

Measuring What Matters: Mandatory Real-Time N₂O Monitoring under the Urban Wastewater Treatment Directive

A joint position paper by the European industry coalition for cost-effective N₂O monitoring

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Executive summary

Nitrous oxide (N₂O) is the single largest climate footprint of an average European wastewater treatment plant (WWTP), as well as a reliable real-time indicator of inefficient biological nitrogen removal. Recent peer-reviewed evidence shows that N₂O emissions vary by more than two orders of magnitude between plants and over time — a universal emission factor is therefore scientifically indefensible, and no predictive model can on its own substitute for direct measurement. Turnkey N₂O monitoring systems from suppliers are cost-comparable to other continuous sensor installations commonly deployed at wastewater treatment plants. We urge the co-legislators to make continuous, real-time N₂O monitoring mandatory at minimum one point in the biological stage for every plant ≥ 10 000 p.e.; should this be considered disproportionate for smaller utilities, we propose a threshold of ≥ 30 000 p.e., which already covers more than half of sector emissions while protecting European technology leadership.

Proposed wording for the implementing act

“Member States shall ensure that operators of urban wastewater treatment plants with a design capacity of 10 000 p.e. or more install and operate continuous, real-time monitoring of nitrous oxide (N₂O) at no fewer than one representative point of the biological treatment stage. Measurements shall comply with a minimum time resolution of 5 minutes, an expanded measurement uncertainty of ≤15 % and calibration traceable to international standards. Plant-specific emission factors based on direct measurements shall be reported annually to the competent authority and to the European Environment Agency. Predictive models or default emission factors shall not be accepted as a substitute for compliance reporting; the use of validated models as decision-support tools for process optimisation, control design and scenario analysis remains encouraged.”

1. Why N₂O monitoring matters — climate and operations in one signal

N₂O is the climate hotspot of the urban water cycle. With a 100-year global warming potential of 273 (IPCC AR6) and typical emission rates of 0.5–2 % of influent nitrogen load, N₂O routinely accounts for **60–80 % of the operational carbon footprint** of a biological WWTP, more than electricity, sludge and chemicals combined. As European electricity grids decarbonise, N₂O becomes the dominant remaining footprint of the sector and the binding constraint on the UWWTD’s 2040 energy-and-climate-neutrality objective.

Monitoring is also abatement. Real-time N₂O measurement is not only a reporting input; it is a process signal. Peaks reveal where nitrification or denitrification is failing — low-DO niches, ammonia shocks, nitrite accumulation, cold-temperature effects and carbon deficits. Published European campaigns demonstrate **simultaneous N₂O reductions of 40–70 % and improvements in effluent total nitrogen (TN)**, often with no additional aeration energy. Monitoring pays for itself before any carbon-pricing mechanism is applied.

2. Compliance accounting must be measurement-based: neither a default emission factor nor a model can substitute

The most comprehensive synthesis to date¹ assembled 376 N₂O emission-factor observations from 119 studies covering ~200 plants worldwide, augmenting the IPCC 2019 database twelve-fold. The conclusion is direct: ‘N₂O emissions from wastewater facilities exhibit **considerable variability and are difficult to be represented by a single EF value**’. European reviews (Vasilaki et al., 2019; Gruber et al., 2020) reach the same conclusion. N₂O can account for up to 80 % of Scope-1 process emissions of a treatment plant (Daelman et al., 2013).

The variability is **not a deficiency of the database, it is an irreducible feature of biological nitrogen conversion**. Most of the annual N₂O load is generated during short transient events (load shocks, DO crashes, cold-temperature episodes, nitrite-accumulation windows) that are intrinsically site- and time-specific. The policy consequences are decisive:

- **Uniform emission factors are wrong by an order of magnitude or more.** Applying the IPCC default of 1.6 % to an individual plant systematically under- or over-states emissions and obscures the largest mitigation opportunities.
- **Predictive models cannot fill the gap on their own.** Even state-of-the-art mechanistic activated-sludge models with N₂O extensions (ASM-N₂O and equivalents) have reported plant-scale prediction errors that can exceed 50 %, because the relevant micro-scale drivers — AOB/NOB balance, local DO, free nitrous acid, free ammonia — and their dynamics remain only partly characterised at the operational level. A model calibrated at one plant cannot be assumed to transfer to another, or to a materially changed process, without site-specific validation against direct measurement.
- **Models are nonetheless an indispensable companion to measurement.** Properly validated models enable root-cause interpretation of measured peaks, scenario and what-if analysis ahead of investment decisions (side-stream treatment, the fourth treatment step, control upgrades) and the design of aeration, DO and nitrite-control logic that delivers the 40–70 % reductions cited above. The coalition position is therefore precise: compliance accounting must be measurement-based, while the use of validated models for decision support is to be encouraged. Measurement and model-based optimisation belong together: every credible N₂O model is built on — and continuously benefits from — good measurement data, so the two are complementary rather than competing. It is precisely high-quality continuous measurement that makes model-based optimisation reliable.

¹Song, C., Zhu, J.-J., Willis, J. L., Moore, D. P., Zondlo, M. A. & Ren, Z. J. (2024). Oversimplification and misestimation of nitrous oxide emissions from wastewater treatment plants. *Nature Sustainability*, 7, 1348–1358.

- **Direct, continuous, in-situ measurement is the only auditable basis for compliance.** This is reflected in the higher-tier (measurement-based) methodologies of the IPCC 2019 Refinement and in the full-scale monitoring evidence of Vasilaki et al. (2019) and Gruber et al. (2020); Song et al. (2024) documents the extreme variability that makes any fixed factor or unvalidated model unreliable. Any compliance scheme that relies on a fixed factor or an unvalidated predictive model will systematically misallocate climate effort.

3. Dual-use: monitoring delivers on nitrogen as well as climate

The recast UWWTD introduces **substantially stricter total-nitrogen limits** (typically 8 mg N/L for plants $\geq 10\,000$ p.e., down from 15 mg/L in the 1991 Directive) and extends tertiary nutrient-removal obligations to a much wider population of utilities. Many of these plants were not designed for that level of performance and will need to optimise rather than rebuild. N_2O is the most sensitive available **indicator of inefficient biological nitrogen removal**: a plant emitting high N_2O is, almost by definition, either leaking reactive nitrogen as nitrite, ammonia bleed-through or incomplete denitrification, or over-aerating at unnecessary energy cost. The marginal cost of a single sensor therefore delivers value against two separate Directive obligations — climate-neutrality reporting and effluent-nitrogen compliance.

4. The technology is ready and was developed for this Directive

Continuous, real-time N_2O monitoring is no longer a research instrument. Multiple European-headquartered suppliers, represented in this coalition, already offer commercial, turnkey monitoring systems **using a range of complementary measurement principles**, covering both in-reactor and off-gas approaches and addressing the full range of European plant configurations. The coalition deliberately does not advocate for any single technology; performance criteria, not technology choice, should drive the policy.

- **Proven at European scale.** Long-term campaigns at Kralingseveer (NL; Daelman et al., 2015), Werdhölzli/Zurich (CH; Gruber et al., 2020) and Strass an der Eyrach (AT) have produced peer-reviewed plant-specific emission factors and documented operational improvements. Coalition members together operate installations across more than ten EU and EEA Member States.
- **Affordable.** Turnkey N_2O monitoring systems from suppliers are cost-comparable to other continuous sensor installations commonly deployed at wastewater treatment plants. Payback typically 1–3 years from aeration optimisation and avoided external-carbon dosing, before any carbon-pricing effect.
- **Specifications are mature.** ‘Real-time’ in this paper means ≥ 1 measurement every 5 minutes, expanded measurement uncertainty $\leq 15\%$ and calibration traceable to international standards. Products represented by the coalition meet or exceed these criteria today.
- **Built for the Directive and at risk if it is weakened.** European suppliers have invested in this product category specifically in anticipation of the climate-and-nitrogen ambition of the recast UWWTD. **If the implementing acts do not deliver a measurement-based obligation, the European supplier base will absorb a sharp demand reduction precisely in a technology segment where Europe is currently the world leader.** A weakened mandate would not save Member States money; it

would hand the next decade of global market growth — given wastewater is decarbonising worldwide — to non-European competitors. This is a direct industrial-policy concern under the Draghi competitiveness agenda and the Net-Zero Industry Act.

5. Anticipated objections, addressed

- **‘Voluntary inventories are enough.’** Inventories using a uniform emission factor mis-estimate plant-level emissions by factors of 5–10 (Song et al., 2024). Climate accounting at that resolution cannot support the EU Climate Law trajectory.
- **‘A predictive model is cheaper than a sensor.’** Generic or unvalidated predictive models cannot capture the short transient peaks that dominate annual N₂O load (see Section 2) and cannot be audited by regulators on a plant-by-plant basis. Validated models add value for process insight and quality assurance, but only direct measurement provides auditable, plant-specific compliance evidence.
- **‘Monitoring without abatement targets is administrative burden.’** Monitoring is itself an abatement lever: documented 40–70 % N₂O reductions follow from feedback-controlled aeration. The measurement is also the mitigation.
- **‘Small utilities cannot afford it.’** Turnkey N₂O monitoring is cost-comparable to other continuous sensor installations already deployed at these plants, and EU instruments (LIFE, Cohesion Fund, ERDF, REPowerEU) can co-finance roll-out in less-resourced Member States. The ≥30 000 p.e. fallback further protects the smallest operators.
- **‘Sensor reliability is unproven.’** Multiple European suppliers, several measurement principles, hundreds of installations and a decade of peer-reviewed evidence: the technology is mature. The EU Methane Regulation (2024/1787) is direct precedent for measurement-based reporting being mandated EU-wide for a potent greenhouse gas.

6. Recommendations to the co-legislators

- **Primary recommendation:** Mandate continuous, real-time N₂O measurement at **at least one point in the biological treatment stage** of every plant ≥ **10 000 p.e.**, with annual reporting of plant-specific emission factors in line with recognised water-industry guidance. Exclude default factors and unvalidated predictive models from compliance accounting.
- **Compromise threshold:** If proportionality concerns prevail, set the threshold at ≥ **30 000 p.e.**. Plants above 30 000 p.e. account for over **50 % of sector-wide N₂O emissions**; the climate dividend — an estimated **4–7 Mt CO₂-eq per year** of avoidable emissions across the EU (extrapolated from Song et al., 2024 and the 40–70 % feedback-control reductions in Vasilaki et al., 2019 and Gruber et al., 2020) — is preserved.
- **European industrial policy:** A clear mandate consolidates Europe’s first-mover advantage in environmental monitoring (Draghi competitiveness agenda, Net-Zero Industry Act). The same European suppliers will export technology globally.

Why now: The implementing and delegated acts under the recast UWWTD are being drafted in 2025–2026, with Member States invited to submit written feedback in the coming weeks. Once a uniform-emission-factor or model-based methodology is enshrined in secondary legislation, it will be effectively impossible to reopen for a decade. The window for measurement-based ambition is open today.

Signatories

The logo for xylem, featuring the word "xylem" in a lowercase, blue, sans-serif font.The logo for VARIOLYTICS, with "VARIOLYTICS" in a blue, sans-serif font. The "O" is replaced by a stylized orange and yellow circular icon.The logo for UNISENSE ENVIRONMENT, with "UNISENSE" in a bold, blue, sans-serif font and "ENVIRONMENT" in a smaller, blue, sans-serif font below it. To the right is a small icon of three circles connected by lines.The logo for Haskoning, featuring a stylized green and blue star icon to the left of the word "Haskoning" in a bold, blue, sans-serif font. Below it is the tagline "Enhancing Society Together" in a smaller, blue, sans-serif font.The logo for upwater, featuring a stylized blue and green wave icon above the word "upwater" in a blue, sans-serif font.The logo for VEOLIA, featuring a red circular icon with a white dot inside, followed by the word "VEOLIA" in a bold, red, sans-serif font.The logo for Cobalt Water Global, featuring a blue square icon with a white wave and dots inside, followed by the text "Cobalt Water" in a blue, sans-serif font and "GLOBAL" in a smaller, blue, sans-serif font below it.The logo for Jacobs, featuring the word "Jacobs" in a bold, black, sans-serif font.The logo for BINDERGROUP, featuring a red triangle icon to the left of the word "BINDERGROUP" in a bold, black, sans-serif font. Below it is the tagline "MEASUREMENT & CONTROL" in a smaller, black, sans-serif font.

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Key references

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- IPCC (2021) *AR6 WG-I, Ch. 7* — GWP₁₀₀(N₂O) = 273; IPCC 2019 Refinement of the 2006 Guidelines, Vol. 5 Ch. 6 (wastewater); Regulation (EU) 2024/1787 on methane emissions reduction in the energy sector; CEN/TS 17198:2018; EN 14181:2014.