



Methane emissions monitoring at wastewater treatment plants in Europe and Australia

P de Jong^a, B Srinamasivayam^{b,*}, A Harrison^b, P Wardrop^a, M Rebsdorf^c , S Thorgaard^c , P Vale^b

^a Melbourne Water, Docklands, VIC, Australia

^b Severn Trent Water, Coventry, CV1 2LZ, United Kingdom

^c Aarhus Vand, Hasselager Allé 29, 34, DK-8260 Viby J, Denmark

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ABSTRACT

Methane (CH₄) emissions from wastewater treatment plants (WWTPs) represent a significant greenhouse gas (GHG) source, challenging utilities aiming for net-zero carbon goals. The majority of the non-biogenic, direct (Scope 1) wastewater treatment plant emissions originate from i) nitrous oxide from the secondary wastewater treatment, and ii) CH₄ from the anaerobic degradation of wastewater and wastewater sludge. *This study evaluates the effectiveness and suitability of various emissions measurement technologies and methodologies for quantifying methane emissions from wastewater treatment processes using data from monitoring trials conducted across treatment plants in Europe and Australia. The results provide a practical framework to guide utilities in selecting the most appropriate methods for monitoring and quantifying fugitive methane emissions from key sources such as open sludge storage, digesters, and sludge drying pans.* Findings across the 3 utilities indicate CH₄ losses of 5%–25% of total CH₄ production, with legacy assets like floating roof digesters contributing 245–2200 tCO₂e/year. At Melbourne Water's Eastern Treatment Plant (ETP), measurement campaigns found that the open sludge drying pans were a major source of emissions and a mobile survey mapping campaign measured site-wide emissions of 46,000–114,000 tCO₂e/year. Aarhus Vand's Egå WWTP measured CH₄ losses at ~7% of total CH₄ production, predominantly from vented sludge storage tanks. The study reviews advanced CH₄ measurement technologies, analysing emissions from WWTPs with sludge treatment centres. Normalised emissions key performance indicators are proposed, with discussions on limitations and mitigation strategies. Recommendations include tailored measurement methods, immediate leak detection and repair, and long-term investments in asset upgrades and alternative sludge treatment technologies.

Introduction

As the global effort to combat climate change intensifies, the wastewater sector has become a focal point for reducing Greenhouse Gas (GHG) emissions. CH₄, a potent GHG with a global warming potential significantly higher than carbon dioxide (28 times (Pachauri et al., 2014)), constitutes a major portion of Scope 1 emissions from wastewater treatment plants (WWTPs). Wastewater treatment is the fifth-largest source of CH₄ emissions worldwide and represents 7–9% of global anthropogenic CH₄ emissions (Khabiri et al., 2022). These emissions primarily arise from anaerobic digestion processes, open sludge storage, and sludge drying facilities. In addition, fugitive

emissions from aging infrastructure, such as leaks in floating roof digesters and valves, contribute significantly to overall emissions, underscoring the urgency of addressing these challenges. Previous studies on measuring methane emissions from WWTPs have typically used generic emissions factors, models or focussed on specific measurement techniques (Parravicini et al., 2022). There are large uncertainties in the quantification of CH₄ emissions from wastewater treatment plants because emissions can vary substantially due to different treatment processes, operational practices, control parameters and site-specific influent characteristics (Li et al., 2024). Kupper et al. (2018) describe the results of field measurements conducted at two WWTPs in Switzerland using flux chamber measurements, total off-gas collection,

* Corresponding author.

E-mail addresses: Pieter.deJong@melbournewater.com.au (P. de Jong), Bharanitharan.Srinamasivayam@severntrent.co.uk (B. Srinamasivayam), Morten.rebsdorf@aarhusvand.dk (M. Rebsdorf).

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and remote sensing techniques such as the tracer gas dispersion. Daelman et al. (2013) measured methane and nitrous oxide emissions from a fully covered municipal wastewater treatment plant in the Netherlands. Zhang et al. (2024) used flux chambers to measure methanogenic activity and developed an activated sludge model to predict the growth of methanogens in the sludge.

Despite its critical importance, methane (CH₄) emissions from wastewater treatment plants (WWTPs) remain significantly under-reported and poorly quantified in the national emission inventories. This is due to the inherent complexity of measuring an unconfined gas with a high level of variability in emission profiles, influenced by site-specific factors such as sludge characteristics, treatment technologies, and operational practices. CH₄ is released from multiple sources across a site, each with distinct emission profiles. For instance, open tanks storing digested sludge may continue to generate and release entrained methane, resulting in diffuse, low-concentration emissions. In contrast, point sources such as leaks in pipework and storage assets, or failures in equipment like flares and combined heat and power (CHP) engines, can produce concentrated plumes. The unpredictable nature and variability of these emissions pose a significant challenge to developing standardised monitoring methodologies and implementing effective mitigation strategies.

To address these challenges, Aarhus Vand (Denmark), Melbourne Water (Australia), and Severn Trent (UK) have initiated a Net Zero Partnership (NZP). This partnership is designed to bring together extensive experience and resources from diverse operational contexts to explore and evaluate solutions to help achieve net carbon neutrality across our sites by 2030. Tackling CH₄ emissions would be instrumental in delivering this target.

This paper presents a comprehensive review of advanced CH₄ monitoring technologies tested by the NZP companies. These technologies have been deployed to capture both point-source emissions from leaks and vents, as well as diffuse emissions from broader site-wide activities. By integrating continuous monitoring systems with targeted measurement campaigns, this study identifies critical emission hotspots and provides actionable data for effective mitigation planning. The results section provides a review of the state-of-the-art technologies in methane monitoring, summary of measurement campaigns at each water authority, and summary of emissions reporting based on emissions factors. The *Discussion* section covers reflections on our learnings, technology limitations, knowledge gaps, and potential mitigation strategies.

In addition to presenting measurement approaches, this paper outlines a framework for emission reduction strategies tailored to site-specific conditions. Short-term measures such as leak detection and repair (LDAR) are essential for addressing immediate emission sources, while long-term strategies focus on asset upgrades and transitioning to advanced sludge treatment technologies. The results highlight the potential of combining low-cost, rapidly deployable measurement tools with state-of-the-art systems for sustained CH₄ monitoring and reduction.

Through these efforts, this study aims to bridge the gap between emission reporting and reality, offering utilities valuable insight to support with planning and achieving their net-zero route map. The findings underscore the critical importance of balancing environmental responsibility with operational efficiency and financial viability, enabling the wastewater treatment sector to contribute meaningfully to global climate goals.

Disclaimer: Working with CH₄ can pose significant safety risks, including potential hazards related to explosive atmospheres (ATEX). Always adhere to applicable safety regulations, follow the guidelines provided by your technology provider, and exercise proper caution and common sense when handling CH₄.

Materials and methods

The following section reviews monitoring methods and techniques, most of which have been trialled by Aarhus Vand (AAV), Melbourne Water (MW), and Severn Trent (ST), including tuneable diode laser absorption spectroscopy (TDLAS), optical gas imaging (OGI), quantum gas LiDAR, tracer gas, Eddy Covariance, flux chamber, inverse dispersion modelling (IDMM), and gas-sniffer technologies. The calculation approaches to measure the emission fluxes from individual unit processes all the way up to facility level are also presented.

Fig. 1 illustrates a generalised schematic of a wastewater treatment plant (WWTP), capturing the core process components observed across the facilities monitored in this study. The diagram incorporates both conventional and alternative treatment elements to provide a comprehensive representation of CH₄ generating and emitting assets typically found in WWTPs. These include emission sources such as sludge storage tanks, anaerobic digester covers, biogas upgrading units, pressure relief valves, and open lagoons - each of which was a focus during the monitoring trials. While the diagram reflects common emission sources identified by the NZP, it is important to acknowledge site-specific variability in CH₄ emissions based on process type and asset conditions. Therefore, a top-down/ broad scale assessment to identify emission sources at each facility is recommended, followed by targeted monitoring to enable accurate quantification.

Table 1 summarises the measurement techniques employed for both broad scale and targeted monitoring, it provides a comparative overview of the techniques used to monitor CH₄ emissions across the different facilities. These techniques were tailored to suit the specific configurations and operational characteristics of each site, ensuring robust data collection and meaningful comparisons. Ideally mass emissions (units in kg) are preferred as it can quantify actual emissions to air. However, many of the technologies currently used are only able to quantify emissions concentrations (ppm, mg/l etc.). Whilst still providing a valuable insight into site emissions (e.g. locating leaks to aid with LDAR), it cannot adequately support with emissions reporting or investment planning.

For a more in-depth exploration, Appendix 1 offers detailed descriptions of the CH₄ measurement techniques deployed in the study. This includes descriptions of technologies such as quantum gas LiDAR, tracer gas dispersion, and optical gas imaging, as well as insights into the application of these techniques at different types of WWTPs. By combining the generalised diagram, summary of measurement techniques (Table 1 below), and detailed appendices, the paper provides a holistic understanding of CH₄ monitoring approaches, supporting the development of effective emission mitigation strategies (Tables 2–4).

Results

This section presents the outcomes from the monitoring trials and implementation of CH₄ monitoring technologies across multiple wastewater treatment plants (WWTPs). As large-scale monitoring efforts continue to evolve, these findings highlight the practical challenges, performance insights, and comparative effectiveness of various techniques trialled by the NZP. By sharing these learnings, the study aims to support the development of tailored monitoring approaches, enabling other operators to enhance methane quantification and mitigation strategies - ultimately contributing to sector-wide progress toward decarbonisation. The obtained results are divided into three sections.

1. Qualitatively Comparison of Monitoring Methods
2. Results of Measuring campaigns
3. Results of emissions reporting based on emission factors

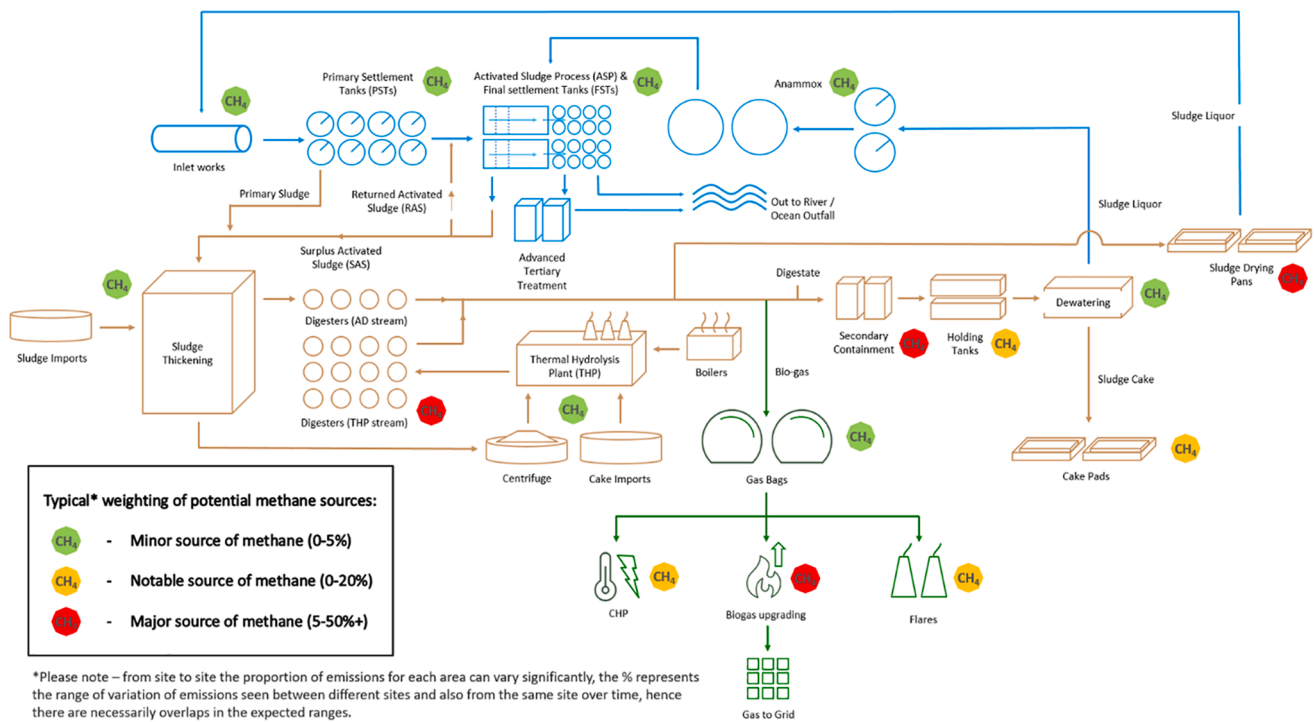


Fig. 1. Generalised diagram of a WWTP showing common CH₄ emitting assets. This is a visual guide based on several measurement campaigns at multiple NZP sites; however, emission levels will also depend on asset operation, age and condition.

Qualitatively comparison of monitoring methods

Selecting the appropriate methods for CH₄ emission monitoring is critical to achieving your goals efficiently. The choice of techniques should be guided by the specific objectives, whether for detecting leaks, quantifying emissions, or capturing long-term trends. Tools and measurement techniques (detailed in Table 1) such as LiDAR campaigns, drone-based Tuneable Diode Laser Absorption Spectroscopy (TDLAS), or handheld Optical Gas Imaging (OGI) systems offer cost-effective and rapid deployment options, making them ideal for many applications. However, there is no universal solution; selecting the right approach requires balancing accuracy, complexity, and cost while aligning with the desired outcomes (Figs. 2 and 3).

The radar plots below provide a comprehensive overview of the methods discussed earlier, introducing a systematic approach to selecting suitable techniques based on key evaluation criteria. Each criterion is rated on a scale where 0 represents the lowest suitability and 5 the highest:

- Affordability – Relative cost comparison at the time of testing
Scale: 0 = very expensive; 5 = low cost
- Ease of implementation at operational sites (factors in process disruption, resource requirement)
Scale: 0 = very difficult (e.g. interferes with operations/ requires specialist resource); 5 = very easy (enables non-intrusive monitoring)
- Leak detection suitability for leak detection and repair (LDAR)
Scale: 0 = no leak detection capability; 5 = highly suited for leak detection
- Quantification at asset level
Scale: 0 = no quantification; 5 = provides reliable asset baseline
- Quantification at site level
Scale: 0 = no quantification; 5 = provides reliable site level baseline
- Ability to capture long-term trends (e.g. seasonal variation)
Scale: 0 = snapshot only; 5 = long-term trends captured
- Certainty of flux or mass emissions estimates
Scale: 0 = low certainty; 5 = high certainty

Development of a facility level baseline is essential to achieve a better understanding of the system performance and provide context for interpreting CH₄ emissions. This would enable improvements in both short-term maintenance activities as well as to help prioritise longer term investment strategies for effective mitigation. Key data to gather as a starting point includes:

- **Biogas Production and CH₄ Concentration:** Measuring biogas production and CH₄ concentration is critical for assessing the efficiency of anaerobic digestion processes and identifying potential CH₄ losses. This data serves as a benchmark for understanding how much CH₄ is captured versus emitted and aids in optimising energy recovery.
- **Sludge Balance (COD and VS Conversion in Digesters):** Monitoring the balance of chemical oxygen demand (COD) and total volatile solids (VS) conversion in digesters is crucial for evaluating anaerobic digestion efficiency. Combined with biogas CH₄ production data, COD mass balances can provide insight into CH₄ capture efficiency and potential emissions. Discrepancies between expected and actual CH₄ recovery can indicate leaks or inefficiencies, helping identify emission sources.

Having this baseline data is important because it informs emission trending, models, supports decision-making for mitigation technology selection, and allows for effective tracking of emission reduction efforts over time. Without accurate initial data, it becomes challenging to quantify CH₄ emissions accurately, evaluate mitigation measures, or validate the success of implemented strategies.

Results of measurements campaigns

The following section summarises direct measurement campaigns and CH₄ monitoring projects conducted at Aarhus Vand, Melbourne Water, and Severn Trent to quantify CH₄ emissions.

Table 1
Techniques to measure CH₄. AAV is Aarhus Vand, Denmark; MW is Melbourne Water, Australia; ST is Severn Trent, United Kingdom (Fredenslund et al., 2023; UKWIR 2023; Mønster et al., 2019; Ricardo 2017; Titchener et al., 2022; GHG Emissions Monitoring and Assessment: Chapter 6 Equipment/Instrumentation Selection 2023).

Equipment / Measurement techniques	Description	Best suited Application (e.g. point sources, diffuse sources, site wide etc.)	Advantages & Benefits	Limitations	Intrusive or non-intrusive	Quantifies CH ₄ concentration or flux	CH ₄ limit of detection	Flux calculation basis	Continuous or single measurements	Trialled by
Handheld Optical Gas Imaging (OGI)	Infrared gas imaging camera	Point source	Portable	Quantification is limited, more suited for LDAR	Non-intrusive	Quantification is limited, more suited for LDAR	≈5 ppm	N/A	Single measurement	AAV, ST
Sniffer/ Hi-Flow Sampler	Infrared gas detection	Point source	Portable	Only good for leak detection	Non-intrusive	Concentration	≈5 ppm	N/A	Handheld	AAV, MW
OP-FTIR	Fourier transform infrared spectroscopy (FTIR)	Individual area emissions and asset wide with additional IR sources	Can measure other compounds and cover wide area	Cannot pinpoint location of emissions. May require external IR source	Non-intrusive	Concentration/ Flux	<1 ppm or 20 ppm*m	Mass balance or inverse dispersion modelling	Continuous	MW
Pitot tube	Flame ionisation detectors or photoacoustic gas analysers	Exhaust stacks or ventilation shafts only	Low uncertainty	Cannot be used for leaks or diffuse emissions sources	Intrusive	Flux		Mass balance	Continuous	AAV, MW
Analyse CH ₄ concentration in liquid phase	Headspace sampling of dissolved CH ₄	Diffuse liquid sources only	Can validate other techniques	Only good for liquid sources	Intrusive	No	0.01 mg/L	N/A	Single measurements	MW
Closed surface flux chambers/ hoods	Hoods have built in sensors	Diffuse liquid sources only	Low uncertainty with multiple hood deployment	Hoods can impact the rate of emissions because they reduce the emissions that result from convection	Intrusive	Flux		Mass balance	Continuous	MW, ST
Open surface flux chambers/hoods	Hoods are combined with a gas analyser	Ideal for aeration tanks	Low uncertainty with multiple hood deployment	If several hoods are needed the method is time and labour intensive	Intrusive	Flux	0.3 ppm	Mass balance	Continuous	MW
Mobile surveying	Cavity ring-down or portable flame ionization detector	Asset wide (including diffuse sources) or site wide emissions	Vehicle based which means the instrument is portable	Very high uncertainty. Susceptible to interfering emissions sources and requires consistent weather conditions	Non-intrusive	Concentration/ Flux (only if good wind measurements are also completed)	0.001ppm	Pasquill/ Gaussian analyses	Measurements only during survey period	MW
Tracer gas dispersion method (e.g. acetylene, C ₂ H ₂)	Uses a continuous release of a gaseous tracer at the facility, combined with downwind measurements using a mobile gas analyser	Asset wide (including diffuse sources) or site wide emissions	Low uncertainty	Susceptible to interfering emissions sources and requires consistent weather conditions	Non-intrusive	Flux		Mass balance and ratio of gases	Measurements only during of tracer gas	AAV, MW
Eddy covariance	Measures the turbulent transfer of gases between the ground surface and the atmosphere	Asset wide, but requires uniform emissions (e.g. diffuse sources)	Good in flat terrain and can be done over long periods.	Dependent on wind conditions. Difficult to apply in variable topography and with interfering CH ₄ sources	Non-intrusive	Flux		Inverse dispersion modelling	Continuous	
Radial plume mapping using one or more lasers and mirrors	Uses open-path tuneable diode laser absorption spectroscopy (TDLAS)	Asset wide, but requires uniform emissions (e.g. diffuse sources)	Good in flat terrain and can be done over long periods.	Is limited to measuring only one dimension and relies on a relatively stable wind direction	Non-intrusive	Flux	0.1 ppm	Inverse dispersion modelling	Continuous	MW, ST
Intensity-modulated continuous-wave laser absorption spectroscopy	Uses open-path tuneable diode laser absorption spectroscopy (TDLAS)	Asset wide (including diffuse sources) and site wide	use multiple wavelengths to measure different GHGs over two dimensions	Relies on a relatively stable wind direction and difficult to apply in variable topography	Non-intrusive	Flux	0.1 ppm	Inverse dispersion modelling	Continuous	

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Table 1 (continued)

Equipment / Measurement techniques	Description	Best suited Application (e.g. point sources, diffuse sources, site wide etc.)	Advantages & Benefits	Limitations	Intrusive or non-intrusive	Quantifies CH ₄ concentration or flux	CH ₄ limit of detection	Flux calculation basis	Continuous or single measurements	Trialled by
Aerial measurements using an aircraft or drone	Uses open-path tuneable diode laser absorption spectroscopy (TDLAS)	Asset wide, and site wide with multiple flights	Can quickly identify specific emissions sources, and quantify emissions fluxes	Limit flight range and can only be used for short-term measurement campaigns, so temporal variations cannot be captured	Non-intrusive	Flux	0.1 ppm	Mass balance or inverse-dispersion modelling	Measurements only during flight	
Differential absorption LIDAR (DIAL)	A laser is shot into the atmosphere or from above and the backscattered part is measured	Asset wide and individual area emissions	Provides detailed 3D information and visualization of emission patterns	Site wide emissions require multiple sensors which makes it expensive. Difficult to use for low concentration diffuse emissions	Non-intrusive	Flux	0.05 ppm	Mass balance	Continuous	
Quantum Gas LIDAR	TDLAS and time correlated single photon detection (TCSPC)	Asset wide and individual area emissions	Provides gas leak/plume 3D visualization and localization	Site wide emissions require multiple sensors which makes it expensive. Difficult to use for low concentration diffuse emissions	Non-intrusive	Flux	10 ppm ² m	Mass balance	Continuous	MW, ST

Table 2

Monitoring work carried out at Aarhus Vand facilities.

Monitoring deployment	Learnings
LDAR using Gas sniffer	A simple handheld gas-sniffer (GMI Gasurveyor 700) is used for monthly checking of the biogas-systems on the four WWTPs as “self-control” for internal audit reports. Measurements are point measurements which gives an indication of the concentration at the exact time of the measurement but not quantity. CH ₄ flux is hard to assess from e.g. valves, pipes etc. From ventilation channels a flux can be calculated when having the ventilator specs and a concentration. But it will only be random samples.
Tracer gas dispersion method (TDM)	The tracer gas dispersion method was used to estimate total plant emissions. A continuous release of a gaseous tracer combined with downwind measurements of atmospheric concentrations of CH ₄ and tracer gas. Screening ambient concentrations of CH ₄ in the surrounding areas is necessary to ensure that any interfering emissions sources not from the plant are taken into consideration. Measurements were obtained over 1–2 h, which gave an indication of the plant’s total emissions at that specific time in relation to the gas production. The method was very sensitive to wind directions and weather conditions as well as access to surrounding roads for traversing the plume.
External audit CH ₄ -leakage	The Danish Energy Agency requires audits which is conducted by an external third party (Lundsby biogas). The monitoring campaign utilised the following equipment: FLIR Gas-camera GMI Gassurveyor 700 Leakage spray The audit is used to assess minor and major leaks, incl. acceptable time frame for fixing the identified leaks. Main findings documented in an external audit-report. Measurements are spot/point measurements which gives an indication concentration at the exact time of the measurement but not quantity.

Aarhus Vand – Danish water utility experience

Data on fugitive CH₄ emissions from Aarhus Vand are scarce. As a part of the GHG reporting, the CH₄ emissions from ADs is set to 1.3 % of the CH₄ production according to Danish reporting standards (Nielsen et al., 2023).

Two tests of approximately one hour, using the Tracer Gas Dispersion method, revealed CH₄ emissions from Egå WWTP at approximately 7 % of the CH₄ production. This finding corresponds well with the survey on Danish biogas plants (Fredenslund et al., 2023) where leakage from biogas plants at WWTPs is reported to reach an average value of 6.7 %. The main emission points are an exhaust-vent from a covered sludge storage tank and from the scum-overflow system on the AD. Attempts were made to further quantify the emissions from the point sources, however the results remain inconclusive. A link between sludge level in the sludge storage tank and CH₄ emission was suspected and confirmed by measuring CH₄ flux at varying sludge levels.

Annual external audits are used to assess minor and major leaks, including confirming acceptable timeframes for fixing the identified leaks. The main findings are documented in an external audit-report annually, which is then approved by the Danish Energy Agency (DEA). In August 2024 the DEA updated an obligation where the Danish utilities are requested to submit a mitigation plan regarding leakages specifically from sludge storage tanks.

Melbourne water – Australian water utility experience

At Melbourne Water’s Eastern Treatment Plant (ETP) a long-term open path laser absorption spectroscopy campaign on 1 open sludge drying pan found that it emitted approximately 32 tonnes of CH₄ over a

Table 3
Monitoring work carried out at Melbourne water facilities.

Monitoring deployment	Learning
Sludge Drying Pan CH ₄ Emission Measurement at ETP	This study utilised two open-path lasers (Gasfinder 2.0, Boreal Laser Inc., Edmonton, Canada) to measure CH ₄ concentrations of an open-air sludge drying pan (SDP) at ETP. The Inverse Dispersion Modelling (IDM) technique was then used to quantify CH ₄ emissions from the SDP over an entire drying cycle (90 weeks). Additionally, an open-path Fourier transform infrared spectroscopy (OP-FTIR) sensor was used to measure gas concentrations of CH ₄ , N ₂ O, NH ₃ , and CO ₂ from a sludge drying pan (SDP).
CH ₄ Emission Scoping study at ETP	Three different CH ₄ measurement techniques were trialled including: In line CH ₄ measurement from odour treatment stacks; CH ₄ flux measurements around the entire site (ground mobile surveying method); A tracer release validated CH ₄ flux estimation over one night across southern drying pan area (several downwind measurements taken).
Satellite Monitoring Observations over ETP and WTP by GHGSat	Melbourne Water engaged GHGSat to conduct one-time CH ₄ emissions monitoring over ETP and WTP, using the satellite DATA.SAT product. According to the report, over the duration of the project carried out by GHGSat on the Melbourne Water sites, no emissions were detected. In discussions with GHGSat it was concluded that the emissions were below the sensitivity limit of the technology.
CH ₄ emissions from Pond 1 E55 Lagoon at WTP	Melbourne Water to conduct a survey to monitor CH ₄ emissions from Pond 1 Lagoon E55 at WTP in 2013. To measure CH ₄ concentration in air a Thermo TVA1000B intrinsically safe portable flame ionization detector (FID) was used. The detector was deployed on a vehicle for land-based measurements and on a boat for measurements over Pond 1.
160S NRP GHG Monitoring Project	Gas collection hoods were used for long-term gas phase on-line monitoring of fugitive nitrous oxide and CH ₄ emissions at a step-fed activated sludge treatment plant with four anoxic and four aerobic passes, treating effluent from an anaerobic lagoon at WTP.
Quantum gas LiDAR trial at ETP digester area (QLM Technology)	Melbourne Water trialled a quantum gas LiDAR for 6 weeks at ETP. The preliminary estimate indicated that the total average emissions leaking from the floating roof seals of the digesters is approximately 3–5 % of CH ₄ production, which is equivalent to approximately 15,000 tCO ₂ e per year. Some minor intermittent CH ₄ emissions were also detected from the waste gas burners, and odour control facility, while other facilities (including the power station exhausts, boiler exhausts, primary sedimentation tanks, and dehumidifier area) showed zero detectable emissions.
Measurement of CH ₄ Emissions from 25 W Pond1 at WTP (University of Melbourne)	The University of Melbourne conducted a collaborative study to measure CH ₄ emissions from 25 W Pond 1 at Melbourne Water's Western Treatment Plant using Inverse-Dispersion Modelling (IDM) coupled with open path laser spectroscopy techniques. The summer monitoring campaign was conducted over 5 weeks while the winter campaign was conducted over 7 weeks.

Table 4
Monitoring work carried out at Severn Trent Water facilities.

Monitoring deployment	Learnings
LDAR using drone mounted TDLAS and OGI	Drone-Based Tuneable Diode Laser Absorption Spectroscopy (TDLAS) Sensor (DJI U10) and Handheld OGI (FLIR GF77) for Leakage Detection and Repair (LDAR) Since December 2020, Severn Trent has been using drone-based TDLAS sensors (DJI U10) and handheld OGI (FLIR GF77) for leakage detection and repair (LDAR). LDAR using drone-based TDLAS and handheld OGI helps locate sources of emissions easily, enabling faster repairs. This approach is a good option for CH ₄ reductions due to its low cost, ease of entry, and quick deployment. However, multiple flights may be needed to pinpoint some leaks, and the inability to quantify the volume of gas loss makes it difficult to use the data to prioritise longer-term investments or track the benefits of fixing issues. The nature of a campaign also means that fugitive or temperamental emissions could easily be missed (see more in the LiDAR section).
Long term monitoring via inverse dispersion modelling	Twelve metal oxide sensors and a weather station were installed around the Minworth cake pad, positioned 2 m above ground level. These sensors sampled ambient CH ₄ concentrations at 1-minute intervals continuously for a year, from February 2021 to December 2022. The inverse dispersion modelling, carried out using the data from these ground-based sensors, proved useful in profiling and establishing clear diurnal and seasonal trends in continuous emissions from the cake pad storing digested, dewatered sludge. However, our experience indicates that these types of systems are not well-suited for monitoring tall, heavily built areas or tall assets. The model assumptions may not hold true when wind and gases are channelled through built-up areas of the site. Conversely, an open tanks or storage areas are easier to model due to the absence of such complexities. Because of wind channelling, it is also challenging to pinpoint point emission sources from complex sites, making these types of sensors ineffective for LDAR. Approximate emissions sources can still be estimated using inverse dispersion modelling, emissions occurring at height (such as from PRVs, digester roofs, and flares) may be missed when monitors are placed at ground level.
Short term (campaigns) via inverse dispersion modelling. IDMM utilised gas analyser and an inverse dispersion model	Survey carried out in two separate days of measurement of sludge treatment facility emissions on two days. The pathogen kill tanks were identified as key contributor to the site's total emissions. However high levels of variations observed across the two campaigns (even though they were monitored at the same stage in the process) likely due to seasonal differences and environmental conditions such as wind speeds and direction on the day. In situ measurements taken by measuring concentrations of CH ₄ gas above the tanks indicated CH ₄ emissions rising throughout the fill phase, peaking towards the end and then gradually decreasing through the retain and decant phases. Higher CH ₄ concentrations were observed when volatile solids concentrations entering the pathogen kill tank were higher.
Fugitive emissions monitoring using LiDAR	QLM LiDAR utilises a combination of TDLAS, Differential Absorption LiDAR (DIAL), and Time Correlated Single Photon Counting (TCSPC) to scan gas plumes and measure the amount of CH ₄ within them.

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Table 4 (continued)

Monitoring deployment	Learnings
	LiDAR is a new technology that provides continuous monitoring capabilities on sites, helping to locate and track sources of fugitive emissions. External validation of the technology and quantification methodology at METEC offers additional reassurance that the measured leak rates and quantities are accurate when using a long-term average. These systems have proven valuable for LiDAR, helping us identify several intermittent leaks that were missed during previous campaigns. The long-term data also enables bottom-up accounting of site emissions, although several assumptions need to be made during this estimation process. There are some limitations as well. Line of sight is required to detect and quantify emissions, which can be overcome by using multiple cameras to cover different angles of view. Alternatively, installing the system at height can improve coverage even with fewer cameras.

90-week cycle (Bai et al., 2023). During the first 52 weeks (which is now the average sludge drying cycle period) the measured cumulative emissions totalled 29 tonnes of CH₄, which corresponds to ~41,400 tCO₂e/year for all 51 pans. The findings from the Sludge Drying Pan CH₄ Emission Measurement project at ETP showed that on average the measured emissions were reasonably close to the emissions reporting data which used National Greenhouse and Energy Reporting (NGER) (National Greenhouse and Energy Reporting Scheme 2025) generic emission factors (based on IPCC methodology) (Pachauri et al., 2014), however, the measured emissions were much greater when sludge is first pumped into the pans and as the sludge dries the emissions rate gradually reduces. The tracer gas method extrapolated to all 51 sludge drying pans indicated emissions of 22,100–24,700 tCO₂e/year, however, the method is not suitable for measuring temporal variation of emissions that occur during an entire sludge drying cycle. The mobile survey method conducted at the ETP estimated site-wide CH₄ emissions of 46,000–114,000 tCO₂e/year. While this method has large uncertainties, the reported emissions of 74,000 tCO₂e for the same year were within this range. Preliminary data from the quantum gas LiDAR trial showed that there are significant fugitive emission (approximately 3–5 % of CH₄ production) coming from the floating roof seals of the digesters at ETP and these emissions are not currently reported under the emissions reporting guidelines. The laser absorption spectroscopy-based monitoring completed by the University of Melbourne indicated that the average real emissions from 25 W Pond 1 at WTP could be substantially higher than the emissions currently reported using the NGER emission factors for that particular asset. In general, the preliminary results of measured emissions from specific assets such as digesters and treatment ponds indicated that the real emissions are much higher than emissions that are reported for these assets using the NGER Measurement Determination generic emission factors. Generic emissions factors are typically based on the IPCC guidelines and methodology. These results agree with findings from studies on CH₄ emissions from WWTPs in the US and Sweden which found that measured emissions were approximately 2 times IPCC/EPA estimates based on emission factors (Moore et al., 2023; Song et al., 2023; Gålfalk and Bastviken 2025).

While emissions reporting follows the best practice interpretation of the prescribed NGER methodology, some WWTP processes and atypical assets are not adequately covered by the NGER guidelines because of gaps in the emissions reporting methodology. For these unique processes it is not possible to accurately report emissions based on emission factors alone. Furthermore, emissions reporting derived from direct measurement of emissions is not specifically defined or even permitted for wastewater handling under the present NGER principles. Therefore,

variations between reported and measured emissions arise from the relevant immaturity in the science at the time that the current assumptions in the emission reporting calculation methods under the NGER (Measurement) Determination 2008 were set out in the National Greenhouse and Energy Reporting Regulations 2008. As the wastewater sector's understanding of actual emissions evolves, it is anticipated that emission reporting methods and calculations will need to be updated to enable reported emissions to more closely match measured real emissions. Until this occurs, it is anticipated that emissions measurement research will continue, to ensure that adaptive plans focus on real emissions reductions. In future, methane emissions factors for specific wastewater treatment facilities such as digesters and treatment ponds might be revised higher in line with research and published literature, but there could also be exceptions due to differences in wastewater treatment processes and operational practises.

Severn Trent – United Kingdom water utility experience

Severn Trent have implemented a comprehensive programme of LDAR (Leak Detection and Repair) using gas sniffers, OGI cameras, or drone-mounted sensors. This has proven to be a successful strategy in enabling significant emission reductions whilst also enhancing site safety. This approach can be rapidly deployed and is straightforward to implement. However, accurately quantifying site-level emissions remains complex due to the mixture of continuous and intermittent point source emissions and likely seasonal variability in emissions from digestate storage tanks. A combination of continuous monitoring and targeted campaigns is recommended to capture a comprehensive emission profile, although practical constraints and the required level of accuracy must be considered when selecting the appropriate technology mix.

Preliminary data indicates that point source CH₄ emissions are significantly lower than current UK industry standards (Carbon Accounting Workbook v17) suggest. It is worth noting that emission quantification followed multiple years of LDAR activity using the technologies mentioned above. Therefore, it is difficult to conclude if the findings would be typical of all AD facilities, and further long-term monitoring across multiple sites is necessary to confirm these findings.

As suspected, open tanks containing sludge are also key sources of CH₄ emissions. It will be beneficial to consider asset optimisation strategies or covering to minimise emissions from these sources. Integrating continuous monitoring for leaks with campaigns for open tank emissions, validated by top-down methods like tracer gas studies, offers a promising approach for robust emission accounting.

Results of emissions reporting based on emission factors

Table 5 presents a condensed summary of the reported methane emissions, based on emission factors (typically IPCC emission factors) for different WWTP processes. Each country's specific emissions reporting standards are outlined below.

Reporting standards for each country:

- Denmark: Total plant emission based on CH₄ production (Nielsen et al., 2023)
- Australia: National Greenhouse and Energy Reporting (NGER) Scheme (National Greenhouse and Energy Reporting Scheme 2025)
- United Kingdom: Total plant emissions based on treated sludge volumes and treatment technology (UK Water Industry Research Carbon Accounting Workbook (CAW) 2025)+ literature factors (2024 reported baseline)

The main findings show, not surprisingly, that CH₄ emissions vary significantly, particularly depending on the type of sludge treatment and post-processing technique used. As shown in Table 5, open sludge drying pans emit substantially more CH₄ compared to other drying

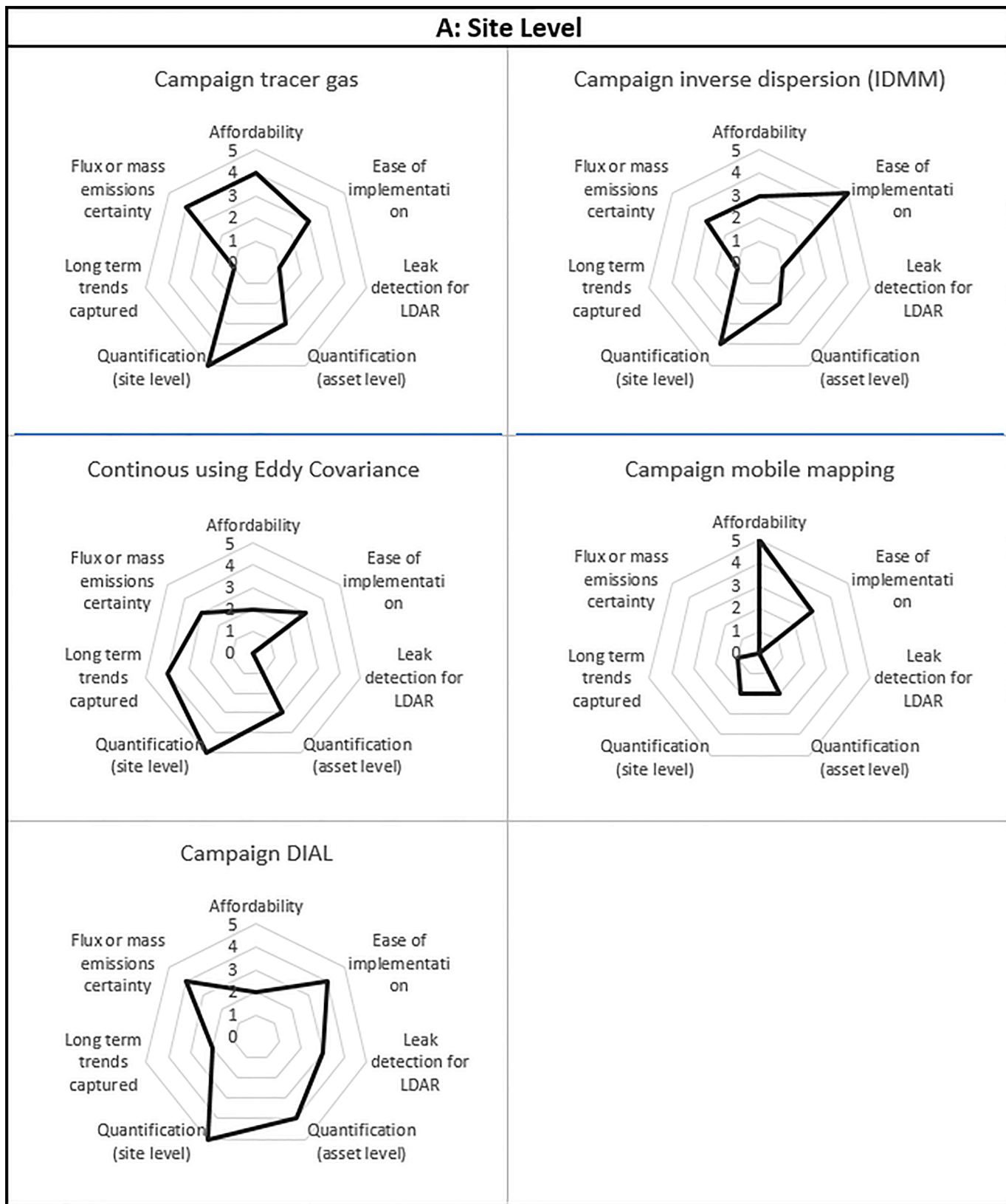


Fig. 2. Radar plots of monitoring technologies and techniques for site level monitoring (prioritising top down/ broad level assessment). The plot shows the NZP assessment of these technologies based on affordability, ease of implementation, leak detection for LDAR, long term trends captured, flux or mass emissions certainty.

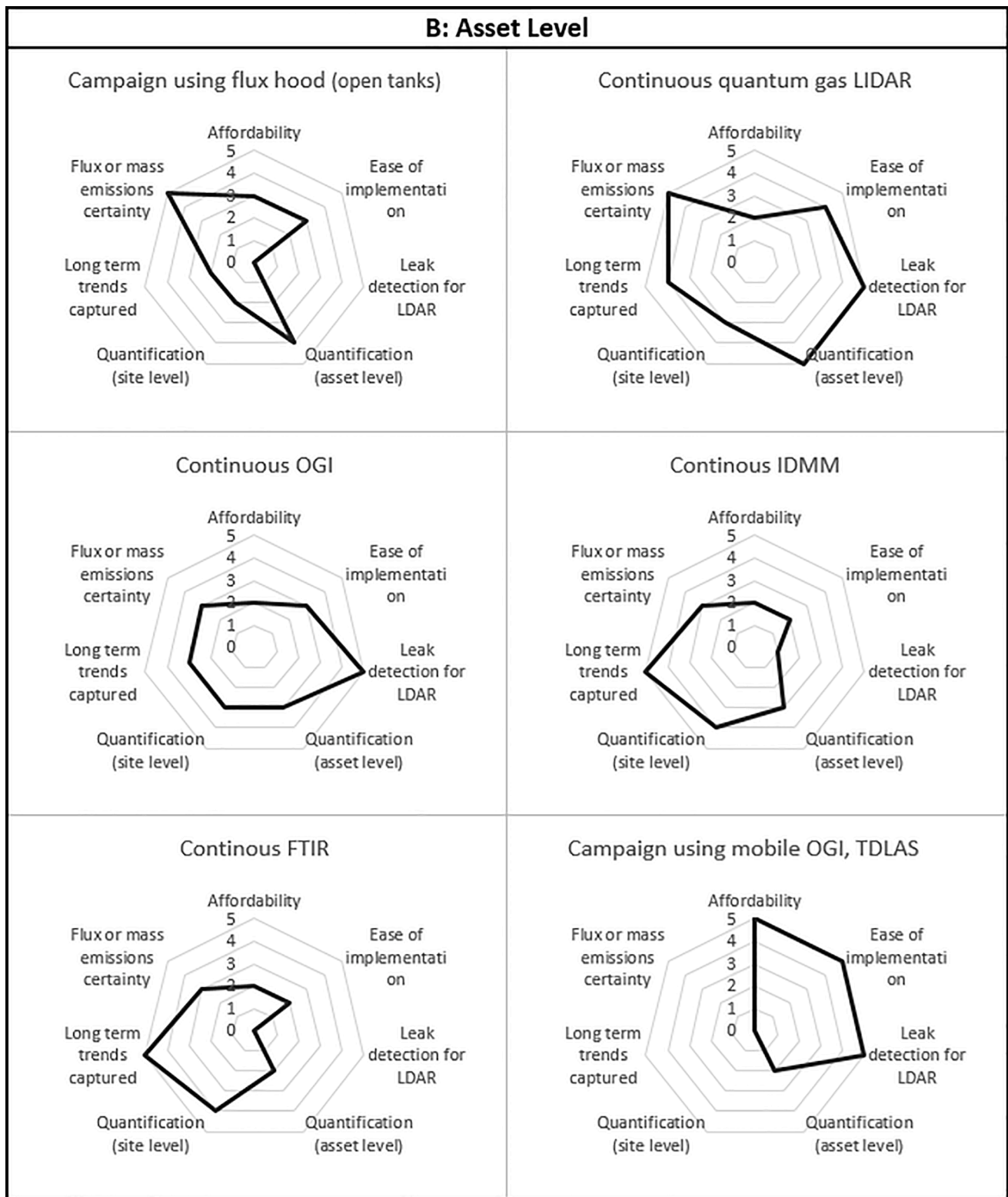


Fig. 3. Radar plots of monitoring technologies and techniques for asset level monitoring (prioritising bottom up/ asset level assessment). The plot shows the NZP assessment of these technologies based on affordability, ease of implementation, leak detection for LDAR, long term trends captured, flux or mass emissions certainty.

technologies. Older assets, which were originally designed with a focus on reducing solids mass rather than GHG emissions, are major contributors to CH₄ emissions. These assets include open sludge storage tanks, anaerobic digesters (AD) with floating roofs, outdated valve technologies (such as hydraulic back pressure valves on ADs), and ATEX-ventilated areas intended for explosion prevention. It should also be

noted that emissions from some of the forementioned assets (e.g. emissions from digesters with floating roofs and pressure relief valves) are not reported under Australian or European reporting guidelines.

There are two key performance indicators (KPIs) in [Table 5](#) which enables the emissions from different WWTPs to be compared side-by-side regardless of each plants total annual influent flow or treatment

Table 5

Key plant information and CH₄ emissions reporting in relation to total COD influent and digester CH₄ production. Further information about each WWTP can be found in Appendix 2. (1) The CH₄ GWP used in this report is 28 ((Pachauri et al., 2014): IPCC 5th assessment report), (2) CH₄ mass was converted to COD using the ratio: 1 g of COD equals 0.25 g of CH₄, (3) Cumulative uncertainty assessment, (4) NGER scheme CH₄ emissions reporting cumulative uncertainty (based on root-sum-of-squares method), however, emission measurement trials indicate that this uncertainty should be substantially higher.

Utility, WWTP	Aarhus Vand Ega	Melbourne Water Western Treatment Plant (WTP)	Melbourne Water Eastern Treatment Plant (ETP)	Severn Trent Water Minworth
Size - Average Dry Weather Flow (ML/d)	86	485	350	450
Serving Population Equivalent	0.1M	2.6M	2.2M	1.8M + 0.7 M from external sludge imports
Wastewater treatment description	Primary, secondary and tertiary treatment. Plug-flow Activated sludge plant, bio-P (ASP)	Activated sludge plant (ASP), diffused aeration lagoons and facultative lagoons	Primary, secondary and tertiary treatment. Activated sludge plant (ASP)	Primary and secondary treatment activated sludge plant (Bio P configuration).
Sludge treatment description	Mesophilic anaerobic digestion, mechanical dewatering	Sludge dredged from lagoons sent to open air sludge drying pans	Mesophilic anaerobic digestion and open-air sludge drying pans	Mesophilic anaerobic Digestion (THP + Conventional) and mechanical dewatering
Total plant influent loading (t COD/year)	4499	187,231	121,697	75,686
Total digester CH ₄ production (tCH ₄ captured/year)	736	21,253	10,481	13,711
Total reported CH ₄ emissions from Sludge treatment (tCO ₂ e/year) (1)	680	46,663	57,885	33,800
Total reported CH ₄ emissions from Liquid (wastewater) treatment (tCO ₂ e/year)	340	85,910	16,679	N/A - as not covered by the UK reporting methodology
Total CH ₄ (treatment process) emissions (tCO ₂ e/year)	1020	132,573	74,564	33,800
Load normalised CH ₄ emissions (t CO ₂ e/t COD influent)	0.23	0.71	0.61	0.45
CH ₄ emission COD (2) / plant influent COD (%)	3.2	10.1	8.8	6.4
Total CH ₄ emissions/ digester CH ₄ production (%)	5 %	22 %	25 %	9 %
Data year	2023/2024	2022/2023	2022/2023	2023/2024
Estimated uncertainty	± 20–30 % (3)	± 7–8 % (4)	± 6–7 % (4)	± 20–30 % (3)

method. The first KPI is the Total CH₄ emissions (tCO₂e/year) / Total COD influent (t/year) which enables a comparison of the total process emissions from each treatment plant independent of their annual total COD influent. The second KPI is total annual CH₄ emissions / total annual digester CH₄ production (%) which enables a comparison of the different treatment plants in terms of their total process emissions as a percentage of CH₄ digester production. It can be observed that both Melbourne Water's ETP and WTP have substantially higher emissions as a percentage of digester CH₄ production compared to the European plants in Table 5, because of the emissions from the sludge drying pans. In addition, WTP has substantial emissions from its diffused aeration lagoons and facultative lagoons. As a result, reported emissions of CH₄ make up 25 % of digester CH₄ production.

Discussion

Reported CH₄ emissions based on emission factors in Table 5 ranged from 0.23–0.71 g CO₂e/g COD, depending on the type of WWTP. Considering the lower end of this range, these results are in line with the findings from Moore et al. (Moore et al., 2023) who concluded that methane emissions are underestimated by a magnitude of 1.5–2.4 times in US wastewater treatment. Actual emissions are reported in a range of 3.3–3.8 × 10⁻² g CH₄/g BOD (depending on plant size and type), which corresponds to approx. 0.5 g CO₂e/ g COD (considering a COD/BOD ratio of 2 of incoming wastewater and GWP(CH₄) of 28 g CO₂e/g CH₄). As an example, Ega WWTP, based on, losses 5 % (Table 5) of the CH₄ production compared to an average of 7 % methane loss on average in Danish Biogas plants (Fredenslund et al., 2023), based on measurements, resulting in this example to an underestimation in magnitude of 1.4 times. This example underlines the crucial need of better and more accurate monitoring of methane losses from WWTPs to highlight the

discrepancy between measured emissions and reporting based on emission factors.

Sewage wastewater treatment acts as a “societal liver”, serving the public through recycling much of society's liquid waste residues while minimising environmental impacts. Utilities face increasing pressure to deliver these essential services with the lowest possible climate footprint, especially given the high variability in GHG emissions, particularly CH₄. Depending on the age and condition of assets, utilities must navigate difficult choices to achieve climate-friendly performance while maintaining operational efficiency.

The phrase you can't manage what you can't measure is at present holds true in the world of carbon reduction. It is possible to develop best practices that could help reduce emissions without needing to monitor assets. However, developing those best practices, assessing compliance and curtailing risk of ‘green washing’ often needs a robust monitoring program.

This study demonstrates the importance of robust CH₄ emission monitoring program, aiming to outline learnings from the partnership to help guide others embarking on a journey to net-zero emissions. Effective CH₄ monitoring not only reduces GHG emissions but also provides co benefits such as improving site safety by identifying potential explosion risks and may also help improve production by providing valuable process/asset insights uncovering operational inefficiencies.

The role of measurement in the path to net-zero

Advanced monitoring technologies, such as quantum gas LiDAR, tracer gas dispersion, and optical gas imaging, have enabled more precise emission profiling, from single assets to site-wide surveys. Any of these methods provides valuable insights from operations that can drive action towards improving site performance in emissions, safety as well

as product retention. However, these still have their own limitations, for example:

- Quantum Gas LiDAR provides detailed visualisation of CH₄ plumes but is less effective for large-area, diffuse emissions.
- Tracer Gas Dispersion excels in capturing site-wide emissions but is highly weather-dependent and may not offer long term trends
- Optical Gas Imaging identifies leaks effectively but at present lacks accurate quantitative capabilities.

A comprehensive CH₄ monitoring program must strategically evaluate and balance technology options to maximise cost effectiveness whilst helping the business achieving business objectives. These may range from more immediate leak detection and repair as well as providing insights for targeted investment and mitigation, and long-term infrastructure upgrades and business planning.

The role of anaerobic digestion and emerging alternatives

A critical question for the sector is whether society would benefit from discontinuing anaerobic digestion (AD) for biogas production, considering the 5–25 % CH₄ leakage rates observed across facilities (Ref. Table 5). Whilst this might initially appear counterproductive for the global push towards renewable energy, it must be considered as part of a decarbonised energy grid powered by other cleaner renewable sources of energy (e.g. solar, wind). In such a scenario, utilities must carefully consider the emissions from a biogas production plant vs. purchasing green energy from a decarbonised grid. While anaerobic digestion generates renewable energy, it also presents significant emission challenges. Transitioning away from AD to alternative processes like pyrolysis, hydrothermal liquefaction (HTL), or hydrothermal carbonisation (HTC) may reduce emissions from digester facilities. However, these alternatives also have inherent emissions, such as CH₄, nitrous oxide (N₂O), and nitrogen oxides (NO_x), which must be carefully assessed.

Furthermore, the implications of discontinuing biogas production extend beyond emissions. How would such a transition impact energy self-sufficiency and the strategic benefits of producing onsite power? These questions remain complex and underscore the need for comprehensive life cycle assessments to compare the carbon, economic, and operational trade-offs of alternative sludge treatment technologies against the current biogas-based systems.

Investment priorities and policy alignment

To invest wisely, utilities must consider not only the lowest TOTEX (total expenditure) but also multi-dimensional metrics that prioritise carbon reductions. Multi-criteria decision analyses, including life cycle assessments, can provide utilities with actionable insights for navigating trade-offs among environmental, economic, and operational goals.

For example, retrofitting or replacing aging infrastructure, such as floating roof digesters, with sealed or covered systems, can yield significant CH₄ reductions. Transitioning from open sludge drying pans to advanced technologies like thermal hydrolysis or incineration offers further opportunities for emission mitigation.

From 2024, Danish utilities face self-control requirements from the Danish Energy Agency mandating regular CH₄ leakage measurements. Annual third-party audits will produce action lists for improvements, emphasising the need for continuous compliance and innovation. These policy shifts provide a model for global utilities aiming to align operational practices with climate commitments.

Unanswered questions and future directions

Although this paper highlights key considerations, significant questions remain unanswered. Comprehensive comparative analyses of

alternative sludge treatment technologies, including their emissions profiles and energy efficiencies, are essential for informed decision-making. Table 5 demonstrates that the normalised reported emissions can vary substantially depending on the national generic emission factors used, this makes comparisons between facilities and national inventories inherently flawed. We would also expect to see a high degree of difference between the measured emission factors based on the different treatment processes, operational practises, control parameters and site-specific influent characteristics, which must be explored in future work.

Additionally, future research must address the scalability of advanced monitoring systems, standardise application and explore synergies between emerging technologies and existing frameworks.

By aligning technological advancements with regulatory standards and operational realities, the water sector can lead global efforts to mitigate CH₄ emissions, reinforcing its pivotal role in achieving net-zero objectives.

Conclusion

This study demonstrates that CH₄ emissions from WWTPs are highly variable, driven by the diverse configurations of liquid and sludge treatment processes, asset design, and operational practices. Through trials conducted at Aarhus Vand, Melbourne Water, and Severn Trent, significant insights into CH₄ emissions measurement and mitigation strategies have been achieved.

Findings across the 3 utilities indicate CH₄ losses ranging from 5 % to 25 % of total CH₄ production, with legacy assets like floating roof digesters contributing 245–2200 tCO₂e/year. Using emission factors, Melbourne Water reported annual CH₄ emissions at ETP equivalent to approximately 25 % of total CH₄ production. The reported emissions were within the range of site-wide CH₄ emissions measured via a mobile survey, (noting that the measurement technique had very large uncertainties). However, measured emissions at specific facilities such as digesters and treatment ponds indicated that the real emissions from these types of assets are substantially higher than reported emissions based on generic emissions factors. Aarhus Vand's Egå WWTP measured CH₄ emissions equivalent to ~7 % of the total CH₄ production, predominantly from vented sludge storage tanks.

The balance between cost and complexity is a central consideration in selecting the method used to assess emissions. Short-term, low-cost methods, such as mobile mapping and tracer gas dispersion, provide initial site-wide estimates and help identify emission hotspots but lack the ability to capture temporal variations. Advanced technologies, such as quantum gas LiDAR, offer high precision for long-term monitoring and Leak Detection and Repair (LDAR) activities, enabling accurate quantification of point-source emissions and plume visualisation. However, these methods are limited in their range and are less effective for large-area, low-intensity diffuse sources, emphasising the need for a tailored mix of technologies based on site-specific conditions.

In the short term, implementing LDAR activities and low-cost measurement techniques can provide immediate reductions in CH₄ emissions, enhance site safety and improve product retention. Long-term strategies should prioritise the modernisation of sludge treatment processes, such as transitioning from open sludge drying pans to advanced methods like thermal hydrolysis, incineration, or mechanical dewatering. Retrofitting or replacing aging assets, such as floating roof digesters, with sealed or covered systems will also yield substantial emission reductions. Continuous monitoring, combined with targeted campaigns, offers a pathway to robust emission accounting and sustained mitigation.

The emissions KPIs and mitigation strategies for CH₄ vary significantly across WWTPs due to differences in wastewater treatment processes, asset configurations and asset age. While short-term methods are effective for initial assessments, long-term monitoring can provide a deeper level of insight into asset performance under different

operational conditions and locate intermittent emission sources. The collective findings from Aarhus Vand, Melbourne Water, and Severn Trent demonstrate the importance of tailored approaches for emissions measurement and mitigation, balancing cost, complexity, and environmental impact. By adopting these strategies, the water industry can address CH₄ emissions effectively and move toward achieving net-zero carbon goals.

As demonstrated in Table 5, there is a high level of variation in the current national reporting methodologies which make comparisons inherently difficult. The subject of future work could further explore revisions of normalised emission factors based on extensive emissions measurement campaigns. This is especially important for specific wastewater treatment facilities such as digesters and treatment ponds; however, it is likely that there will still be variations between measured emissions and emissions reporting based on emissions factors due to differences in wastewater treatment processes, site-specific characteristics and operational practises.

CRedit authorship contribution statement

P de Jong: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **B Srinamasivayam:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation. **A Harrison:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation. **P Wardrop:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **M Rebsdorf:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Funding acquisition, Formal analysis, Conceptualization. **S Thorgaard:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation, Conceptualization. **P Vale:** Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Pieter De Jong reports a relationship with Melbourne Water that includes: employment. Peter Wardrop reports a relationship with Melbourne Water that includes employment. Sofie Thorgaard reports a relationship with Aarhus Vand A/S that includes: employment. Morten Rebsdorf reports a relationship with Aarhus Vand A/S that includes: employment. Alexander Harrison reports a relationship with Severn Trent Water Ltd that includes: employment. Peter Vale reports a relationship with Severn Trent Water Ltd that includes: employment. Bharanitharan Srinamasivayam reports a relationship with Severn Trent Water Ltd that includes: employment.

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Data availability

We maybe able to provide the data on request.

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Further reading

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