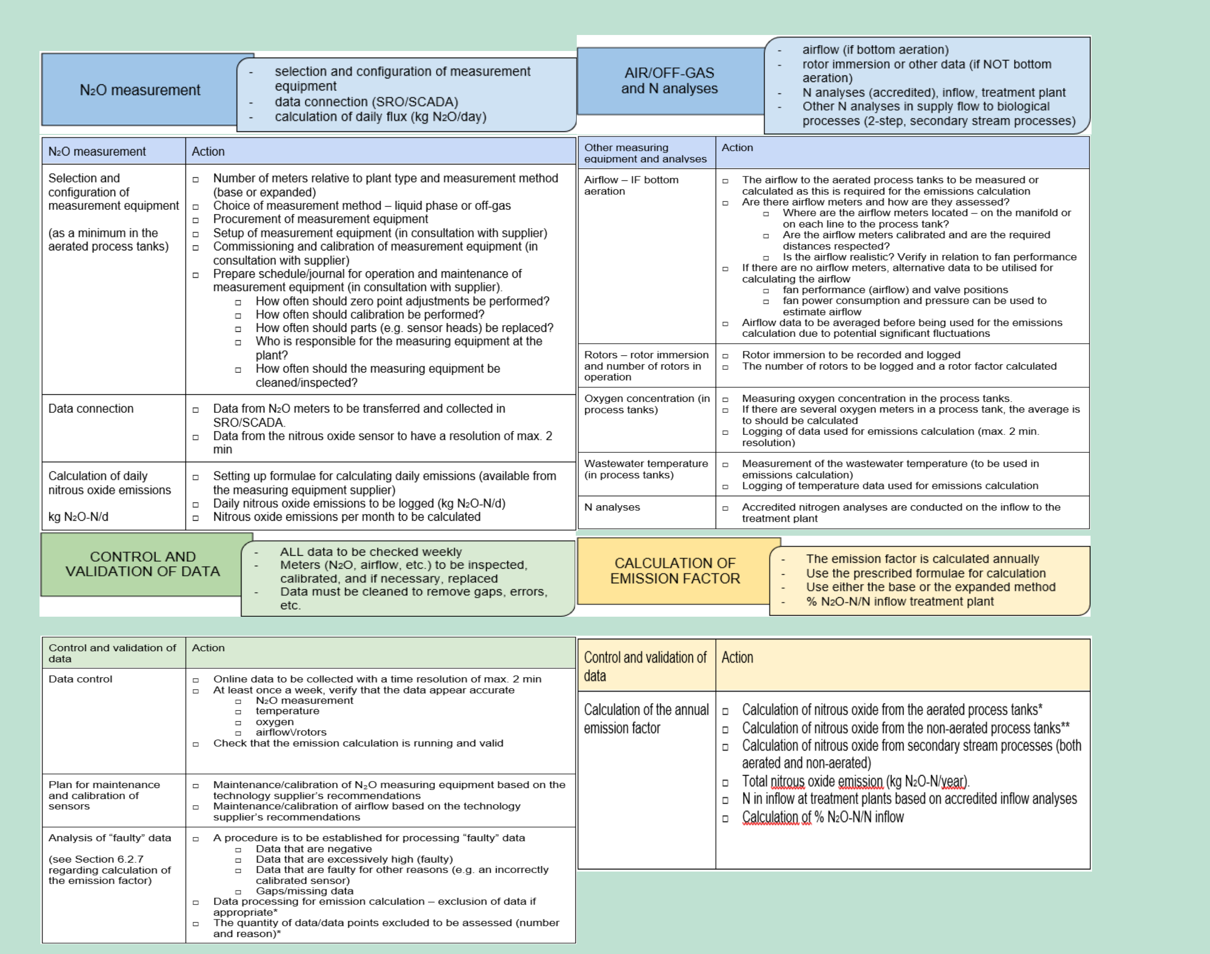
AIR/OFF-GAS and N analyses
- airflow (if bottom aeration)
- rotor immersion or other data (if NOT bottom aeration)
- N analyses (accredited), inflow, treatment plant
- Other N analyses in supply flow to biological processes (2-step, secondary stream processes)

CONTROL AND VALIDATION OF DATA
- ALL data to be checked weekly
- Meters (N_2O, airflow, etc.) to be inspected, calibrated, and if necessary, replaced
- Data must be cleaned to remove gaps, errors, etc.

CALCULATION OF EMISSION FACTOR
- The emission factor is calculated annually
- Use the prescribed formulae for calculation
- Use either the base or the expanded method
- % N_2O-N/N inflow treatment plant

FIGURE 6.3. General guideline intended as inspiration for the Danish Environmental Protection Agency in drafting relevant guidelines for the introduction of nitrous oxide regulation

A checklist of points that treatment plants must verify has been created for the four sub-elements (see also Appendix 5)



N₂O measurement

- selection and configuration of measurement equipment
- data connection (SRO/SCADA)
- calculation of daily flux (kg N_2O/day)

N_2O measurement	Action

Selection and configuration of measurement equipment
(as a minimum in the aerated process tanks)
	☐ Number of meters relative to plant type and measurement method (base or expanded)
	☐ Choice of measurement method – liquid phase or off-gas
	☐ Procurement of measurement equipment
	☐ Setup of measurement equipment (in consultation with supplier)
	☐ Commissioning and calibration of measurement equipment (in consultation with supplier)
	☐ Prepare schedule/journal for operation and maintenance of measurement equipment (in consultation with supplier).
	  ☐ How often should zero point adjustments be performed?
	  ☐ How often should calibration be performed?
	  ☐ How often should parts (e.g. sensor heads) be replaced?
	  ☐ Who is responsible for the measuring equipment at the plant?
	  ☐ How often should the measuring equipment be cleaned/inspected?

Data connection	☐ Data from N_2O meters to be transferred and collected in SRO/SCADA. ☐ Data from the nitrous oxide sensor to have a resolution of max. 2 min
Calculation of daily nitrous oxide emissions kg N_2O-N/d	☐ Setting up formulae for calculating daily emissions (available from the measuring equipment supplier) ☐ Daily nitrous oxide emissions to be logged (kg N_2O-N/d) ☐ Nitrous oxide emissions per month to be calculated

AIR/OFF-GAS and N analyses

- airflow (if bottom aeration)
- rotor immersion or other data (if NOT bottom aeration)
- N analyses (accredited), inflow, treatment plant
- Other N analyses in supply flow to biological processes (2-step, secondary stream processes)

Other measuring equipment and analyses	Action

Airflow – IF bottom aeration	☐ The airflow to the aerated process tanks to be measured or calculated as this is required for the emissions calculation
	☐ Are there airflow meters and how are they assessed?
	  ☐ Where are the airflow meters located – on the manifold or on each line to the process tank?
	  ☐ Are the airflow meters calibrated and are the required distances respected?
	  ☐ Is the airflow realistic? Verify in relation to fan performance
	☐ If there are no airflow meters, alternative data to be utilised for calculating the airflow
	  ☐ fan performance (airflow) and valve positions
	  ☐ fan power consumption and pressure can be used to estimate airflow
	☐ Airflow data to be averaged before being used for the emissions calculation due to potential significant fluctuations

Rotors – rotor immersion and number of rotors in operation	☐ Rotor immersion to be recorded and logged ☐ The number of rotors to be logged and a rotor factor calculated
Oxygen concentration (in process tanks)	☐ Measuring oxygen concentration in the process tanks. ☐ If there are several oxygen meters in a process tank, the average is to should be calculated ☐ Logging of data used for emissions calculation (max. 2 min. resolution)
Wastewater temperature (in process tanks)	☐ Measurement of the wastewater temperature (to be used in emissions calculation) ☐ Logging of temperature data used for emissions calculation
N analyses	☐ Accredited nitrogen analyses are conducted on the inflow to the treatment plant

CONTROL AND VALIDATION OF DATA

- ALL data to be checked weekly
- Meters (N_2O, airflow, etc.) to be inspected, calibrated, and if necessary, replaced
- Data must be cleaned to remove gaps, errors, etc.

Control and validation of data	Action

Data control	☐ Online data to be collected with a time resolution of max. 2 min
	☐ At least once a week, verify that the data appear accurate
	  ☐ N_2O measurement
	  ☐ temperature
	  ☐ oxygen
	  ☐ airflow\/rotors
	☐ Check that the emission calculation is running and valid

Plan for maintenance and calibration of sensors	☐ Maintenance/calibration of N_2O measuring equipment based on the technology supplier's recommendations ☐ Maintenance/calibration of airflow based on the technology supplier's recommendations

Analysis of "faulty" data
(see Section 6.2.7 regarding calculation of the emission factor)
	☐ A procedure is to be established for processing "faulty" data
	  ☐ Data that are negative
	  ☐ Data that are excessively high (faulty)
	  ☐ Data that are faulty for other reasons (e.g. an incorrectly calibrated sensor)
	  ☐ Gaps/missing data
	☐ Data processing for emission calculation – exclusion of data if appropriate*
	☐ The quantity of data/data points excluded to be assessed (number and reason)*

CALCULATION OF EMISSION FACTOR

- The emission factor is calculated annually
- Use the prescribed formulae for calculation
- Use either the base or the expanded method
- % N_2O-N/N inflow treatment plant

Control and validation of data	Action
Calculation of the annual emission factor	☐ Calculation of nitrous oxide from the aerated process tanks* ☐ Calculation of nitrous oxide from the non-aerated process tanks** ☐ Calculation of nitrous oxide from secondary stream processes (both aerated and non-aerated) ☐ Total nitrous oxide emission (kg N_2O-N/year) ☐ N in inflow at treatment plants based on accredited inflow analyses ☐ Calculation of % N_2O-N/N inflow

FIGURE 6.3.1. A checklist of points

6.4.3 Conceptual sketches for the types and calculation of emission factors

Regardless of whether nitrous oxide emission measurements are performed using the BASE method or the expanded method (TABLE 6.3), a number of measurements must be taken and extrapolations performed. It is essential to adhere to the general guidelines, irrespective of the method used.

TABLE 6.3. Principles of the BASE and EXPANDED methods for measuring nitrous oxide emissions from Danish treatment plants

BASE method	**EXPANDED method**
Less accurate emission factor **Less comprehensive to perform**	**Most accurate emission factor** **Most comprehensive to perform**
Few N_2O measurement points (potentially just one)	Numerous N_2O measurement points
Multiple extrapolations	Few extrapolations
Refer to conceptual sketches and examples as well	Refer to conceptual sketches and examples as well

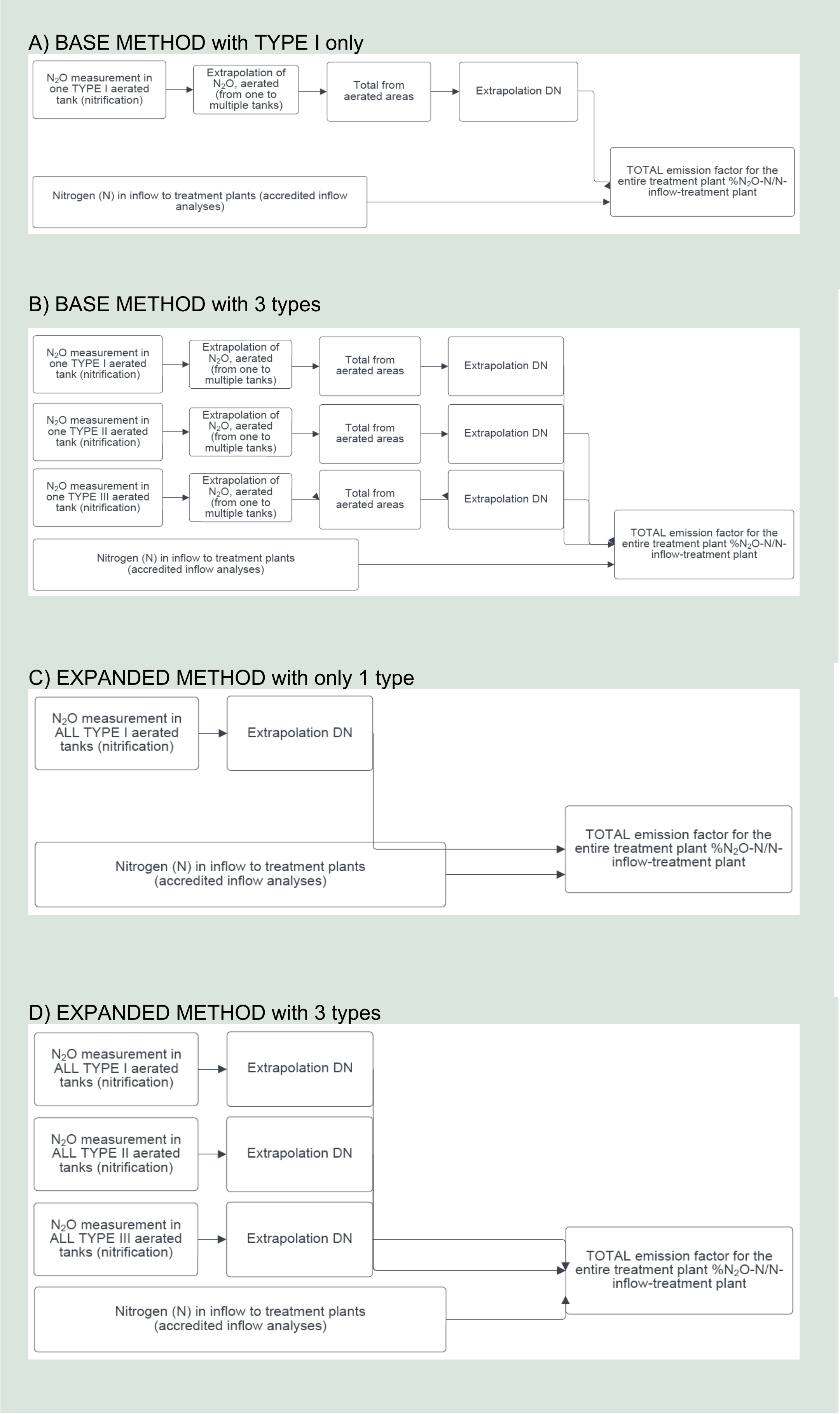
A number of conceptual sketches have been compiled to illustrate the calculation of the emission factor, dependent on whether the BASE or EXPANDED method is applied and which type(s) of plant are measured (see TABLE 6.1).

A. Conceptual sketch for BASE METHOD with only TYPE I (general activated sludge primary processes).

B. Conceptual sketch for BASE METHOD with 3 types – I + II + III (general activated sludge primary processes, biofilm/hybrid plant primary processes and secondary stream processes).

C. Conceptual sketch for EXPANDED METHOD with only TYPE I (general activated sludge primary processes).

D. Conceptual sketch for EXPANDED METHOD with 3 types – I + II + III (general activated sludge primary processes, biofilm/hybrid plant primary processes and secondary stream processes).



FIGUR 6.4 Conceptual sketches to illustrate the calculation of the emission factor

6.5 Implementation of nitrous oxide regulation under the *Environmental Protection Act*

It is anticipated that the coming regulation of nitrous oxide emissions from Danish treatment plants will be enforced under the Environmental Protection Act (LBK no. 1218), potentially under Sections 3 and 4, which also address emissions related to wastewater treatment. Should this be the case, the regulation of nitrous oxide could be incorporated into the *Executive Order on Wastewater* (BEK no. 1393), for instance, by adding additional clauses under Section 9 (targeted at treatment plants owned by a wastewater utility) and Section 10 (treatment plants owned by industrial enterprises).

Alternatively, an *Executive Order on Nitrous Oxide* could be developed, possibly drawing inspiration from the recently introduced *Executive Order on Sustainability* (BEK no. 1535).

It is not recommended to introduce the regulation of nitrous oxide emissions from Danish treatment plants under Section 28 of the Environmental Protection Act, as this would exclude the limit value(s) from the treatment plants' discharge permits. The reason for this is that implementing it under Section 28 would require utilities and companies with treatment plants exceeding 30,000 PE to apply for a new discharge permit in connection with introduction of the regulation. This could result in an administrative backlog in Danish municipalities, potentially delaying the enactment process.

Whether the regulation is implemented as an extension of existing executive orders or a new executive order on nitrous oxide is drafted, it will be necessary to establish a number of elements and guidelines, including:

- Self-monitoring
- Reporting and documentation
- Supervision
- Evaluation

Possible guidelines and elements in this regard will be discussed in the following section.

6.5.1 Elements in the regulation

Self-monitoring

The self-monitoring mechanism in the regulation of nitrous oxide emissions from Danish treatment plants will differ from current practices under the Executive Order on Wastewater, as it cannot be required to have these emissions tested through accredited technical inspection by an accredited laboratory. The reason for this is that the fundamental criteria required for enterprises to obtain under the Danish Accreditation Fund (DANAK) – the national body responsible for accreditation – have not yet been established. Instead, the regulation and self-monitoring will need to draw on a series of guidelines issued by the Danish Environmental Protection Agency to utilities in order to ensure *optimal validity* of the measurements of nitrous oxide emissions from treatment plants (see Sections 6.2, 6.3, and 6.4 for recommended *guidelines*).

Wastewater supply companies and industries with treatment plants that have an approved capacity of 30,000 PE or more must ensure that self-monitoring is established to measure nitrous oxide emissions accurately and in line with the guidelines from the Danish Environmental Protection Agency (see Sections 6.2, 6.3 and 6.4 for recommended *guidelines*). The term "self-monitoring" is taken to refer to clarifying and documenting the method used for the measurement and calculation of nitrous oxide emissions from the treatment plant, overseen or requested by the owner company, and ensuring that it is accurate and in compliance with current guidelines. Moreover, the self-monitoring programme must allow the supervisory authority to conduct oversight.

It must likewise ensure that the measurement of nitrous oxide emissions is carried out continuously and regularly throughout the year in order to record emissions across seasonal variations and the operational and load patterns at the plant.

The self-monitoring programme should include the following elements to ensure a comprehensive review of nitrous oxide emissions:

- System demarcation: Reference to the processes/plants expected to produce nitrous oxide emissions.
- Plant and monitoring: A reference to which plants/processes are subject to emission measurement.
- Operating log: A description of the operation and maintenance of the equipment used to measure emissions (for example, nitrous oxide sensor, temperature sensor, airflow meter, etc.), including the frequency of checks/calibration and the date of the most recent check/calibration.
- Corrective action plan: An action plan for reducing nitrous oxide emissions if the annual emissions of the treatment plant exceed the current limit value.

Reporting and documentation

A treatment plant's emissions are stated annually as the proportion of nitrous oxide emissions per the total inflow of nitrogen, calculated in accordance with the guidelines from the Danish Environmental Protection Agency (see Section 6 for recommended *guidelines*).

Wastewater utilities must report the calculated nitrous oxide emissions annually, along with the associated data basis, in a format specified by the supervisory authority.

The annual statement and report should include the following data basis to provide the supervisory authority with the relevant conditions to conduct supervision effectively:

- An overview of the emission points at the treatment plant, including established measurement points for nitrous oxide emissions and the processes/facilities from which emissions are calculated/extrapolated.
- An operating log for the measurement equipment used in calculating emissions.
- Data basis for nitrous oxide emissions from the treatment plant, including:
    - Calculated daily nitrous oxide emissions from measurement points established in the treatment plant processes/facilities (kg N_2O / day).
    - Estimated daily nitrous oxide emissions from processes/facilities at the treatment plant where measurement has not been established; includes any extrapolations applied (kg N_2O / day).
- Summary of the annual volume of nitrogen supplied to the treatment plant, with reference to accredited analyses conducted according to guidelines from the Danish Environmental Protection Agency for the measuring method that applies to the owner's treatment plant.
- The treatment plant's stated emission factor for the reporting year (% N_2O / $TN_{inflow,RA}$).
- Account of the operational conditions that cause an increase in nitrous oxide emissions if the treatment plant exceeds the established limit value for nitrous oxide emissions.

- Action plan for reducing emissions if the treatment plant exceeds the established limit value for nitrous oxide emissions.
- Assessment of the impact of emission reduction measures previously implemented in the event that the established value limit was previously exceeded, with a corresponding plan having been prepared and accepted.

Supervision

The Danish Environmental Protection Agency verifies whether the reporting basis and documentation for the treatment plant's nitrous oxide emissions are accurate, and whether the treatment plant is in compliance with the specified limit. This verification process is conducted annually and is based on the reporting framework for self-monitoring over 12 consecutive months.

If a treatment plant exceeds the established limit value for nitrous oxide emissions to which it is subject, the Danish Environmental Protection Agency must check that the measures outlined in the action plan for nitrous oxide emissions submitted are adequate and proportional to both the emission excess and its reduction potential. Once the action plan submitted has been approved by the Danish Environmental Protection Agency, the owning company is obligated to implement the measures described with a view to reducing nitrous oxide emissions.

In addition, the Danish Environmental Protection Agency must verify the effectiveness of emission reduction initiatives already commenced, if the established limit value was previously exceeded and a plan had been formerly devised and accepted.

Further actions by the Danish Environmental Protection Agency may include:

- Mandating that the owning company implement emission-reducing initiatives at treatment plants where the specified limit for nitrous oxide emissions is exceeded.
- Provide an exemption for a treatment plant that exceeds the specified limit value for nitrous oxide emissions if the owning company has demonstrated initiatives to reduce emissions through economically and technically feasible reduction measures.
- The Danish Environmental Protection Agency may adjust the measurement method for self-monitoring (*BASE/EXPANDED* method) applicable to each treatment plant, either relaxing or tightening regulations as deemed necessary.
- The Danish Environmental Protection Agency is responsible for overseeing the treatment plants' measurement, calculation and extrapolation of nitrous oxide emissions in order to ensure these processes comply with current guidelines and are executed correctly.

In addition to the routine annual inspections of treatment plants – which include reviewing sensor placements and calculations within the reporting framework – the supervisory authority may opt to conduct national validation campaigns using plant-wide measurement methods to check the accuracy of total emissions calculations from the treatment plants.

Evaluation

Limit values, measurement methodologies and guidance documents should be evaluated regularly and revised if necessary to accommodate advancements in technology and emerging knowledge in the sector.

A “progress” scenario example has been developed (see appendix 7) as *inspiration* for utilities and the Danish Environmental Protection Agency concerning the implementation of regulations and their associated oversight.

6.6 Emission reduction strategies

The goal of a 50% reduction in nitrous oxide emissions from treatment plants requires effective strategies that can be adopted by individual facilities in order to achieve it. There are numerous examples in the academic literature that describe and demonstrate the effectiveness of different strategies across different treatment plant systems. Common to these is the fact that they state a reduction potential – rather than a guarantee – and that they have principally been tested over short periods. The aims of the different strategies are to reduce nitrous oxide production, minimise the stripping of nitrous oxide from liquids and post-treat emissions directly in the gas phase itself.

Most initiatives intended to reduce production also lead to a decrease in emissions, and vice versa. These initiatives can be classified into various categories, but by their very nature they largely affect the same aspects: Balancing and optimising biological processes along with physical and chemical conditions to lower the total nitrous oxide emissions. The different initiatives are categorised as follows:

- Operational enhancement – including management
- Reduction of loading
- Expansion of capacity

There are also new technologies under development with the potential to decrease nitrous oxide in the atmosphere after it has been emitted from liquid sources. These include a catalytic (thermal) process developed by Haldor Topsøe, that is currently being demonstrated in the MUDP project “N_2O Abatement by Catalytic Treatment – NACAT”, and a catalytic (UV) process as seen in the ActiLayer technology developed by SUEZ, which is being demonstrated in the UK. However, it is not possible at present to detail the effects or costs involved.

6.6.1 Operational enhancement

The operational enhancement category includes measures such as optimisation and management – essentially initiatives that do not necessarily require new structures or unit operations. The focus here is thus on making better use of existing conditions to cut nitrous oxide emissions. This implicitly means that not all facilities can utilise all operational optimisation measures without capital investments; for example, carbon dosing cannot be controlled unless a carbon dosing facility is in place. Nonetheless, most systems can easily tweak existing control and operation parameters such as aeration and phase control, sludge age, mixing and, to some extent, load, without any capital expenditure. And if a carbon dosing system already exists, its management can be easily optimised to prioritise reducing nitrous oxide emissions. A brief overview of individual initiatives is provided below:

- Aeration and phase control
  This initiative can implement multiple strategies with the same “tools”.
  It should be noted that Veolia Water Solutions & Technologies Support (2023) holds a patent for a method to control aeration in treatment plants, which includes diminishing nitrous oxide.

- Control of oxygen concentration
  A high oxygen concentration can increase the ammonium turnover rate, potentially leading to the production of nitrous oxide via the hydroxylamine oxidation

mechanism and through nitrifying denitrification, which is linked to nitrite accumulation. Studies have shown that reducing oxygen concentration can decrease nitrous oxide emissions by 35% (Duan et al. 2020) and 60% (Chen et al. 2019). The principle of simultaneous nitrification-denitrification has been also utilised, with MST (2022) demonstrating a 27–46% reduction in nitrous oxide emissions. On a practical level, limited aeration directly reduces emissions on account of decreased mass transfer from liquid to gas, and Chen et al. (2016) estimated that a 75% reduction in aeration reduces nitrous oxide emissions by 53%.

- Control of aeration phases (nitrification vs. denitrification)
  Denitrification can be crucial to the removal of nitrous oxide – if it is produced – but it can also contribute to its production. In both scenarios, it is important to prevent dissolved nitrous oxide from transferring from denitrification to nitrification, as this could result in aeration causing stripping and emission of the dissolved gas. It is therefore a matter of ensuring adequate denitrification so that any nitrous oxide is denitrified and removed prior to aeration. This can be accomplished by increasing agitation, ensuring sufficient carbon availability and providing adequate anoxic time, for example. It is likewise important to avoid the unintentional introduction of oxygen from processes such as nitrification via recirculation.

- Sludge age
  Managing the sludge age is a direct method for influencing the overall sludge volume in a treatment plant. Increasing sludge age reduces the sludge load at the treatment facility, enhances biological capacity and decreases the specific ammonium turnover rate. This affects hydroxylamine oxidation, thereby reducing the risk of nitrous oxide production via this route (Law et al. 2012). The Danish Environmental Protection Agency (2023a) (VARGA) demonstrated a reduction in nitrous oxide emissions of 48–74% by increasing sludge concentration by 0.5–1.1 g SS/L. An increased sludge age can also promote the growth of nitrite-oxidising bacteria, which will help reduce the risk of nitrite accumulation and the subsequent production of nitrous oxide (Li et al. 2016).

- Load management
  Reducing the sludge load in a treatment plant affects the ammonium turnover rate, as previously noted in connection with sludge age management. It is not just the reduction of the total sludge load that has this effect. Adjustments in the management of, for instance, wastewater supply through flow equalisation, step-feed or alternating supply, or levelled reject water supply can result in a reduction of up to 66% in nitrous oxide emissions (Duan et al. 2021). Research by the Danish Environmental Protection Agency (2020) has also demonstrated that switching from serial to parallel flow operation resulted in decreased nitrous oxide production.

- Carbon
  Denitrification can both cause unwanted production of nitrous oxide and serve as a removal mechanism. As noted under aeration phase control, it is important to prevent nitrous oxide being transferred from a non-aerated to an aerated process, as this will lead to active emissions. If denitrification is restricted by either the limited availability of readily decomposable organic matter or restricted hydraulic residence time, the addition of external carbon sources such as acetate, molasses, ethanol, methanol or glycerol can expedite and enhance denitrification. Kishida et al. (2004) demonstrated a 90% reduction in a laboratory study by increasing the COD/N ratio from 2.6 to 4.5. The Danish Environmental Protection

Agency (2023a) (VARGA) conducted a full-scale carbon dosing test and observed a 5.1% reduction in nitrous oxide emissions during the trial period. Denitrification can also be enhanced by controlling the by-pass of primary treatment, for example, or incorporating internal hydrolysis processes (Danish Environmental Protection Agency, 2023b) (KLIVER).

6.6.2 Load reduction

The load reduction category includes measures that require capital investment. Both the measures selected target the same mechanisms as described in load management, but incorporate new unit operations here.

- Reject water – balancing tank
  The introduction of a balancing tank for reject water from dewatering of digested sludge facilitates the levelling of the reject water, which contains high nitrogen concentrations, throughout the day or during periods of low load. Unpublished findings at a Danish treatment plant have shown a 30% reduction in nitrous oxide emissions (Krüger A/S).
- Primary treatment – settling tank
  A primary treatment stage, such as settling, precipitation or filtration, decreases the volume of particulate matter entering the biological processes. Chen et al. (2020) report that approximately one-sixth of total nitrogen (TN) is present as particulate nitrogen, and that 50-80% of the particulate matter can typically be removed during pretreatment. It is therefore plausible to expect reduction in total nitrogen of at least one-twelfth through pretreatment. The reduction is therefore, the reduction is estimated at 10–12%. Moreover, removing organic matter will reduce the organic load. This decreases the oxygen required for organic matter degradation, freeing up more indirect time for slower nitrification or extended denitrification, which can both prove beneficial with regard to reducing nitrous oxide emissions.

6.6.3 Expansion of capacity

The capacity expansion category includes measures that require infrastructure investment. The measures selected primarily target the same mechanisms as described in load management, but incorporate new unit operations here. These represent expansions of biological capacity, but instead of increasing sludge concentration, they expand through the addition of biofilm using MABR and IFAS in existing volumes, along with new process volumes as extra active sludge. Aeration is aimed at the same mechanisms as detailed in aeration control.

- Membrane Aerated Biofilm Reactor – increased biological capacity in the same volume.
  MABR is likely to have a direct positive impact on reducing nitrous oxide emissions from treatment plants, and Uri-Carreño et al. (2023) demonstrated emission factors of 0.82% and 0.88% respectively for two MABR installations in Denmark. The total impact on the entire plant's nitrous oxide emissions is not known, although it is assumed that this technology holds potential similar to increasing sludge concentration as mentioned in sludge age management.

- Integrated Fixed-Film Activated Sludge – increased biological capacity within the same volume.
  Enhancing biological capacity by incorporating carrier media into biofilms within an integrated activated sludge process is assumed to offer potential similar to increasing sludge concentration, as discussed in sludge age management.

- Activated Sludge – expanding with increased process volume.
  Enhancing the biological capacity by augmenting the total process volume with additional activated sludge is assumed to have the same potential as increasing sludge concentration, as mentioned in sludge age management.

- Aeration – enhanced capacity and control, e.g. through bottom aeration.
  Increasing aeration capacity by switching from surface to bottom aeration or by installing bottom aeration in an existing denitrification process – and thus increasing the total aerated area – has the potential to increase opportunities to manage aeration better and adapt operations so as to reduce nitrous oxide emissions. This would be particularly relevant for high-load plants with insufficient capacity. While the precise impact of this measure in isolation is unclear, it may be essential for bringing more of the previously mentioned process optimisations into play.

TABLE 6.4 summarises reduction measures, their anticipated impact and related costs.

TABLE 6.4. Types of interventions that could be advantageously implemented at treatment plants to reduce nitrous oxide emissions, along with investment costs (one-time sums), expected delivery times and maintenance expenses.

Type of initiative	Option expected to achieve a 50% reduction	Measures	Reduction	Investment cost (< 40,000 PE, primary line)	Technical service life	Maintenance	Additional investment for extra lines (> 40,000 PE per line)
Operational enhancement	**Option A** 3 optional operational optimisations	Control: Aeration	**>50% reduction (cumulative effect of 3 measures)**	**DKK 250,000–400,000**	10 years	2%	**DKK 75,000–150,000**
		Control: Sludge age					
		Control: Load					
		Control: Carbon					
Load-reducing	Insufficient as stand-alone	Reject water balancing tank	**>30% reduction**	**DKK 1.5–2 million**	20 years	2%	**DKK 1.5–2 million**
		Primary treatment – e.g. settling or pre-filtration	**>10% reduction**	**DKK 15–30 million**	30 years	2%	**DKK 15–30 million**
Capacity expansion	**Option B** 1 optional capacity expansion	MABR – integration	**>50% reduction (1 measure)**	**DKK 10–15 million**	20 years	2%	**DKK 10–15 million**
		IFAS – integration					
	Excluded due to cost	AS – expansion – more process volume	**>50% reduction**	**DKK 50–80 million**	30 years	1.25%	**DKK 50–80 million**
	Insufficient as stand-alone	Aeration – increased capacity and control, e.g. through bottom aeration	**>10% reduction**	**DKK 10–15 million**	20 years	2%	**DKK 10–15 million**

7. Consequences of implementing measurement methods and limit values

7.1 Introduction

Setting a limit value for nitrous oxide emissions from Danish treatment plants will lead to a range of costs that should be weighed against the benefits. The main advantage of introducing a limit value is its central purpose: To reduce the climate impact of the treatment plants from nitrous oxide emissions. Costs for compliance with the limit value consist not only of costs for measuring and monitoring nitrous oxide emissions at the treatment plants, but also of the expenses associated with implementing measures to reduce nitrous oxide emissions. There may also be derivative costs related to other operations at the plant, such as reduced focus on energy production. Given the current level of knowledge, however, these cannot be included in the calculations.

The costs for measurement and reduction initiatives can be compared with the expected reduction in climate impact from these measures, which makes it possible to calculate a reduction cost for $CO_{2,}$, also known as a “shadow price”. The shadow price reflects the cost of reducing climate impact per tonne of CO_2-equivalents (CO_2-e), and it can be compared to shadow prices for other initiatives, both within and outside the water sector.

The foundation for calculating a shadow price from treatment plants' nitrous oxide reduction efforts will be reviewed in the following sections, including an examination of key uncertainties in the data basis and calculations. Finally, shadow prices will be calculated and presented for different sizes of treatment plants and reduction measures.

7.2 Uncertainties and limitations

It should be emphasised that there are significant uncertainties related to the calculation of shadow prices. For example, the information currently available regarding the baseline of nitrous oxide emissions from treatment plants is limited, which translates into significant uncertainty around the reductions achieved through implementation of different measures. Uncertainty also exists with regard to the costs of the possible reduction initiatives as these are defined by specific conditions at the individual treatment plants.

Given these uncertainties, the shadow prices have been calculated and presented as an interval, spanning from “the lowest possible expected shadow price” to “the highest possible expected shadow price”. The results should therefore be interpreted as estimates of magnitude rather than precise figures.

It should be noted that data are lacking for a number of the treatment plants, specifically the industrial treatment plants. While extensive data are available for common treatment plants managed by wastewater companies, data are less readily available for industrial treatment plants and for this reason they have not been factored into the calculated shadow prices.

The primary focus is on treatment plants with an approved capacity of 30,000 PE or more. Nevertheless, the calculation results for those plants with a capacity of 10–29,999 PE have also been included with a view to demonstrating the consequences of their likewise being required to comply with a nitrous oxide emissions limit.

7.3 Method and data

Highly detailed data from Danish sewage treatment plants have been used in order to provide the best possible basis for the calculations. These data have been made available by the Danish Environmental Protection Agency and cover 673 Danish treatment plants registered with the agency. The dataset includes details of the approved capacity of the plants, which can be utilised for categorising these plants, along with information about the measured volumes of nitrogen (N) in the inflows to the treatment facilities[12]. These data form the basis for conducting a range of impact assessments which in principle cover all Danish treatment plants – excluding industrial treatment plants – with an approved capacity of 30,000 PE or more.

The highly detailed basis in the form of information about capacity and nitrogen in the inflows to the treatment plants has been integrated with two different assumptions about nitrous oxide emission factors from Danish treatment plants. These emission factors are compared with others and, on this basis, are considered to be the most accurate for representing average nitrous oxide emissions from Danish treatment plants at the baseline.

The information regarding the treatment plants' approved capacity, nitrogen (N) inflow and estimated baseline nitrous oxide emissions is complemented by estimated costs for two distinct measurement technologies, namely liquid phase and off-gas sensors (see section 4.2), as well as the estimated costs for two groups of reduction strategies, i.e. optimisation and management, and capacity expansion (see Section 6.6).

On this basis, cost estimates and the resulting shadow prices have been calculated for different plant types on implementing recommended measurement and regulation methods aimed at achieving a 50% reduction from the stated baseline.

7.4 Treatment plant capacity and nitrogen volumes

According to data from the Danish Environmental Protection Agency, there are 673 common treatment plants operated by wastewater utilities. The data indicate an approved capacity of under 10,000 PE for almost 500 of these plants. In the table below, treatment plants from the data set are categorised by stated approved capacity, while the following table provides supplementary information on the recorded volume of nitrogen (N) in the inflow.

TABLE 7.1. Approved capacity of treatment plants

Approved capacity	Number	Number with approved capacity stated	Percentage with approved capacity	Approved capacity (PE)	Percentage of total approved capacity
0: 0–999 PE	296	292	44%	51,223	0%
1: 1–1,999 PE	48	48	7%	65162	1%
2: 2–9,999 PE	153	153	23%	781766	6%
3: 10–29,999 PE	84	84	13%	1486112	11%

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[12] Such data are unavailable for industrial treatment plants, however.

Approved capacity	Number	Number with approved capacity stated	Percentage with approved capacity	Approved capacity (PE)	Percentage of total approved capacity
4: 30–49,999 PE	28	28	4%	1055315	8%
5: 50–124,999 PE	39	39	6%	3043963	23%
6: 125–200,000 PE	14	14	2%	1986990	15%
7: > 200,000 PE	11	11	2%	4500500	35%
Total	**673**	**669**	**100%**	**12,971,031**	**100%**

The smallest plants with an approved capacity of less than 10,000 PE represent 74% of the 669 treatment plants numerically, but just 7% of the total approved capacity of slightly under 13 million PE. Similarly, the treatment plants with an approved capacity of 10–29,999 PE constitute only 11% of the total approved capacity.

TABLE 7.2. Approved capacity and recorded volume of nitrogen (N) in inflow

Approved capacity	Number with registered N	Total N in inflow (kg)	Percentage of N in inflow	Percentage of N in inflow, acc.
0: 0–999 PE	280	156558	1%	1%
1: 1–1,999 PE	48	156326	1%	1%
2: 2–9,999 PE	151	2082307	7%	8%
3: 10–29,999 PE	84	3889865	13%	21%
4: 30–49,999 PE	27	2684819	9%	30%
5: 50–124,999 PE	38	7178675	24%	55%
6: 125–200,000 PE	14	4045557	14%	68%
7: > 200,000 PE	10	9376491	32%	100%
Total	**652**	**29570598**	**100%**	

The table indicates that the smallest plants with an approved capacity of less than 10,000 PE account for approximately 8% of the total recorded volume of nitrogen (N) in the inflow. Including treatment plants with approved capacities of 10–29,999 PE adds a further 13%, whereby treatment plants below 30,000 PE collectively represent 21% of the total recorded volume of nitrogen (N) in inflows to the treatment plants.

The following sections will primarily focus on treatment plants with an approved capacity of 30,000 PE or more, as the following conditions apply to plants with lower capacities:

- Smaller treatment plants with an approved capacity of less than 30,000 PE exhibit significant variability in design and size, leading to differing potential for nitrous oxide emissions from their purification processes.
- Smaller treatment plants with an approved capacity below 30,000 PE represent only 18% of the total approved capacity across all treatment plants.
- The share of total recorded nitrogen (N) in inflow attributed to smaller treatment plants is around 21%, i.e. a small percentage of the nitrogen that potentially contributes to nitrous oxide emissions at these facilities.
- Most available data on nitrous oxide emissions pertain to treatment plants with an approved capacity of more than 30,000 PE (see Section 5).

As mentioned above, the following analyses focus primarily on treatment plants with an approved capacity of 30,000 PE and above. Treatment plants with an approved capacity of 1029,999 PE are included in calculations solely as a possible option with a view to illustrating magnitudes, in the event that this group should also be regulated under nitrous oxide emission limit values. Treatment plants with a capacity below 10,000 PE have been excluded from the following analyses.

TABLE 7.3. Approved capacity for treatment plants of 10,000 PE or more.

Approved capacity	Number of treatment plants	Percentage of plants	Approved capacity (PE)	Percentage of total approved capacity
4: 30–49,999 PE	28	16%	1055315	9%
5: 50–124,999 PE	39	22%	3043963	25%
6: 125–200,000 PE	14	8%	1986990	16%
7: > 200,000 PE	11	6%	4500500	37%
Total	**92**	**52%**	**10586768**	**88%**
[3: 10–29,999 PE	*84*	*48%*	*1486112*	*12%]*

For plants with an approved capacity of 10,000 PE and more, those under 30,000 PE comprise 48% in number, but represent only 12% of the total approved capacity.

TABLE 7.4. Approved capacity and recorded volume of nitrogen (N) in the inflow for treatment plants of 10,000 PE and over

Approved capacity	Number with N in inflow stated	Total N in inflow (kg)	Percentage of N in inflow	Percentage of N in inflow, acc.
4: 30–49,999 PE	27	2684819	10%	24%
5: 50–124,999 PE	38	7178675	26%	51%
6: 125–200,000 PE	14	4045557	15%	65%
7: > 200,000 PE	10	9376491	35%	100%
Total	**89**	**23285542**	**86%**	
[3: 10–29,999 PE	*84*	*3889865*	*14%*	*14%]*

Information is lacking with regard to the volume of nitrogen in the inflow to three treatment plants with a capacity of 30,000 PE and above, leaving 89 plants remaining. In principle, it is assumed that direct proportionality exists between the volume of nitrogen (N) in the inflow and nitrous oxide emissions from the treatment plants. As a result, approximately 86% of the total nitrous oxide emissions from the treatment plants are estimated to originate from the 89 plants with an approved capacity of 30,000 PE and above.

The group of plants with an approved capacity of 10–29,999 PE thus accounts for 14% of the recorded of nitrogen (N) in the inflow. This is approximately the same percentage as this group’s share of the approved capacity: 12%.

7.5 Factors that influence baseline nitrous oxide emissions

Familiarity with the baseline nitrous oxide emissions is crucial to the reductions achieved and ultimately in determining the shadow price for reducing the climate impact of nitrous oxide. Due to significant uncertainty regarding current emission levels (baseline), the following section presents various levels for the existing emissions, i.e. several potential baselines. In this context, it is imperative to take the following points into account:

- Considerable uncertainty exists regarding the current nitrous oxide emissions from treatment plants (baselines), as these emissions are not yet measured systematically. This in turn results in substantial uncertainty regarding the volume of nitrous oxide that can be reduced through the implementation of a limit value.

- Analyses of the most comprehensive Danish database currently available indicate an average emission factor of 0.84% $N_2O\text{-}N/TN_{inflow}$ (see Section 5.1.5). The IPCC uses a baseline of 1.6% $N_2O\text{-}N/TN_{inflow}$ (see Section 5.1.5), which is nearly double the average emission factor expected in Denmark. Calculations are also performed to determine the shadow price given this baseline.
- Studies suggest that the baseline nitrous oxide emissions (emission factors) of treatment plants tend to increase with greater plant capacity (see Section 5).
- Some processes at treatment plants emit more nitrous oxide than others, which means that the nitrogen load, as well as variations in plant types and configurations, can have a crucial effect on nitrous oxide emissions.

Given these focus points, there is currently substantial uncertainty regarding the overall potential reduction of nitrous oxide emissions at Danish treatment plants and at each specific facility.

To illustrate the impact of the uncertainty in emission factors related to nitrous oxide emissions from treatment plants, the following consequence analyses are based on the aforementioned emission factors of 0.84% $N_2O\text{-}N\backslash TN_{inflow}$ and 1.6% $N_2O\text{-}N\backslash TN_{inflow}$. To put these results into context even more clearly, a differentiated emission factor is also presented, which ranges between 0.5–2.25% $N_2O\text{-}N\backslash TN_{inflow}$, depending on the approved capacity of the treatment plants. The differentiated emission factors are determined from a relatively limited number of measured emission factors, as indicated in TABLE 7.5. The table also illustrates the average emission factors that are included in the following sections.

TABLE 7.5. Emissions factors used in the baseline

Approved capacity	Number	Average of 0.84%	Average of 1.6%	Differentiated emission factor	cf. MUDP 2020 and VARGA
4: 30–49,999 PE	27	0.84%	1.60%	0.79%	Skanderborg (1.2), Kalundborg (0.4)
5: 50–124,999 PE	38	0.84%	1.60%	1.25%	Søholt (0.3), Aalborg East (0.25)
6: 125–200,000 PE	14	0.84%	1.60%	2.25%	
7: > 200,000 PE	10	0.84%	1.60%	2.25%	Avedøre (approx. 4 prior to reduction); Marselisborg (approx. 3.5 prior to reduction)
Total	**89**	**0.84%**	**1.60%**	-	
[3: 10–29,999 PE	*84*	*0.84%*	*1.60%*	*- 0.50%*	*Hyllingeriis (0.4), Næstved (0.1)]*

Assuming an average emission factor of 0.84% $N_2O\text{-}N\backslash TN_{inflow}$, the limit value needs to be set at 0.42% $N_2O\text{-}N\backslash TN_{inflow}$ to achieve a total reduction of 50%. Similarly, assuming an average emission factor of 1.60% $N_2O\text{-}N\backslash TN_{inflow}$ in the baseline, the limit value needs to be set at 0.80% $N_2O\text{-}N\backslash TN_{inflow}$ to achieve a total reduction of 50%.

With regard to the differentiated emission factors included in the perspectivation, they have been established based on a limited dataset mainly from MUDP projects (Danish Environmental Protection Agency, 2020 and 2023). It is important to emphasise that this is an estimate of how the emission factors for different sized treatment plants may vary. However, given that the data is based solely on two projects, there is considerable uncertainty regarding the levels of these differentiated emission factors. Consequently, this should merely be viewed as an illustrative perspective on the implications of assuming varying emission factors.

The following table shows the proportion of nitrogen (N) at inflow that is annually converted to nitrous oxide at different rates: 0.84% $N_2O\text{-}N/TN_{inflow}$, 1.60% $N_2O\text{-}N/TN_{inflow}$, and according to the differentiated emission factor presented in TABLE 7.5.

TABLE 7.6. Proportion of nitrogen (N) at inflow that is converted to nitrous oxide annually

Approved capacity	**N in inflow (tonnes)**	**Avg. at 0.84%, Activated N (tonnes)**	**Avg. at 1.6%, Activated N (tonnes)**	**Diff. emission factor, Activated N (tonnes)**
4: 30–49,999 PE	2685	23	43	21
5: 50–124,999 PE	7179	60	115	90
6: 125–200,000 PE	4046	34	65	91
7: > 200,000 PE	9376	79	150	211
Total	**23286**	**196**	**373**	**413**
Average emission coefficient		0.84%	1.60%	1.77%
[3: 10–29,999 PE	*3890*	*33*	*62*	*19]*
[Avg. emission coefficient		*0.84%*	*1.60%*	*1.59%]*

The table indicates that the weighted average emission factor is 1.77% $N_2O\text{-}N/TN_{inflow}$, assuming it varies between plant sizes as mentioned in TABLE 7.5, with a substantial portion of total emissions stemming from the large plants. This weighted average emission factor of 1.77% $N_2O\text{-}N/TN_{inflow}$ is close to the average factor of 1.60% $N_2O\text{-}N/TN_{inflow}$ from the IPCC (see Section 5.1.5), although it is more than double the factor of 0.84% $N_2O\text{-}N/TN_{inflow}$ derived from MUDP projects (see Section 5.1.5).

Including plants with an approved capacity of 10–29,999 PE reduces the average weighted emission factor to 1.59% $N_2O\text{-}N/TN_{inflow}$, as the differentiated emission factor of 0.50% $N_2O\text{-}N/TN_{inflow}$ for this group lowers the overall average.

7.6 Limit values for nitrous oxide emissions

Based on a target of a 50% reduction in nitrous oxide emissions from Danish treatment facilities (see Section 2), the requisite limit values can be unequivocally determined, assuming all facilities start with a uniform emission factor as a baseline.

Assuming that all treatment facilities have an emission factor of 0.84% $N_2O\text{-}N/TN_{inflow}$, they must, as outlined in section 5.1.5, reduce the emission factor to 0.42% $N_2O\text{-}N/TN_{inflow}$ and similarly for a baseline emission factor of 1.60% $N_2O\text{-}N/TN_{inflow}$. However, with varying baseline emission factors, the treatment plants in each size category must either halve their emission factor, or a single limit value must be introduced that all facilities must comply with to meet the 50% reduction target for nitrous oxide emissions from Danish treatment facilities. If a single limit value for all treatment facilities is introduced, those plants below the threshold would be exempt from implementing reduction measures, while facilities with the highest emission factors would be required to cut their nitrous oxide emissions by more than 50%.

The following points need to be taken into account in this regard:

- Treatment plants that are already operating with a low emission factor might find it challenging to reduce their emissions even further, or they may find that the necessary measures incur significant costs. This suggests that a single limit value for all could be more appropriate.

- Differentiated limit values based on varying baseline emission factors could be viewed as “fairer”, as they more precisely account for the group classification of each facility than a single limit value [13].

The table below illustrates the impacts of implementing a single limit value in order to achieve the target of a 50% reduction in nitrous oxide emissions from Danish treatment plants. Please note that as in TABLE 7.6, the table states the proportion of nitrogen in the inflow that is converted into nitrous oxide. As there is direct proportionality in the calculations between the percentage of nitrogen from the inflow converted to nitrous oxide and the climate impact indicated in CO_2 equivalents, the calculated climate impact is not shown in the table.

TABLE 7.7. Single limit value of 0.90% and differentiated emission factors in the baseline

Approved capacity	Number of treatment plants	N in inflow (tonnes)	Diff. emission factors used in the baseline	Activated N (tonnes) in baseline	Activated N (tonnes) at limit value of 0.90%
4: 30–49,999 PE	27	2685	0.79%	21	21
5: 50–124,999 PE	38	7179	1.25%	90	65
6: 125–200,000 PE	14	4046	2.25%	91	36
7: > 200,000 PE	10	9376	2.25%	211	84
Total	**89**	**23286**		**413**	**207**
Average emission coefficient				1.77%	0.89%
Change in calculated N discharge				-	50%

The table above makes it clear that with the specified emission factors at the baseline, a 50% reduction in nitrous oxide emissions can be achieved by introducing a limit value of 0.90% $N_2O\text{-}N/TN_{\text{inflow}}$ for all treatment plants with an approved capacity of 30,000 PE and above. The assumption is that all treatment plants adhere to this limit, meaning those with higher emission factors (1.25% $N_2O\text{-}N/TN_{\text{inflow}}$ and higher) will reduce them to 0.90% $N_2O\text{-}N/TN_{\text{inflow}}$, while those below the limit maintain their current emission factor (0.79% $N_2O\text{-}N/TN_{\text{inflow}}$).

As illustrated by the table, only treatment plants with an approved capacity of 50,000 PE and above will need to reduce their emissions in this scenario. This corresponds to 62 treatment plants. With the introduction of the 0.90% $N_2O\text{-}N/TN_{\text{inflow}}$ limit, the average emission factor would decrease from 1.77% $N_2O\text{-}N/TN_{\text{inflow}}$ to 0.89% $N_2O\text{-}N/TN_{\text{inflow}}$, resulting in an overall reduction of 50%.

Including smaller treatment plants with an approved capacity of 10–29,999 PE reduces the average emission coefficients. However, it is still the 62 treatment plants with an approved capacity of 50,000 PE and above that are required to implement the reductions if the goal is to achieve a 50% reduction. In that case, the limit value would have to be lowered – to 0.85% – since emissions from smaller treatment plants of 10–29,999 PE are also included.

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[13] See Section 3 for a review and discussion of the benefits and drawbacks of different limit value designs for nitrous oxide emissions from Danish treatment plants.

TABLE 7.8. Single limit value of 0.85% and varying emission factors in the baseline

Approved capacity	Number of treatment plants	N in inflow (tonnes)	Varying emission factors	Nitrogen (N), baseline (tonnes)	Nitrogen (N), with a limit value of 0.85% N_2O-N/TN inflow
[3: 10–29,999 PE	*84*	*3890*	*0.50%*	*19*	*19]*
4: 30–49,999 PE	27	2685	0.79%	21	21
5: 50–124,999 PE	38	7179	1.25%	90	61
6: 125–200,000 PE	14	4046	2.25%	91	34
7: > 200,000 PE	10	9376	2.25%	211	80
Total	**173**	**27175**		**432**	**216**
Average emission coefficient				1.59%	0.79%
Change in calculated N discharge				-	50%

TABLE 7.7 and TABLE 7.8 thus show the level for a single limit value if the goal is a 50% reduction in nitrous oxide emissions, with emission factors varying according to the approved capacity of the treatment plants.

7.7 Costs associated with measuring nitrous oxide emissions

As outlined in Section 4, various technologies are available for measuring nitrous oxide emissions from treatment plants. The basis for the following calculated costs for measuring nitrous oxide emissions takes as its starting point the estimated average annual costs for the two measurement technologies: liquid-phase sensors and off-gas sensors. The estimated average annual costs for the sensors include investment in sensors, controllers, cables and calibration kits, as well as the annual operational costs for replacing sensor heads and calibration kits. It is assumed that both types of sensors have a service life of 15 years, and a calculation interest rate of 3.5% has been applied, corresponding to the socioeconomic discount rate for the years 0–35[14]. As the socioeconomic discount rate is a real interest rate, calculations have also been performed in fixed prices at the 2024 price level. The calculation interest rate of 3.5% is applied in both the socioeconomic and corporate economic calculations, as this rate is considered to align with the rate used by wastewater utilities[15].

It should be noted that the estimated average annual costs for the two measurement technologies do not include costs associated with electrical work for sensor installation, potential service agreements, extra salary costs for operational staff or programming and extensions of PLCs (Programmable Logic Controllers) at the treatment plant. These costs are likely to vary significantly between plants of a similar size and approved capacity.

TABLE 7.9. Assumptions for Cost Calculations for Measurement

	Liquid-phase Sensor	Off-gas Sensor
Service life (years)	15	15
Discount rate (real)	3.5%	3.5%
Price level (year)	2024	2024

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[14] Ministry of Finance, Documentation memo – the socioeconomic discount rate, 7 January 2021.

[15] Given the overall uncertainty of the estimates, the calculated average annual costs in the economy are not adjusted by the net tax factor of 1.28. The corporate economic costs are therefore presumed to equal the societal economic costs associated with the measurement technologies. For more information, see Ministry of Finance, Guidance in Socioeconomic Impact Assessments, June 2023.

	Liquid-phase Sensor	Off-gas Sensor
Investment	Sensors, Controllers, Cables and Calibration Kits	
Operating costs	Sensor Heads and Calibration Kits	

7.7.1 Costs for Measurement Using the "BASIS Method"

If the “BASE method” for measuring nitrous oxide emissions described in Section 6.2 is implemented at the treatment plants, this will require 92 treatment plants[16] with an approved capacity of at least 30,000 PE to install a single sensor per plant. A small number of plants may need to install more than one sensor using the BASE method, as they might be operating several types of aerated biological processes (secondary stream treatment or MBBR plants, etc.). There is no cohesive overview of which treatment plants this will apply to, but it is not expected to affect more than a few. For this reason, one sensor per plant is assumed for further calculations. The estimated investment costs for installing one sensor per plant range from DKK 7.2–13.8 million for the 92 plants, depending on whether liquid or gas sensors are used. The calculated average annual costs are similarly DKK 1.7–2.3 million for off-gas sensors and liquid-phase sensors, respectively. As TABLE 7.10 also shows, the estimated investment costs for treatment plants with an approved capacity of 10–29.999 PE total DKK 6-6–12.6 million, while the calculated average annual costs amount to DKK 1.5–2.1 million for this group of plants.

It should be noted that although the investment costs for off-gas sensors are nearly double those for liquid-phase sensors, the calculated average annual costs are lower for off-gas sensors as the annual operating expenses for these sensors are significantly lower than those of liquid-phase sensors. The distribution of costs across the different categories of treatment plants is presented in the table below.

TABLE 7.10. Simple measurement programme, “BASE method”, sensor costs

Approved capacity	Number of treatment plants	Total of average annual costs, liquid-phase sensor (DKK million/year)	Total of average annual costs, off-gas sensor (DKK million/year)	Total investment, liquid-phase sensors (DKK million/year)	Total investment, off-gas sensors (DKK million/year)
4: 30–49,999 PE	28	0.7	0.5	2.2	4.2
5: 50–124,999 PE	39	1.0	0.7	3.1	5.9
6: 125–200,000 PE	14	0.4	0.3	1.1	2.1
7: > 200,000 PE	11	0.3	0.2	0.9	1.7
Total	**92**	**2.3**	**1.7**	**7.2**	**13.8**
[3: 10–29,999 PE	*84*	*2.1*	*1.5*	*6.6*	*12.6]*

7.7.2 Costs for Measurement Using the “EXPANDED Method”

If the “EXPANDED method” described in Section 6.2 is used instead of the “BASE method”, the treatment plants will be required to install not just a single sensor per plant, but one measuring point (one sensor) per aerated tank, corresponding to approximately one sensor per 40,000 PE of approved capacity[17]. For instance, a hypothetical treatment plant with an approved capacity of 1,000,000 PE must would be required to install 25 measuring points if subject to the “EXPANDED method”. As shown

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[16] The data basis identifies 92 treatment plants with an approved capacity of 30,000 PE or more, but no information on nitrogen volumes in the inflow is available for three of these.

[17] An average process line is estimated to have a capacity of 40,000 PE, which is a general assessment for approved capacity and process lines at Danish treatment plants with 30,000 PE and above.

in the following table, the estimated investment costs under the expanded measurement programme rise to DKK 17.0–45.8 million for the 92 facilities, depending on whether liquid or gas sensors are used. The calculated average annual costs similarly rise to DKK 5.5–7.0 million for off-gas sensors and liquid-phase sensors, respectively.

TABLE 7.11. Expanded measurement programme, “EXPANDED method”, sensor costs

Approved capacity	Number of treatment plants	Total of average annual costs, liquid-phase sensor (DKK million/year)	Total of average annual costs, off-gas sensor (DKK million/year)	Total investment, liquid-phase sensors (DKK million/year)	Total investment, off-gas sensors (DKK million/year)
4: 30–49,999 PE	28	0.9	0.7	2.4	5.6
5: 50–124,999 PE	39	2.2	1.7	5.3	14.0
6: 125–200,000 PE	14	1.3	1.0	3.1	8.7
7: > 200,000 PE	11	2.7	2.1	6.2	17.6
Total	**92**	**7.0**	**5.5**	**17.0**	**45.8**
[3: 10–29,999 PE	*84*	*2.1*	*1.5*	*6.6*	*12.6]*

Comparing the estimated costs in TABLE 7.11 with TABLE 7.10, we see that the costs for treatment plants with a capacity of 10–29,999 PE remain unchanged, as the number of measuring points for this group of plants remains at one point per plant. For the other treatment plants, the estimated costs rise gradually and are expected to be highest for the largest plants, which, under the expanded measurement programme, must install relatively most measurement points compared to the simpler measurement programme[18].

7.8 Costs for reduction measures

Section 6.6 has identified two types of potential measures to achieve *at least* a 50% reduction in nitrous oxide emissions from treatment plants. The two categories are referred to as “Option A” and “Option B”. The first category comprises operational optimisation, primarily through process management, whilst the second entails capacity expansions at the treatment facilities. In theory, there is also a category that involves fundamental changes to the treatment plant processes, such as the elimination of biogas production. However, the feasibility of these changes is highly individualistic, as are the cost implications, including alternative costs. The following sections therefore focus exclusively on the reduction strategies “Option A” and “Option B” as outlined in Section 6.6.

In the same way as for the costs for measurement, the average annual costs for the two technologies have been calculated on the basis of both estimated investment and operational costs. It has been assumed that the reduction measures under “Option A” are expected to last 10 years, while those under “Option B” are expected to last 20 years.

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[18] It should be noted that 40,000 PE per measurement point/process line/aerated tank is an average consideration for Danish plants over 30,000 PE. There will be small facilities that will require two measuring points on account of operating two process lines, for example, and some of the larger treatment plants will have process lines capable of handling more than 40,000 PE. The analysis is sensitive to the fact that costs may be higher for the small plants and lower for large ones, depending on the capacity of the individual process lines.

Table 7.12. Assumptions for the calculation of costs for reducing nitrous oxide emissions

	Option A	**Option B**
Service life (years)	10	20
Discount rate (real)	3.5%	3.5%
Price level (year)	2024	2024
Investment	Operational optimisation measures	Capacity-expanding measures
Operating costs	Assumption: 2% of investment costs	

The table below summarises the estimated investment costs for the reduction measures categorised under “Option A” and “Option B”. A cost range is provided for the two types of measures because they can vary significantly from one treatment plant to another.

TABLE 7.13. Estimated investment costs for reduction measures under “Option A” and “B”

Approved capacity	**Number of treatment plants**	**Total investment, Option A, low (DKK million)**	**Total investment, Option A, high (DKK million)**	**Total investment, Option B, low (DKK million)**	**Total investment, Option B, high (DKK million)**
4: 30–49,999 PE	28	8	13	390	585
5: 50–124,999 PE	39	14	24	950	1,425
6: 125–200,000 PE	14	7	12	590	885
7: > 200,000 PE	11	11	21	1,190	1,785
Total	**92**	**40**	**70**	**3,120**	**4,680**
[3: 10–29,999 PE	*84*	*21*	*34*	*840*	*1,260]*

The table shows that if it does prove possible to achieve the desired 50% reduction in full with the measures under “Option A”, and if the costs remain at the lower end of the estimated range, then the total estimated investments are approximately 40 million DKK. For the 84 treatment plants with an approved capacity of 10–29,999 PE, the estimated investment is correspondingly DKK 21 million.

In the worst-case scenario, investments could be nearly 100 times higher if the reduction measures under “Option B” are implemented and the costs land at the upper end of the estimated investment range: In that case, the investments could then amount to DKK 4.7 billion if the desired 50% reduction is to be achieved through the most capital-intensive capacity expansions. The extra investment needed for the 84 treatment plants with an approved capacity of 10,000–29,999 PE is DKK 1.3 billion in this scenario.

The table below summarises the calculated average annual costs for “Option A” and “Option B”.

TABLE 7.14. Average annual costs for reduction measures under "Option A" and "B"

Approved capacity	Number of treatment plants	Total average annual costs, Option A, low (DKK million/year)	Total average annual costs, Option A, high (DKK million/year)	Total average annual costs, Option B, low (DKK million/year)	Total average annual costs, Option B, high (DKK million/year)
4: 30–49,999 PE	28	1	2	35	53
5: 50–124,999 PE	39	2	3	86	129
6: 125–200,000 PE	14	1	2	53	80
7: > 200,000 PE	11	2	3	108	161
Total	**92**	**6**	**10**	**282**	**423**
[3: 10–29,999 PE	*84*	*3*	*5*	*76*	*114]*

The calculated average annual costs range from DKK 6–423 million for the 92 treatment plants with an approved capacity of more than 30,000 PE. There could potentially be a more than 70-fold difference in the average annual costs, depending on whether the lowest estimated costs are achievable or whether the highest anticipated costs are incurred.

For the 84 treatment plants with an approved capacity of 10,000–29,999 PE, the interval is DKK 3–114 million per year.

7.9 Calculating shadow prices for reduction of nitrous oxide emissions

Given the variation in the estimated costs and the uncertainties surrounding the magnitude of reductions in nitrous oxide emissions from treatment plants, the following section illustrates shadow prices over a given range:

- The lowest shadow price arises when the costs for measurement and reduction measures are the lowest possible, and the maximum reduction in nitrous oxide emissions is achieved.
- The highest shadow price arises when the costs for measurement and reduction measures are highest, and the reduction in nitrous oxide emissions is the lowest possible.

The table below outlines the range in costs for measurement and reduction measures across the different categories of treatment plants. As the table illustrates, all categories of treatment plants share the costs, as they are required both to measure their nitrous oxide emissions and to implement reduction measures with a view to achieving the goal of a 50% reduction in these emissions:

TABLE 7.15. Costs associated with measurement and reduction measures

Approved capacity	**Number of treatment plants**	**Total of average annual costs, off-gas sensor, BASE method,** (DKK million/year)	**Total of average annual costs, liquid-phase sensor, EXPANDED measurement programme** (DKK million/year)	**Total average annual costs, Option A, low** (DKK million/year)	**Total average annual costs, Option B, high** (DKK million/year)
4: 30–49,999 PE	28	0.5	0.9	1.1	52.9
5: 50–124,999 PE	39	0.7	2.2	2.0	128.8
6: 125–200,000 PE	14	0.3	1.3	1.0	80.0

Approved capacity	Number of treatment plants	Total of average annual costs, off-gas sensor, BASE method, (DKK million/year)	Total of average annual costs, liquid-phase sensor, EXPANDED measurement programme (DKK million/year)	Total average annual costs, Option A, low (DKK million/year)	Total average annual costs, Option B, high (DKK million/year)
7: > 200,000 PE	11	0.2	2.7	1.5	161.3
Total	**92**	**1.7**	**7.0**	**5.5**	**422.9**
[3: 10–29,999 PE	*84*	*1.5*	*2.1*	*2.9*	*113.9]*

The table demonstrates that the lowest possible estimated costs for measurement and reduction measures are DKK 7.2 million/year (1.7+5.5), while the highest estimated costs are around DKK 429.9 million (7.0 +422.9). For the 84 treatment plants with an approved capacity of 10–29,999 PE, the annual costs are correspondingly estimated at DKK 4.4–116 million (1.5+2.9 and 2.1+113.9).

As regards the reduction of nitrous oxide emissions, the greatest overall reduction is achieved by assuming the highest emission factor. The table below summarises the calculated reductions of 50% for assumed emission factors of 0.84% $N_2O\text{-}N/TN_{inflow}$ and 1.60% $N_2O\text{-}N/TN_{inflow}$.[19]

TABLE 7.16. CO_2-e reductions at a 50% reduction

Approved capacity	Number of treatment plants	Reduction at EMF 0.84% (tonnes CO_2-e/year)	Reduction at EMF 1.60% (tonnes CO_2-e/year)
4: 30–49,999 PE	27	5,281	10,058
5: 50–124,999 PE	38	14,119	26,893
6: 125–200,000 PE	14	7,957	15,156
7: > 200,000 PE	10	18,442	35,127
Total	**89**	**45,798**	**87,234**
[3: 10–29,999 PE	*84*	*7,651*	*14,573]*

Combining the data from the tables makes it possible to determine the shadow prices for CO_2-e reductions.

TABLE 7.17. Calculated intervals for shadow prices for CO_2-e reduction through nitrous oxide reduction

Approved capacity	Number of treatment plants	Reduction at EMF 1.60% (tonnes CO_2-e/year)	Total average annual costs, low (DKK million/year)	Shadow price, low (DKK/tonne CO_2-e)	Reduction at EMF 0.84% (tonnes CO_2-e/year)	Total average annual costs, high (DKK million/year)	Shadow price, high (DKK/tonne CO_2-e)
4: 30–49,999 PE	28	10,058	1.6	**159**	5,281	54	**10,178**
5: 50–124,999 PE	39	26,893	2.7	**99**	14,119	131	**9,272**
6: 125–200,000 PE	14	15,156	1.2	**80**	7,957	81	**10,217**
7: > 200,000 PE	11	35,127	1.7	**49**	18,442	164	**8,891**
Total	**92**	**87,234**	**7.2**	**83**	**45,798**	**430**	**9,387**

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[19] Note that the data basis identifies 92 treatment plants with an approved capacity of 30,000 PE or more, but no information on nitrogen volumes in the inflow is available for three of these. For this reason, CO_2-e reductions have only been calculated for these 89 treatment plants. Including costs for 92 treatment plants, but calculating CO_2-e reductions for just 89, is not expected to have a significant impact on the overall uncertainty of the calculated shadow prices.

Approved capacity	**Number of treatment plants**	**Reduction at EMF 1.60%** (tonnes CO_2-e/year)	**Total average annual costs, low** (DKK million/year)	**Shadow price, low** (DKK/tonne CO_2-e)	**Reduction at EMF 0.84%** (tonnes CO_2-e/year)	**Total average annual costs, high** (DKK million/year)	**Shadow price, high** (DKK/tonne CO_2-e)
[3: 10–29,999 PE	*84*	*14,573*	*4.5*	*306*	*7,651*	*116*	*15,157]*

As the table illustrates, the range for the calculated shadow prices for CO_2-e reduction through nitrous oxide reduction spans from DKK 49/tonne CO_2-e to DKK 10,217/tonne CO_2-e, which is over a 200-fold difference. Generally speaking, the following can be observed:

- The lowest shadow prices are typically calculated for the treatment plants with the largest capacity. This is a consequence of the reduced marginal costs for both measurement and reduction initiatives, coupled with the higher relative nitrogen load (N) found in several treatment plants with larger approved capacities.
- Reducing nitrous oxide emissions from Danish treatment plants through straightforward measurements and operational optimisation is typically a cost-effective method for most plant sizes to reduce the climate impact, especially when comparing the calculated shadow prices with other non-quota sector measures[20].
- Reducing emissions of nitrous oxide from Danish treatment plants via capacity extensions is a relatively costly approach to reducing climate impact.
- At first glance, treatment plants with an approved capacity of less than 30,000 PE tend to have slightly higher calculated shadow prices compared to larger plants. This may argue for not placing them under a limit value regulation initially, but potentially including them in the regulation at a later stage.

7.10 Calculation of Total Tariff Impact

In the same way as for the calculated intervals for shadow prices for CO_2-equivalent reductions, it is possible to calculate a total tariff impact for the sector as a whole. Utilising the previously estimated costs for measurement and reduction initiatives for the different treatment plant categories, as well as data on the debited water volumes in the catchment areas from the results of the Danish Environmental Protection Agency's Performance Benchmarking 2022[21], it is possible to estimate the tariff impact.

TABLE 7.18. Costs associated with measurement and reduction measures

Approved capacity	**Number of treatment plants**	**Total of average annual costs, off-gas sensor, BASE method,** (DKK million/year)	**Total of average annual costs, liquid-phase sensor, EXPANDED measurement programme** (DKK million/year)	**Total average annual costs, Option A, low** (DKK million/year)	**Total average annual costs, Option B, high** (DKK million/year)
4: 30–49,999 PE	28	0.5	0.9	1.1	52.9
5: 50–124,999 PE	39	0.7	2.2	2.0	128.8
6: 125–200,000 PE	14	0.3	1.3	1.0	80.0
7: > 200,000 PE	11	0.2	2.7	1.5	161.3
Total	**92**	**1.7**	**7.0**	**5.5**	**422.9**
[3: 10–29,999 PE	*84*	*1.5*	*2.1*	*2.9*	*113.9]*

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[20] The Danish Energy Agency, Socioeconomic Calculation Assumptions 2022.

[21] The Danish Environmental Protection Agency's Performance Benchmarking, Results for Wastewater 2022

Approved capacity	**Number of treatment plants**	**Total of average annual costs, off-gas sensor, BASE method,** (DKK million/year)	**Total of average annual costs, liquid-phase sensor, EXPANDED measurement programme** (DKK million/year)	**Total average annual costs, Option A, low** (DKK million/year)	**Total average annual costs, Option B, high** (DKK million/year)
[Total including 3: 10–29,999 PE]	***176***	***3.2***	***9.1***	***8.4***	***536.8***

According to the Danish Environmental Protection Agency’s Performance Benchmarking for 2022, the total reported “debited water volume in the catchment area of the sewage system” was just under 280 million m^3 in 2022. It is assumed that this water volume includes the catchment areas of both large and small treatment plants, thereby encompassing those potentially subject to a nitrous oxide emissions limit and those not covered by it. Here, however, a sector-wide perspective is considered, so such distinctions are not drawn between the treatment plants.

The table demonstrates that the lowest possible estimated costs for measurement and reduction measures are DKK 11.6 million/year (3.2+8.4), while the highest estimated costs are around DKK 545.9 million (9.1+536.8). The average rate impact can thus be calculated as ranging between DKK 0.04 and DKK 1.95 per debited m^3 of water. As this is an average estimation, there may can be wastewater utilities where the impact on rates is either greater or smaller, as it depends on each company’s debited water volume and its costs for measurement and reduction initiatives.

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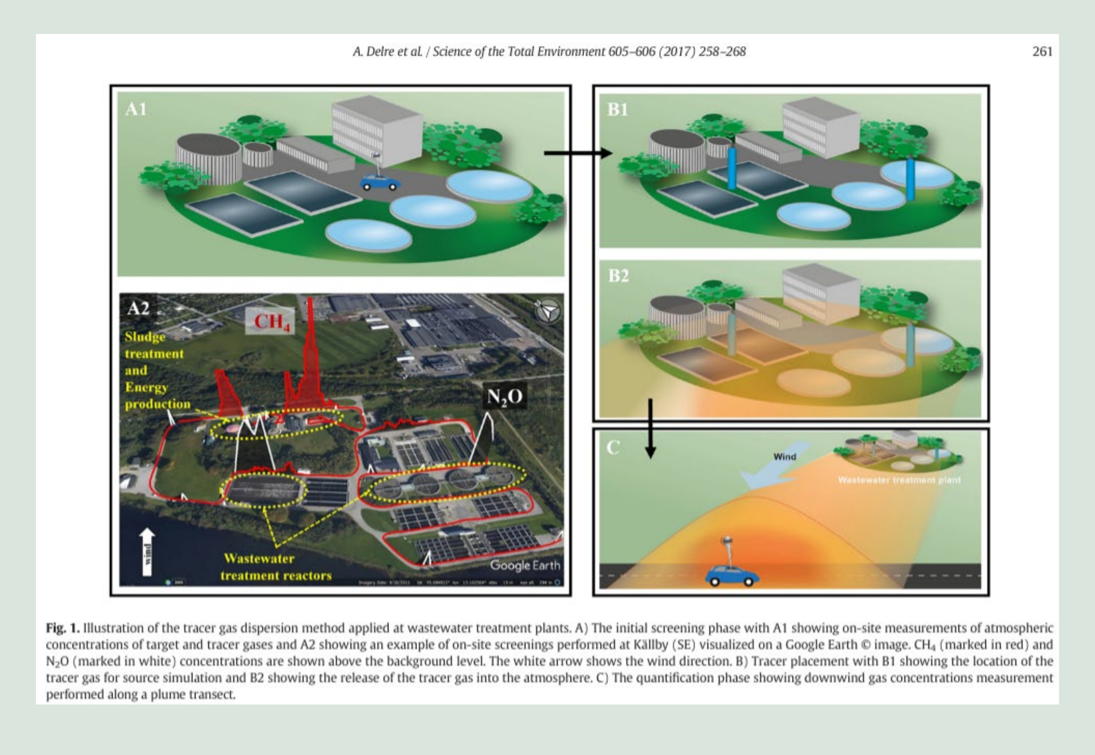
Bilag 1. Technology Overview

Bilag 1.1 Comprehensive Plant-wide Measurement Method – Mobile Tracer Gas Dispersion Method

Tracer gas measurements are based on the principle of directly measuring nitrous oxide in the gas phase (Figure B1). This technology employs the release of a tracer gas (acetylene) with a known concentration at the emission point, assuming the tracer gas will disperse similarly in the atmosphere as the nitrous oxide emitted (Delre *et al.*). 2017). Assuming a specific wind direction and well-mixed air both above and around the emission source, the concentration ratio between the tracer gas and nitrous oxide remains constant. Both tracer gas and nitrous oxide are detected downwind from the emission source and it is then possible to calculate nitrous oxide emissions at the source based on the degree of dilution of the tracer gas.

Tracer gas measurement is also utilised in other contexts for measuring greenhouse gas emissions, where the technology is acknowledged for the measurement of methane emissions from landfills (Mønster 2014).

DTU uses a custom-made N_2O and C_2H_2 analyser (Picarro), mounted on the rear of a vehicle. The driver continuously monitors the real-time gas readings via a display. Both gases (tracer gas and nitrous oxide) are measured downwind from the emission source. During the measurement campaign, a minimum measurement distance must be observed to ensure proper mixing of tracer gas and nitrous oxide. The vehicle, equipped with the gas analyser, travels through the wind plume several times to complete the measurement, thus ensuring that the entire wind plume is mapped.



A. Delre et al. / Science of the Total Environment 605–606 (2017) 258–268 261

Fig. 1. Illustration of the tracer gas dispersion method applied at wastewater treatment plants. A) The initial screening phase with A1 showing on-site measurements of atmospheric concentrations of target and tracer gases and A2 showing an example of on-site screenings performed at Källby (SE) visualized on a Google Earth © image. CH_4 (marked in red) and N_2O (marked in white) concentrations are shown above the background level. The white arrow shows the wind direction. B) Tracer placement with B1 showing the location of the tracer gas for source simulation and B2 showing the release of the tracer gas into the atmosphere. C) The quantification phase showing downwind gas concentrations measurement performed along a plume transect.

***Figure B1**: Illustration of the tracer gas dispersion method as applied at wastewater treatment plants. A) The initial screening phase A1 displays on-site measurements of atmospheric concentrations of target and trace gases, while A2 presents an example of on-site screening conducted in Källby (SE), visualised on a Google Earth © image. Concentrations of CH_4 (red) and N_2O (white) are shown above the background* *level. The white arrow illustrates the wind direction. B) B1 shows tracer gas location for source simulation while B2 illustrates tracer gas release into the atmosphere. C) The quantification phase demonstrates the downstream gas concentration measurement along a plume transect. Copied from Delre et al. (2017).*

Potential Uses

One of the merits of this method is that an experienced operator can carry out the measurements unassisted, and data processing remains straightforward when the gases are fully mixed. MTDM is also capable of detecting the primary areas of emissions, particularly when they occur close to ground level. This method provides insight into the total nitrous oxide emissions from a treatment plant at a specific moment and is therefore not sensitive to variations among the individual processes at the plant. The method can thus potentially be employed as a benchmark when calibrating emission models. This measurement technique allows for direct gas readings, unlike measurement of nitrous oxide concentrations in the liquid phase, and therefore avoids the uncertainties tied to emission calculations.

Limitations

As with other land-based plant-wide measurement techniques, accurate quantification of nitrous oxide emissions is impossible if interfering sources of nitrous oxide or trace elements are found upstream of the emission source. In addition, the method relies on favourable wind conditions, as well as road access in the vicinity of the emission source. As such, the timing and frequency of measurement campaigns are restricted to periods of favourable wind conditions. Moreover, MTDM cannot be used for long-term and continuous monitoring, and the transport of tracer gas cylinders must comply with specific safety regulations.

Weather conditions such as wind speed and direction, incoming solar radiation and topography can influence the detection limit (Yoshida, 2014).

The TDM method is not suited to continuous emission examinations and only provides a snapshot of emissions. Consequently, the method cannot be used to establish emission factors, as spot measurements have previously been shown to underestimate emissions (Vasilaki *et al.* 2019).

Technology Readiness Level (TRL) and Application

The technology is deemed to have a TRL of 8–9, which indicates that it is ready for immediate commercial deployment. Measurement campaigns have been conducted at more than ten full-scale treatment plants in Denmark (Scheutz & Fredenslund, personal communication, 1 October 2023).

MTDM is well-suited to determining a treatment plant's current and overall nitrous oxide emissions, although uncertainty remains as to whether the method can accurately compute a plant's EF. This uncertainty is attributable to the dynamic and varying nature of nitrous oxide emissions. Although MTDM can measure the current emission level accurately, it is impossible to ascertain whether this is representative of the treatment plant's general emissions, or if the measurement refers to a particularly low or high emission period.

Measurement uncertainties

To determine the overall uncertainty of TDM, a study (Fredenslund, 2019) encompassed five controlled release tests, conducted by two different teams. These controlled release tests systematically analysed each process to allocate an individual error subsequently. The study ultimately concluded that the overall uncertainty of the method was below 20%.

It should be noted that the aforementioned studies were carried out through methane emission quantification. The uncertainty could potentially differ when the method is used to quantify nitrous oxide emissions instead. In addition, during the measurements by Ledermann, L.L. (2022), as part of the AWAIRE project, a measurement uncertainty of 8.7% was calculated.

Suppliers
There are currently two recognised suppliers: DTU and FORCE Technology.

Bilag 1.2 Drone Flux Method

An alternative plant-wide approach for assessing nitrous oxide emissions from treatment facilities is through drone measurements (DFM), a technique developed by Explicit. The method was previously utilised during the MUDP project "The Plane Project" (Knudsen *et al.* 2022), where it proved to be effective and was validated by comparing it with trace gas measurements for the detection of methane.

DFM has recently been used for measuring nitrous oxide emissions from treatment plants in Denmark (MUDP_AWAIRE, in preparation) alongside MTDM and ECM, and the results were compared with emission calculations derived from process-specific liquid sensor measurements.

In order to map nitrous oxide emissions from a treatment plant using DFM, a remote-controlled drone equipped with various sensors – including the MIRA Strato N_2O/CO_2 sensor from Aeris Technologies – is employed. The drone operates downwind of the emission source, capturing data on wind speed and direction, nitrous oxide concentration, GPS location, temperature, air pressure, etc. The drone thus maps the wind plume across a two-dimensional area perpendicular to the wind direction downwind of the emission source, recording measurements of nitrous oxide concentration (air samples), water velocity and area coverage (the principle is illustrated in figure B2).

Figure B2: A schematic illustration shows the two-dimensional area in which the drone operates when mapping the nitrous oxide plume from a treatment plant. Adapted from Lallana, Arturo L. (2023), modified after Knudsen et al. (2022).

Potential Uses

DFM features many of the same options as tracer gas measurement, providing insight into total nitrous oxide emissions from a treatment plant at a given time. The method can thus potentially be employed as a benchmark when calibrating emission models. Moreover, DFM can measure a variety of gases, not just nitrous oxide.

This measurement technique allows for direct gas readings, unlike measurement of nitrous oxide concentrations in the liquid phase, and therefore avoids the uncertainties tied to emission calculations.

Limitations
As with other land-based plant-wide measurement techniques, accurate quantification of nitrous oxide emissions is impossible if interfering sources of nitrous oxide or trace elements are found upstream of the emission source.

The method is only applicable during specific weather conditions, such as wind speeds between 2 and 12 metres per second, and a consistent wind direction. High turbulence may likewise compromise the data quality. Another major limitation is the need for ample space to establish a flight path, which also necessitates skilled labour for conducting measurements. To achieve reliable results for total emissions, the flight path of the drone must cover a transect of the entire downstream emission plume. This demands precise planning and coordination to ensure that no emissions are missed. As such, the timing and frequency of measurement campaigns are restricted to periods of favourable wind conditions.
The DFM method is not suited to continuous emission examinations and only provides a snapshot of emissions. Consequently, the method cannot be used to establish emission factors, as spot measurements have previously been shown to underestimate emissions (Vasilaki *et al.* 2019)

Technology Readiness Level (TRL) and Application
The technology is deemed to have a TRL of 8–9, which indicates that it is ready for immediate commercial deployment.

Measurement campaigns have been conducted at four full-scale treatment plants in Denmark and seven abroad (Explicit, personal communication, 2023).

DFM is well-suited to determining a treatment plant's current and overall nitrous oxide emissions, although uncertainty remains as to whether the method can accurately compute a plant's EF. This uncertainty is attributable to the dynamic and varying nature of nitrous oxide emissions. Although DFM can measure the current emission level accurately, it is impossible to ascertain whether this is representative of the treatment plant's general emissions, or if the measurement refers to a particularly low or high emission period.

Measurement uncertainties
To calculate the emission rate, a minimum of three flights must be performed. The final result carries a 20% uncertainty, as outlined on the Explicit website.

Suppliers
Explicit ApS is currently the sole known supplier of the DFM method. Explicit is ISO certified under ISO 17025 as an accredited laboratory. The DFM measurement for CH_4 was recently accredited by Denmark's national accreditation authority (DANAK) in accordance with ISO 17025. Equivalent accreditation for nitrous oxide is currently in progress, as per the supplier.

Bilag 1.3 Process-specific measurement methods – N_2O process-specific sensors in the liquid phase

What are known as Clark-type sensors (Unisense) are used for detecting nitrous oxide in the liquid phase. These are electrochemical devices where nitrous oxide (the analyte) traverses an ion-permeable membrane and is reduced on the metal surface of the cathode, generating an electric current. The interaction of nitrous oxide with the cathode is documented as a function of the analyte concentration (Andersen *et. al.* 2001).

Potential Uses

These sensors thus provide continuous, real-time monitoring of nitrous oxide levels in the process tank (liquid phase) and can be integrated with other types of online sensor data. Employing process-specific nitrous oxide sensors in the liquid phase is broadly applicable across different plant types. This method can be utilised on any process unit involving liquid-gas transfer, making it suitable for both aerated and non-aerated zones. This method does not necessitate covering the surface area of the process unit being studied, making it relatively straightforward to monitor nitrous oxide concentrations. At the same time, the method is user-friendly and incurs relatively low costs. It is particularly effective for plants with continuous aeration operating in a steady state (Ye et al., 2022).

Although the sensor is designed to measure nitrous oxide in liquids, Marques *et al.* (2016) successfully modified a standard liquid sensor to measure nitrous oxide concentrations in the gas phase. This modification is not currently available commercially, but it could potentially be included in the catalogue of measurement methods and used, for example, in verifying emission models.

Limitations

Measuring the concentration of nitrous oxide in the liquid phase requires conversion to determine the emission of nitrous oxide into the atmosphere. This depends on both the flow rate of aeration in the process tank and the mass transport coefficient for nitrous oxide. The conversion varies depending on whether the process tank is bottom-aerated or surface-aerated and carries a significant level of uncertainty, particularly in surface-aerated plants. A number of general limitations apply to the use of process-specific sensors. Firstly, a sensor measures only at a single location, which will rarely be representative of the total nitrous oxide emissions from a process unit or plant. Multiple representative locations might therefore be necessary. Secondly, the accuracy of these sensors is open to debate, as measurements are based on the assumption that the bioreactor is under steady state conditions, which may not always hold true – i.e. what is considered the “correct” location can change with the shifting dynamics in the process. That said, this is a general limitation for all types of process-specific measurements. Thirdly, changes in wastewater content, such as increased salt levels, can result in nitrous oxide being stripped from the liquid phase, which can affect the uncertainty of emission calculations (Kosse et al. 2017). Mass transport from water to air (and thus emission levels) is dynamic and depends on aeration and environmental factors such as temperature. Therefore, relying on a single value to calculate the mass transfer coefficient, K_La, may be problematic (Ye et al., 2022).

The sensors require several forms of maintenance, including calibration and the replacement of the sensor head.

Technology Readiness Level (TRL) and Application

Sensors for measuring nitrous oxide in the liquid phase are an established and mature technology with more than 20 references both in Denmark and abroad. The technology is considered to have a Technology Readiness Level (TRL) of 9.

A large number of different treatment plants utilise sensors for measuring nitrous oxide.

Sensors can be used in facilities irrespective of whether surface or bottom aeration is employed (Unisense Environment A/S, 2022). However, greater uncertainty generally exists in emission calculations for surface-aerated systems, as estimating the air supply and degassing precisely is more challenging.

Unisense sensors can also be used on reject water from sludge dewatering, which is treated in anammox (Unisense Environment A/S, 2022).

Measurement uncertainties
The measurement is sensitive to temperature variations and must therefore be calibrated for temperature changes of 3°C. Furthermore, the sensor heads become worn over time and need to be replaced every 4–6 months to ensure accurate measurements. Neglecting routine maintenance can lead to measurement inaccuracies.

- The measurement of the liquid concentration itself is highly precise, with an uncertainty of +/- 5%.
- The “major” uncertainty is linked to emission model calculations.
  This depends in part on the accurate determination of airflow and the mass transport coefficient (K_La) for nitrous oxide.

Studies have demonstrated that this emission calculation can align with gas-phase control measurements with over concordance in excess of 87% (Baresel *et al.* 2016 & Marques *et al.* 2016). In addition, Myers *et al.* (2021) found that the methodology for determining K_La influences the emission calculation, confirming the importance of a calibrated Kla_La for this calculation.

Unisense estimates that the overall uncertainty in emission calculations is less than 20% (Andersen, M.H., personal communication, 2 November 2023).

The sensors must not be exposed to concentrations of hydrogen sulphide, as this can compromise their sensitivity. High concentrations of NO are similarly discouraged (Unisense Environment A/S, 2022).

Suppliers
The only supplier of liquid sensors is Unisense A/S.

Bilag 1.4 N_2O process-specific measurements in the gas phase

For process-specific measurements in the gas phase, a variety of measurement techniques or analyses are available to perform the concentration measurement. A non-exhaustive list is:

- FTIR: Fourier-transform infrared spectroscopy
- NDIR: Nondispersive infrared spectroscopy
- MS: Mass spectroscopy
- GC: Gas chromatography
- PAS: Photoacoustic spectroscopy.

A trait shared by all these methods is the ability to measure the concentration of nitrous oxide (and sometimes other gases) in the gas phase with precision. In addition, they all need a corresponding gas flow measurement to calculate the flux for a specified area. Each analysis method is a standard approach, and will not be discussed in more detail here.

For off-gas and gas flow measurements in open tanks, the most common approach is to use the flux chamber method. This involves using floating hollow units (float chambers) fixed in a specific position to capture gases emitted at the water-air interface. Flux chambers are usually submerged a few centimetres in the water to prevent movement and the introduction of external air. Flux chamber designs vary, but they are generally divided into two categories: closed flux chambers and dynamic flux chambers (Ye et al., 2022).

The ultimate solution for process-specific measurement of nitrous oxide in the gas phase therefore involves combining a gas analysis method to determine nitrous oxide concentration with a flux chamber method to ascertain gas flow.

A notable exception is covered tanks or treatment plants, where off-gas measurements are taken directly from the ventilation system, eliminating the need for flux chambers in favour of a flow measurement from the “chimney”. This is essentially regarded as a plant-wide method, although it fundamentally relies on the same analytical techniques as the process-specific gas phase measurements.

The subsequent sections describe different types of flux chambers (Figure B3).

Closed Chambers: The principle behind closed flux chambers is to isolate a specific surface area from the atmosphere, allowing gases to accumulate inside the chamber over time. The emission rate is then determined by the change in gas concentration over time. The concept here is therefore to measure an increase in concentration within a close volume rather than measuring an actual flow of gas. Gas mixing is typically achieved by installing a fan inside the hood, or by recirculating the gas flow between the chamber and the nitrous oxide analyser. This method is particularly useful for non-aerated processes, such as anoxic tanks. The technique is best known for measuring greenhouse gas emissions from soil.

It is not recommended to allow high gas concentrations to accumulate in the chamber, as this can lower the emission rate and lead to an underestimation of the actual emission rate. It is therefore crucial to operate with short sampling intervals and introduce fresh air between sampling rounds (Ye et al., 2022). Utilising this principle means that measurements are taken intermittently, with intervals for accumulation, measurement and emptying, etc. This approach is therefore unsuitable for measuring nitrous oxide emissions from aerated processes.

Dynamic Chambers: Dynamic flux chambers are fitted with tubes and vent ports that permit gas to escape from the chamber. Gas samples from aerated zones can typically be extracted directly from the chamber. In non-aerated zones, a purge gas may be introduced to ensure efficient gas flow through the flux chamber (Ye et al., 2022).

In practice, most dynamic flux chambers are specifically designed to measure emissions in aerated zones, as having a single chamber capable of measuring both aerated and non-aerated zones significantly complicates the measurement process.

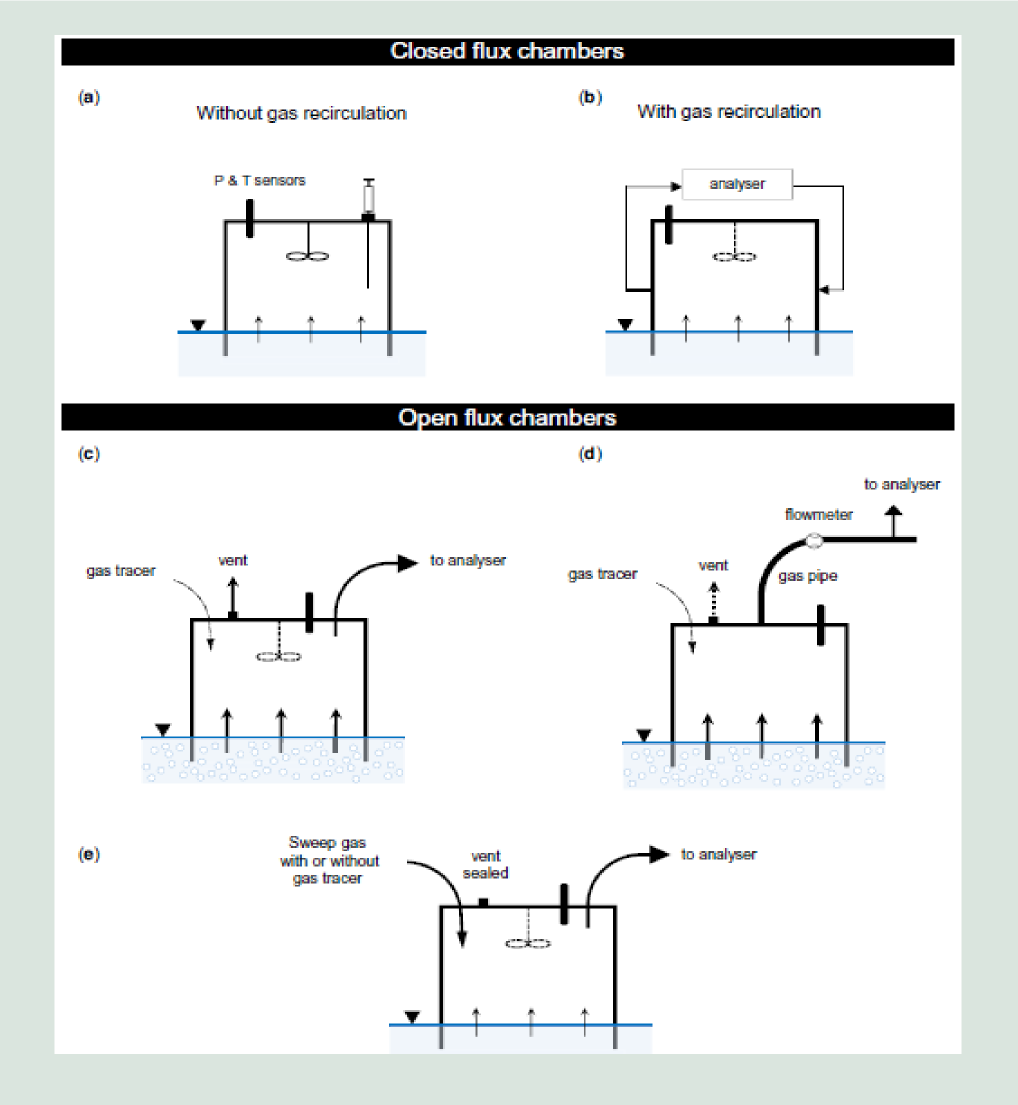


Figure B3. *Overview of different types of flux chambers. Copied from Ye et al. (2022)*

As previously noted, numerous different analysis techniques are to be found for evaluating nitrous oxide concentrations in the gas phase, with multiple suppliers available within each category. Many examples of utilised floating chambers with differing designs and operations are likewise available. Different designs have been documented by Chandran, K. (2011), Gruber & Joss (2021), and Duan *et al.* (2020). A variety of bespoke float chambers are available. In Denmark, both Stjernholm and Duotec manufacture their own float chambers.

In the following section, we will focus solely on the comprehensive solutions available, where a single supplier can provide float chambers and nitrous oxide measurement as a combined package.

Potential Uses

Essentially, the float chamber method can be utilised to collect off-gas from any process where the segment of the water surface, acting as an interface for liquid/air transfer, can be covered by the float chamber. The principal advantage lies in the capacity of the method to measure nitrous oxide emissions directly, thus eliminating the need for emission model calculations for the mass transport of nitrous oxide.

The main strength of this method is its the real-time and continuous quantification of emissions specific to processes, which can be utilised for management and optimisation. Furthermore, it allows for the quantification of spatial variation in emissions across different zones within the facility.

Limitations

A number of general limitations apply to the use of process-specific sensors. Firstly, a sensor measures only at a single location, which will rarely be representative of the total nitrous oxide emissions from a process unit or plant. Multiple representative locations might therefore be necessary. Secondly, the accuracy of these sensors is open to debate, as measurements are based on an assumption that the bioreactor is under steady state conditions, which may not always hold true – i.e. what is considered the "correct" location can change with the shifting dynamics in the process. That said, this is a general limitation for all types of process-specific measurements.

The technique is unsuitable for use in plants with surface aeration on account of complications in gas collection and placement of the floating chamber caused by foaming and turbulence. This approach does not allow for the quantification of nitrous oxide emissions across the entire plant (Ye et al., 2022).

Technology Readiness Level (TRL) and Application

For many years, the combination of float chambers with measurements of nitrous oxide concentration in the gas phase and gas flow has been regarded as the reference method – and the only available method in practice.

This method has been applied across numerous treatment facilities in various configurations, with its application thoroughly documented in a large number of peer-reviewed articles.

In addition, comprehensive solutions are provided and the method is therefore generally regarded as having a TRL of 9. In practice, however, an individual assessment from supplier to supplier is necessary.

Measurement uncertainties

Particularly when utilising float chambers on stagnant fluid surfaces: On non-aerated surfaces, the main uncertainty arises when conditions inside the chamber – such as variations in surface structure or currents and waves – are not comparable to those outside. Within closed flux chambers, a significant build-up of gases can alter the diffusive flux, which makes it necessary to adjust sampling duration and sample count according to site-specific conditions. It is important to ensure adequate mixing of gases inside the chamber. It is expected that spherical chambers optimal conditions for gas mixing, as they feature no corners where air might stagnate. Alternatively, mixing can be enhanced by deploying a fan or blower within the chamber, recirculating the gas in a closed system, or utilising a flow of purge gas. The mixing inside the chamber should ideally match the wind speed over the water surface outside. When using purge gas, care must be taken to ensure that the concentration of diluted gas remains precisely measurable.

Particularly when utilising float chambers in aerated zones: In aerated zones, the size and design of the chamber do not affect nitrous oxide measurements, as long as the chambers are well-ventilated to prevent pressure build-up. When using fixed chambers (rather than floating chambers), there is a risk of increased gas compression because of variations in the water level within the chamber. It is therefore recommended to equip the chamber with adequate ventilation openings (in terms of

number and size) and to monitor and log the pressure beneath the chamber in order to be able to adjust the concentration of off-gas and the flow rate accordingly.
The chamber volume should be determined based on the gas flow time, tank dynamics, and the subsequent use of the gathered data. Should the gas undergo moisture removal through silica gel columns or condensers prior to measurement, increased retention time must be factored in (Ye et al., 2022).
Suppliers
DUOTEC
Duotec provides a comprehensive solution involving a self-manufactured float chamber and a compensated NDIR measurement technique sourced from Novasis innovazione. The float chamber is an open chamber equipped with a valve and suction system. Duotec's solution is currently being demonstrated at a treatment plant in Denmark as a part of the MUDP development project "*New cost-effective technology for measuring climate gas emissions from treatment plants*". The solution remains in development and is estimated to have a TRL (Technology Readiness Level) of 7.

Duotec currently only provides this solution for bottom-aerated systems and only in aerated zones.

Data on measurement uncertainties are not yet available.

Upwater
Upwater offers a complete solution featuring a self-manufactured float chamber based on the EAWAG design (Gruber & Joss 2021) and an NDIR analyser from Witec-sensorik, which features a measurement uncertainty of less than 1%. The float chamber is an open chamber equipped with a valve and suction system. Upwater currently only provides this solution for bottom-aerated systems and only in aerated zones. The "Notos" system can connect up to 14 measurement points to a single analyser, and flow measurements can be integrated into each chamber individually as an optional feature. Multiple gases are measured simultaneously.

Upwater has 16 full-scale case studies and has accumulated up to 20 years of measurement experience. The system is largely automated and virtually maintenance-free. Upwater's solution is assessed to be at Technology Readiness Level 9.

VarioLytics
Variolytics provides an alternative approach for process-specific measurements in the gas phase. The EmiCo system from Variolytics employs a mass spectrometer to measure real-time concentrations and emissions of greenhouse gases in both the gas and liquid phases. In the same way as the other solutions for gas phase measurements, EmiCo utilises gas collection in an open float chamber using a valve and suction system. The measuring technique used is mass spectrometry (MS). Gases are channelled from the float chambers to the mass spectrometer via sampling lines, utilising a multiplexing system that makes it possible to switch between different measuring points. EmiCo can connect up to 12 different measuring points to a single analyser. The principle of membrane inlet mass spectrometry (MIMS) is utilised for direct measurements from the liquid phase. Special probes are installed in the aeration tanks for this function. Each of these probes is fitted with a membrane in the sensor head. The liquid phase contacts one side of the membrane, while a vacuum is applied to the opposite side. The resulting pressure gradient causes all volatile components from the liquid phase to evaporate into the vacuum and be transmitted to the mass spectrometer for analysis. This system provides high temporal resolution, al-

lowing the capture of gases such as O_2, N_2O, CH_4, N_2, and CO_2 directly from the liquid phase. For all components measured with the EmiCo system, the uncertainty is no more than 3% of the measured value.

VarioLytics has five full-scale case studies and is assessed to be at Technology Readiness Level 9.
A distinct advantage of EmiCo is its capacity to combine gas and liquid phase measurements, which makes the solution suitable for measuring emissions from both aerated and non-aerated zones and processes.

Bilag 2. Spreadsheet containing data from literature review and other collated data

Bilag 3. NIRAS report "Nitrous Oxide from Treatment Plants – Preliminary Analysis on Regulation" from 2022 (only in Danish language).

Bilag 4. Sensor placement case studies.

Recirculating systems.

Figure B4. *Case A: Hyllingeris treatment plant.*

In recirculating systems, the biological treatment comprises separate aerated and non-aerated biological tanks. At the Hyllingeris treatment plant, the innermost ring is not aerated, whereas the outer one is. The N_2O sensor (yellow circle) is positioned one third of the way downstream in the aerated zone (grey area) of the outer ring.

Biodenitro system

Figure B5. *Case B: Mølleåværket treatment facility – a biodenitro system featuring bottom aeration*

In alternating systems (such as biodenitro/biodenipho), wastewater is sequentially supplied to series-connected tanks grouped into sets, where nitrogen removal occurs as an alternating process. Situating a sensor in the aeration zone makes it possible to measure N_2O concentration during both nitrification and denitrification. At Mølleåværket, the N_2O sensor (yellow circle) was installed one third of the way into the aeration zone (grey area).

Plug Flow

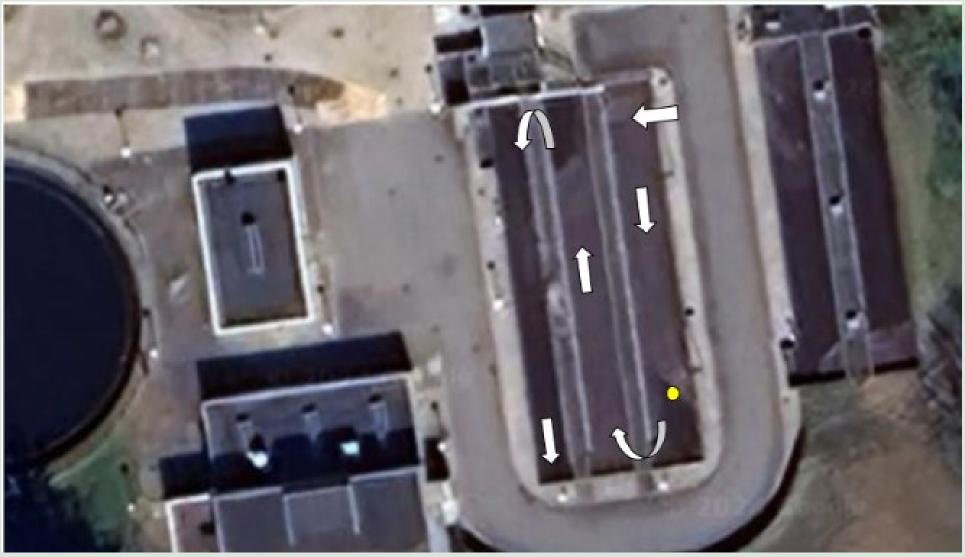


Figure B6. *Case C: Stavnsholt treatment plant (Novafos) – a plug flow system*

The Stavnsholt treatment facility features a plug flow system with bottom aeration. The N_2O sensor was positioned approximately one third of the way downstream within the plug flow channel to detect the N_2O that can be formed under high nitrogen loads.

Figure B7. *Case D: Plug flow system – Melby RA (Halsnæs Forsyning)*

The principles that apply in a plug flow system are the same as those for recirculating and biodenitro systems. It is beneficial to position an N_2O one third of the way into the diffuser area.

Biofilm systems and other hybrid systems (e.g. biostyr, IFAS and Anammox processes)
The sensor should be positioned in the tank where the contents are well-aerated and mixed (and where it is feasible).

As limited data are available in this area, plants adhere to general recommendations.

Figure B8. *Case E: Biofilm and other hybrid systems*

Here, measurements are conducted atop or close to "the technology" where air bubbles rise.

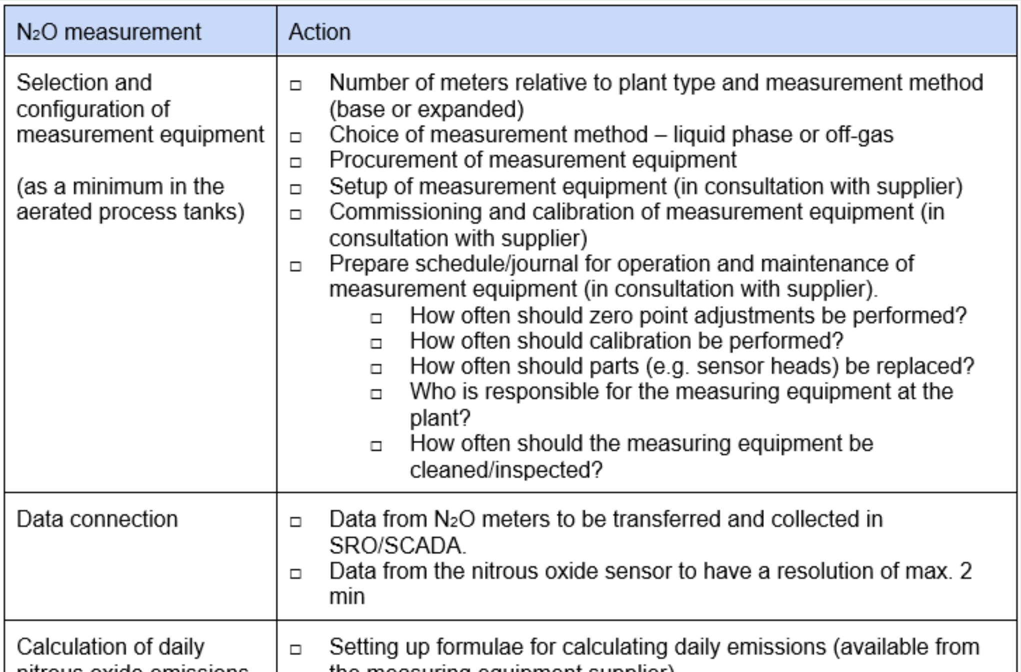
Figure B9. *Case E: Næstved (NK – Spildevand A/S treatment facility) – a surface aerated system*

The Næstved treatment facility is a biodenitro system featuring bottom aeration. At this facility, the N_2O sensor was positioned midway along one of the long sides.

Bilag 5. Guidelines for accurate and uniform measurement and emission calculation

Nitrous oxide measurement
Nitrous oxide must be continuously monitored using a process-specific sensor – either a liquid-phase sensor or an off-gas sensor. The checklist below can be used for setting up and maintaining measuring equipment, ensuring data collection and calculating the daily nitrous oxide emissions from the measurement point.

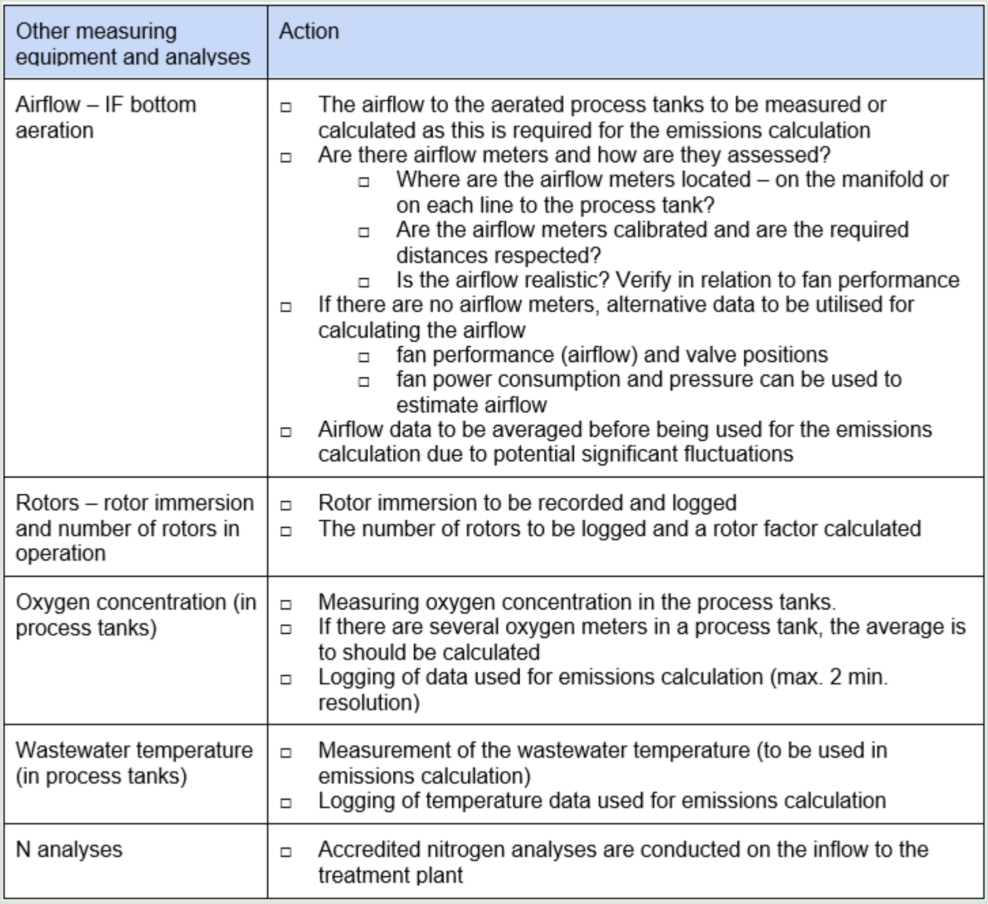
Calculating nitrous oxide emissions from the measuring point depends on the technology used and should always comply with the supplier's instructions. For example, see the formulae for the Unisense liquid-phase sensor in Appendix 6.



N_2O measurement	Action
Selection and configuration of measurement equipment (as a minimum in the aerated process tanks)	☐ Number of meters relative to plant type and measurement method (base or expanded) ☐ Choice of measurement method – liquid phase or off-gas ☐ Procurement of measurement equipment ☐ Setup of measurement equipment (in consultation with supplier) ☐ Commissioning and calibration of measurement equipment (in consultation with supplier) ☐ Prepare schedule/journal for operation and maintenance of measurement equipment (in consultation with supplier). ☐ How often should zero point adjustments be performed? ☐ How often should calibration be performed? ☐ How often should parts (e.g. sensor heads) be replaced? ☐ Who is responsible for the measuring equipment at the plant? ☐ How often should the measuring equipment be cleaned/inspected?
Data connection	☐ Data from N_2O meters to be transferred and collected in SRO/SCADA. ☐ Data from the nitrous oxide sensor to have a resolution of max. 2 min
Calculation of daily nitrous oxide emissions kg N_2O-N/d	☐ Setting up formulae for calculating daily emissions (available from the measuring equipment supplier) ☐ Daily nitrous oxide emissions to be logged (kg N_2O-N/d) ☐ Nitrous oxide emissions per month to be calculated

Additional relevant measurements and analyses

The calculation of nitrous oxide emissions relies on several additional process measurements and analyses, which must be assured and validated. The checklist below can be used for this purpose.



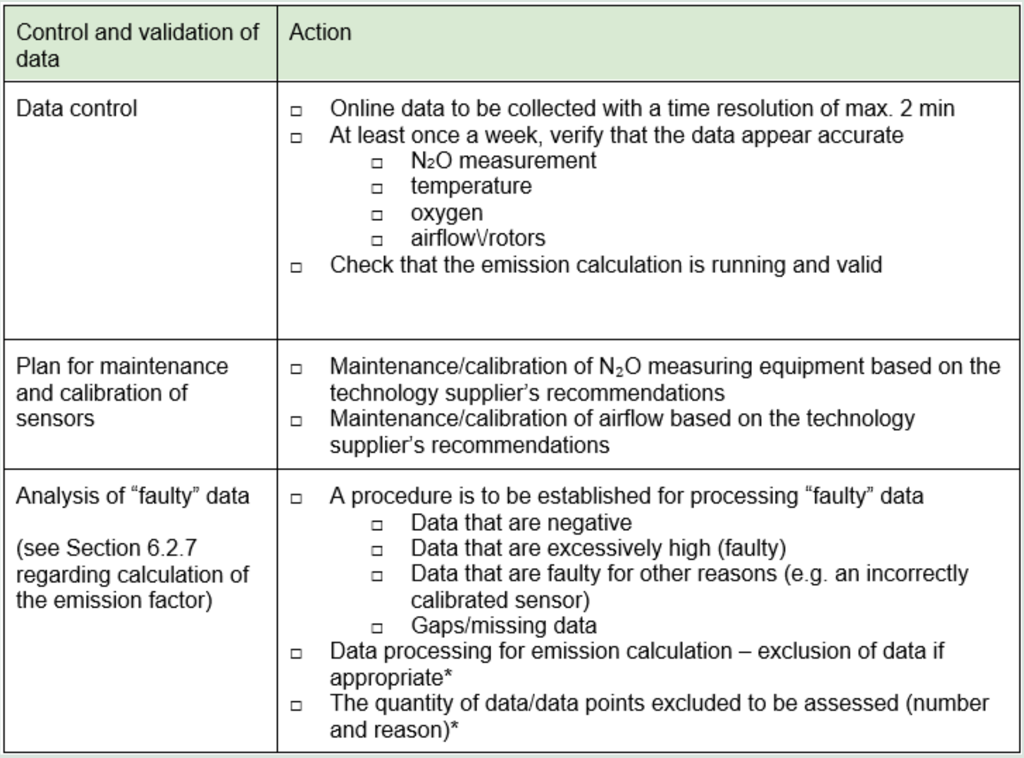
Other measuring equipment and analyses	Action
Airflow – IF bottom aeration	☐ The airflow to the aerated process tanks to be measured or calculated as this is required for the emissions calculation ☐ Are there airflow meters and how are they assessed? ☐ Where are the airflow meters located – on the manifold or on each line to the process tank? ☐ Are the airflow meters calibrated and are the required distances respected? ☐ Is the airflow realistic? Verify in relation to fan performance ☐ If there are no airflow meters, alternative data to be utilised for calculating the airflow ☐ fan performance (airflow) and valve positions ☐ fan power consumption and pressure can be used to estimate airflow ☐ Airflow data to be averaged before being used for the emissions calculation due to potential significant fluctuations
Rotors – rotor immersion and number of rotors in operation	☐ Rotor immersion to be recorded and logged ☐ The number of rotors to be logged and a rotor factor calculated
Oxygen concentration (in process tanks)	☐ Measuring oxygen concentration in the process tanks. ☐ If there are several oxygen meters in a process tank, the average is to should be calculated ☐ Logging of data used for emissions calculation (max. 2 min. resolution)
Wastewater temperature (in process tanks)	☐ Measurement of the wastewater temperature (to be used in emissions calculation) ☐ Logging of temperature data used for emissions calculation
N analyses	☐ Accredited nitrogen analyses are conducted on the inflow to the treatment plant

Continuous checking and validation of data

All pertinent data should be checked and validated each week to guarantee a statistically valid emissions calculation. A number of factors are significant in this context:

- The amount/frequency of data (avoid long periods without data)
- Specific time resolution of data – e.g. 2 minutes (to capture dynamics*).
- Ensuring data are realistic – for instance, there should be no negative values, unrealistically high values, or values that deviate significantly from the norm. Here, it is important to assess whether the data appear realistic in relation to the operation of the treatment facility.

The checklist below can be used to ensure the checking and validation of nitrous oxide emission data, as well as other relevant process information.



Control and validation of data	Action

Data control	☐ Online data to be collected with a time resolution of max. 2 min
	☐ At least once a week, verify that the data appear accurate
	    ☐ N_2O measurement
	    ☐ temperature
	    ☐ oxygen
	    ☐ airflow\/rotors
	☐ Check that the emission calculation is running and valid

Plan for maintenance and calibration of sensors	☐ Maintenance/calibration of N_2O measuring equipment based on the technology supplier's recommendations ☐ Maintenance/calibration of airflow based on the technology supplier's recommendations

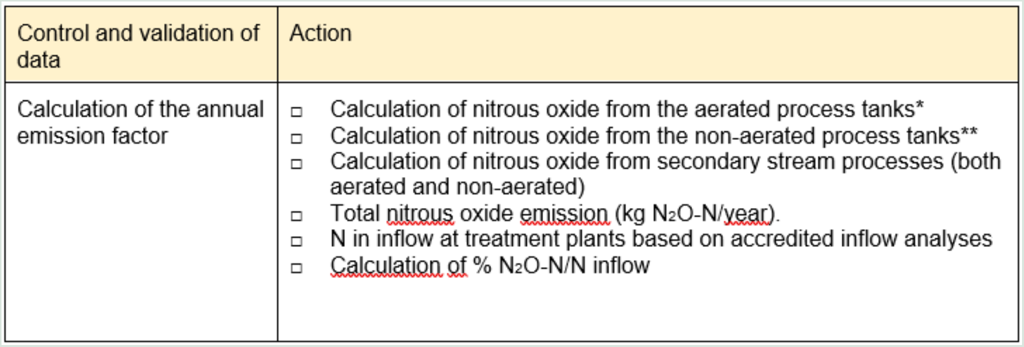
Analysis of "faulty" data
(see Section 6.2.7 regarding calculation of the emission factor)
	☐ A procedure is to be established for processing "faulty" data
	    ☐ Data that are negative
	    ☐ Data that are excessively high (faulty)
	    ☐ Data that are faulty for other reasons (e.g. an incorrectly calibrated sensor)
	    ☐ Gaps/missing data
	☐ Data processing for emission calculation – exclusion of data if appropriate*
	☐ The quantity of data/data points excluded to be assessed (number and reason)*

**Processing data essential for emission calculations:*

Data that present negative values (e.g. N_2O measurements) should NOT be discarded, but should instead be adjusted/corrected, after which they can be used in the emissions calculations.
Data with significantly high and evidently erroneous values should be excluded from the dataset prior to performing the emissions calculations.
Any missing data/gaps should be filled – for example, by employing a standard emission value.

Calculation of the emission factor

The nitrous oxide emission factor (% N_2O-N / N inflow to the treatment plant) is calculated as the annual average from January to December. The following checklist can be used to ensure that the calculation of the overall annual emission factor is accurate and incorporates the necessary extrapolations.



Control and validation of data	Action
Calculation of the annual emission factor	☐ Calculation of nitrous oxide from the aerated process tanks* ☐ Calculation of nitrous oxide from the non-aerated process tanks** ☐ Calculation of nitrous oxide from secondary stream processes (both aerated and non-aerated) ☐ Total nitrous oxide emission (kg N_2O-N/year). ☐ N in inflow at treatment plants based on accredited inflow analyses ☐ Calculation of % N_2O-N/N inflow

**Calculation of nitrous oxide emissions from aerated process tanks*

The largest emissions stem from the aerated process tanks and secondary stream processes, as this is where the greatest ammonium conversion takes place (approximately 90%).

The nitrous oxide emissions are calculated daily – kg N_20-N/d.

The calculation of emissions depends on the type of measurement: liquid phase or off-gas. The “formulae” adhered to here are those associated with the measuring and aeration technologies (surface or bottom aeration).

***Calculation of nitrous oxide emissions from non-aerated tanks*
Current experience indicates that only approximately 10% of nitrous oxide emissions stem from the DN tanks. Measuring in the DN tanks is therefore not mandatory.
If measurements are not taken, 10% must be added to the calculated emissions from the aerated tanks.

Utilising a liquid-phase sensor makes it possible to measure in the DN tanks, and in this case it is essential to use the actual measurement rather than extrapolating.

Bilag 6. Formulae for calculating emissions from aerated areas

***Example:** Calculating nitrous oxide emissions using the Unisense liquid-phase sensor:*

- *N_2O Mass Transfer Coefficient Calculation from Aeration Field Size and Air Flow.*

- *Estimate of mass transfer coefficient and emission of N_2O from surface aeration systems*

Bilag 7. *Process* case study for inspiration

The following case has been prepared as an exemplification of how a utility's process with nitrous oxide measurement and reporting – as well as the authorities' supervision and control – *might* look in connection with the introduction of nitrous oxide regulation. This example should only be considered as inspiration; the practical implementation by utilities and supervisory authorities should take existing procedures into account.

Background
Utility X owns treatment plant A, which has an approved capacity of 30,000 PE and is thus subject to a new limit value for nitrous oxide emissions. During the commissioning phase, the utility is required to measure nitrous oxide emissions using the BASE method.

Treatment Plant A is a single-stage plant with two identical N/DN tanks (process tanks 1 and 2), both equipped with bottom aeration with the associated airflow measurement and sensors for oxygen, temperature, NH_4, NO_3, and SS. The wastewater is evenly distributed between the two process tanks.

Start-up, commissioning and measurement period
The utility procures and installs a single liquid-phase sensor in consultation with the supplier, following the guidelines set by the Danish Environmental Protection Agency. The sensor is placed centrally within the aeration field of process tank 1. A permanent connection is established so that the utility's SCADA system continuously gathers and logs nitrous oxide concentrations in the process tank, in parallel with data from other the measuring devices installed in the tank. The utility also establishes an emissions calculation (in accordance with the supplier's formulae) in the SCADA system utilised that calculates nitrous oxide emissions from the aerated zone in process tank 1 (kg N_2O/d).

In partnership with the supplier, the utility drafts an operational log to ensure that the nitrous oxide sensor is maintained correctly, according to the supplier's instructions. This includes the frequency for cleaning, calibrating and zero-adjusting the sensor, as well as for replacing the sensor head. During the measurement period, operating staff must continuously log which maintenance actions are performed, when they are done, and by whom. The operational log is supplemented with guidelines and dates for maintaining the airflow meter, which also factors into the emissions calculations.

The utility already has six accredited inlet analyses conducted per year, as per the discharge permit of the treatment plant, including for nitrogen. These analyses are logged in the PULS system on an ongoing basis.

Every week, the utility's operating staff or process engineer reviews the process curves (oxygen, N_2O, temperature and airflow) in the SCADA system to ensure that the values are valid (no negative or abnormally high values) and that there are no major drop-outs that give rise to protracted periods with missing data. The staff also regularly check that the calculated daily emissions from the aerated area in process tank 1 appear realistic.

Reporting and documentation
After a one-year measurement period, the utility is now required to compile the basis for reporting to the supervisory authority. This includes:

System delimitation: The utility outlines the configuration of the treatment plant, explaining that nitrous oxide emissions are anticipated from both process tanks 1 and 2, in both the aerated (N) and non-aerated areas (DN). As the treatment plant uses only activated sludge for biological processes, no nitrous oxide emissions are expected from other parts of the facility.

Description of established measurements: The utility explains that a nitrous oxide sensor has been installed centrally within the aerated area (N) of process tank 1. It also notes that emissions from the non-aerated area (DN) are not measured, but are assumed to be 10% of those from the aerated area (N), based on prevailing key data. In addition, no measurement has been established in process tank 2; emissions here are presumed to be identical to those from process tank 1, since both tanks are identical in structure, operation and wastewater distribution.

Operational log: The utility attaches the updated operational log detailing the maintenance frequency for the nitrous oxide sensor (and the airflow meter), as well as records of maintenance activities conducted within measurement period for the last year, including the personnel involved.

Emission data and calculation of the emission factor: The utility prepares an extract of the daily nitrous oxide emissions (kg N_2O/d) from the aerated area (N) of process tank 1 using the SCADA system. The data are presented in a spreadsheet. The spreadsheet also includes calculations of emissions from the non-aerated area (DN) in process tank 1, which are considered to be 10% of those from the aerated area. The total emissions from process tank 1 are then calculated as the sum of emissions from the N and DN areas. Emissions from process tank 2 are also extrapolated, assuming these are the same as those from process tank 1, since the tanks are identical, operated in the same manner, and the wastewater is distributed evenly between them. Finally, the total emissions are calculated as the sum of the emissions from process tanks 1 and 2.

This may take the following form:

		Process tank 1		Process tank 2	Both tanks
Date	**Emission from N (kg N_2O/d)**	**Emission from DN (kg N_2O/d)**	**Total emission (kg N_2O/d)**	**Total emission (kg N_2O/d)**	**Total emissions (kg N_2O/d)**
1 February	1.5	0.15	1.65	1.65	3.3
1 March	2	0.2	2.2	2.2	4.4
1 April	1	0.1	1.1	1.1	2.2
31 December	1.2	0.12	1.32	1.32	2.64
Total	**500**	**50**	**550**	**550**	**1,100**

On another tab in the spreadsheet, the utility provides an overview detailing the nitrogen supply to the treatment plant via information extracted from PULS, showing nitrogen analyses and inflow, with clear references to the analysis report numbers. These data are then used to calculate the average daily nitrogen supply to the treatment plant (kg TN/d) and the annual nitrogen load (kg TN/year).

Finally, the utility creates an overview tab in the spreadsheet, where the annual total emission factor of the treatment plant is calculated as the percentage of the nitrogen supply to the plant that is released as nitrous oxide from the biological processes. The utility highlights whether the emission factor exceeds the specified threshold, using a colour indicator such as green or red.

The comprehensive reporting basis is submitted to the supervisory authority.

Supervision
During the supervisory authority’s annual review to ensure compliance with the treatment plant’s discharge permits, it also monitors nitrous oxide emissions. Here, the case officer examines:

System demarcation: Whether all potential sources of nitrous oxide emissions have been identified (relative to the plant’s configuration), or whether any are missing – for example, has a secondary stream process been overlooked?

Description of established measurements: Is there a clear indication of which measurement points have been established, and are they compliant with the measurement programme (BASE or EXPANDED) to which the treatment plant is subject, as well as with the guidelines in the area – regarding sensor placement, for instance?

Operational log: Is there a clear indication of how often the sensor must be cleaned/calibrated/adjusted/replaced? Have the maintenance tasks been performed at the same frequency? Or is there an extended period where the sensor has been neglected, such as during holidays?

Emission data and calculation of the emission factor:
- Is the dataset from daily emissions in the aerated area of process tank 1 complete, or are there prolonged periods of drop-out (and if so, why)?
- Have emissions from the non-aerated area in process tank 1 been calculated correctly (and as outlined in the utility’s description of established measurement)?
- Have the emissions from process tank 2 been extrapolated correctly (and as outlined in the utility’s description of established measurements)?
- Has the total daily emission calculation for process tanks 1 and 2 been performed correctly (and as outlined in the utility’s description of established measurement)? And have the total annual emissions been calculated correctly?
- Are the calculations for average daily nitrogen supply to the treatment plant accurate, and has the total annual nitrogen load been calculated correctly?
- Has the total annual emission factor for the treatment plant been calculated correctly?
- Does the emission factor exceed the current limit value for nitrous oxide emissions?

Unfortunately, it appears that the nitrous oxide emissions from the treatment plant exceed the prevailing limit value by 20%. The supervisory authority therefore engages in dialogue with the facility, requesting that the facility identify the cause of the excess and develop an action plan to reduce nitrous oxide emissions going forward. Furthermore, the supervisory authority refines the measurement method, requiring the utility to use the *EXPANDED method* in future assessments. The report for the coming year will therefore be more precise, providing actual measurements of emissions from process tank 2 rather than relying on extrapolation.

The utility proceeds to purchase an additional liquid-phase sensor and install it in the aerated area of process tank 2. This is set up and operated in the same manner as the sensor in process tank 1, and it is also logged in the SCADA system and the operational log in the same way as the existing sensor.

The utility investigates the nitrous oxide dynamics at the treatment plant on the basis of the measurement period in the past year and discovers that the sludge age at the plant is inappropriately low, particularly during the peak season for nitrous oxide production.

The utility therefore drafts an action plan, specifying that the process tanks will be operated with a higher sludge concentration in future (on average, 0.5 g/l higher than during the recent measurement period) to reduce sludge load. At the same time, it will attempt to raise the concentration by 0.8 g/l during the period of highest nitrous oxide production. This optimisation strategy is expected to reduce nitrous oxide emissions by approximately 50% (cf. the Varga study). The action plan is submitted to the supervisory authority for approval.

The case officer subsequently checks that both liquid-phase sensors have been installed and positioned correctly in the process tanks, as specified. The case officer likewise assesses the proposed action plan for reducing nitrous oxide at the treatment plant to be adequate and proportional to the breach of the limit value, given that the expected nitrous oxide reduction surpasses the breach.

The process going forward …
A new annual measurement period begins, during which the utility measures nitrous oxide emissions using the *EXPANDED method* and operates the process tanks with a higher sludge concentration, as outlined in the action plan. After a year’s measurement, a new reporting basis is prepared using the same method as before, but now with greater accuracy in emission calculations since emissions from the aerated area in process tank 2 are now measured rather than extrapolated.

The case officer revisits the reporting basis (following the same procedure as before) and concludes that the measures implemented by the utility have positively affected nitrous oxide emissions, given that the emission factor is now below the limit value.

The supervisory authority approves the reporting basis and the impact of the action plan executed over the past year. Now that plant is in compliance with the limit value again, the utility can *choose* to revert to measuring and reporting through the *BASE method.*

Proposals for regulatory methods to reduce nitrous oxide emissions from treatment facilities

One of the goals set in the “Climate Plan for a Green Waste Sector and Circular Economy” is to reduce nitrous oxide emissions from treatment plants with a capacity of 30,000 PE or more. Analysis work has therefore been initiated to determine how such regulation could be designed and implemented so as to achieve a 50 per cent reduction in nitrous oxide emissions from Danish treatment plants.

This report examines various types of limit values (regulatory methods) that could all be used to regulate nitrous oxide emissions from treatment facilities.
In order to enforce a limit value, precise measurements of the plant’s nitrous oxide emissions are essential. This requires both valid, accurate measurement technology and a reliable method for calculating total nitrous oxide emissions from the plant. An assessment of various available measurement technologies has therefore been conducted.

The report also propose a specific measurement and regulation method and presents estimates of the total costs of the proposed method.

Danish summary:
I ”Klimaplan for en grøn affaldssektor og cirkulær økonomi” er opsat en målsætning om at reducere lattergasudledningen fra renseanlæg med en godkendt kapacitet på 30.000 PE og over. Der er derfor igangsat et analysearbejde som udgangspunkt for, hvordan en sådan regulering kan designes og implementeres, således at lattergasemission fra danske renseanlæg reduceres med 50 %. Denne rapport præsenterer det gennemførte analysearbejde og giver anbefalinger til en sådan regulering.

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