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INDUSTRIAL EFFICIENCY & DECARBONIZATION OFFICE

Measuring Life Cycle Greenhouse Gas Emissions From Water Resource Recovery Facilities Workshop Report

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Disclaimer

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List of Acronyms

AD	Anaerobic digestion
AI	Artificial intelligence
CEO	Chief executive officer
CH_4	Methane
CO_2	Carbon dioxide
CO_{2eq}	Carbon dioxide equivalent
DOE	U.S. Department of Energy
EERE	Office of Energy Efficiency Renewable Energy
EF	Emissions factor
EPA	U.S. Environmental Protection Agency
GHG	Greenhouse gas emissions
IEDO	Industrial Efficiency and Decarbonization Office
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
Mtons	Million U.S. tons
ML	Machine learning
N_2O	Nitrous oxide
NGO	Nongovernmental organization
NO_x	Nitrous oxide
O&M	Operation and maintenance
PDNA	Partial denitrification
PFAS	Per- and polyfluoroalkyl substances
POTW	Publicly owned treatment works
QA	Quality assurance
QC	Quality control
R&D	Research and development
RFP	Request for proposals
SOP	Standard operating procedure

WRF	The Water Research Foundation
WRRF	Water resource recovery facility
WWTP	Wastewater treatment plant

Executive Summary

The U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE), Industrial Efficiency and Decarbonization Office (IEDO) hosted the Measuring Life Cycle Greenhouse Gas Emissions From Water Resource Recovery Facilities Workshop on Jan. 23–24, 2024, in Washington, D.C. The event brought together representatives from water resource recovery facilities (WRRFs), national laboratories, technology providers, academic researchers, industry consultants, and government agencies, to gather input on the challenges and opportunities in greenhouse gas (GHG) measurement at WRRFs and how to effectively leverage future DOE efforts to reduce these uncertainties through potential measurement campaign(s). This report is a summary of the views expressed by individual participants during the workshop; it is not intended to represent DOE's views or programmatic priorities.

Context

There is a great deal of uncertainty about the quantities of direct and indirect GHG emissions from the full WRRF life cycle, including both collection systems and ultimate disposal. In particular, there are questions about the empirical basis for existing emissions factors, and recognition that those factors are incomplete on a life cycle basis. The purpose of this workshop was to inform possible future DOE efforts to reduce these uncertainties through potential measurement campaign(s). In essence, the workshop sought to identify key factors for a design-of-experiment approach to any such future activities.

Total GHG emissions from WRRFs, previously known as either wastewater treatment plants (WWTPs) or publicly owned treatment works (POTWs), are estimated at approximately 44 million tons (Mtons) of carbon dioxide equivalent (CO_{2eq}) (EPA 2022), the bulk of which are comprised of nitrous oxide (N_2O) and methane (CH_4) (United Nations 1992). As reducing industrial GHG emissions is a key goal of DOE, IEDO recognizes the imperative to decarbonize the water sector. This strategy is key to addressing the climate crisis and achieving economywide net-zero emissions by 2050.

Emissions estimates for WRRFs are based on emissions factors (EFs) produced by the Intergovernmental Panel on Climate Change (IPCC), and the wastewater EFs were most recently updated in 2019 (IPCC 2019). Although a tool such as EFs is necessary to produce annual GHG inventories, many authors have questioned their accuracy, applicability, and completeness for estimating WRRF-specific GHG emissions (Demir and Yapicioglu 2019; Li et al. 2022; Willis, Yuan, Murthy 2016), as expressed in the opening plenary presentation. Other topics discussed in the plenary presentations that helped contextualize the workshop included opportunities for WRRF collaboration, international insights from GHG monitoring in Canada and the United Kingdom, using artificial intelligence to model N_2O emissions, quantifying CH_4 emissions in sewer collection systems, and ongoing GHG measurement projects in the United States.

Decarbonization of WRRFs presents unique challenges compared to other industries due to the complex interconnected nature of water, energy, and emissions. Wastewater facilities are principally concerned about managing treatment of influent so plant effluent can meet certain water quality objectives, as mandated by law through discharge permits. Because utility leaders can be held liable for failure to meet effluent discharge permits, WRRFs tend to be risk averse with improvements largely focused on meeting regulatory requirements. WRRFs are also highly accountable to the ratepayers they serve, so cost is a leading consideration. Large capital and ongoing operation and maintenance (O&M) improvements must be justified to ratepayers.

Although large-scale GHG monitoring efforts at WRRFs are more common in other countries, specific challenges exist with widespread adoption in the United States. A coordinated effort combining knowledge across diverse facilities and treatment scenarios is required to better understand GHG emissions at WRRFs, techniques to routinely measure them at various scales, possible mitigation measures, and opportunities for synergies and co-benefits of implementing GHG monitoring.

A Coordinated Effort

The goal of a coordinated GHG monitoring campaign is to inform a coordinated measurement protocol and develop accessible data. Because only a fraction of facilities can participate in a measurement campaign, identification of a representative set of WRRF partners that can propagate results to the wider sector is vital. This could be accomplished through a prioritization exercise to identify variances of most value or other technical approaches. A key benefit to such a collaborative effort is the ability to collect data through a standard methodology. Standardization enables more impactful research outcomes due to comparable datasets across different experiments. This methodology may also provide a roadmap for measurement at various scales using techniques applicable to specific WRRF needs. Equally important to high-quality data collection and valuable insights are data analysis and sharing. Sharing data presents a potential liability for treatment plants, therefore a critical component of a successful coordinated effort is the establishment of confidential data sharing practices.

The execution of a complex measurement campaign will require organized coordination amongst diverse stakeholders across the wastewater sector. A leading "voice"—whether it be a single organization or a collective—is needed to effectively manage such an effort. Expertise in areas like program management, contracting and grant experience, data management, and process and operating backgrounds will be crucial to a successful campaign. Relationships with utilities with diverse treatment trains and process instrument capabilities that also have the willingness to participate and share process GHG emission data are another vital component to success. Proposed projects will need to be vetted for their ability to achieve practical outcomes that provide public benefit, technical expertise with access to adequate resources, and scope that includes efforts toward the central campaign mission of quality data and results sharing.

There is a fundamental tension between the desire for improved and more comprehensive measurements and the need to take mitigation steps now. This workshop was premised on the idea that the DOE would be uniquely positioned to sponsor a large-scale measurement campaign that could help address the limitations of EFs in developing mitigation strategies for individual facilities or types of treatment trains. In the course of the workshop discussions, it became clear that a large-scale measurement campaign is not the only option to advance the state of the art. So, while much of the conversation was about the particulars of what such a campaign might look like, a concurrent finding was that the DOE might consider alternative approaches to meet the overall decarbonization objectives driving the workshop.

Future Needs

Compared to other countries and other industries within the United States, there is a dearth of GHG monitoring at WRRFs. Regarding emissions monitoring throughout the life cycle of wastewater treatment, more research and development (R&D) is necessary to answer the questions of where and how to measure emissions, both inside and outside of a facility. Technological R&D is necessary to allow for accurate and reliable measurements and provide affordable monitoring technologies to WRRFs. Additional research is necessary to inform future standards development in GHG measurements for WRRFs. Lastly, broader scale R&D is needed for analysis that could inform a strategy to maximize the breadth of the campaign’s impact while conserving resources. Although research in this field is growing, there are many additional knowledge gaps that should be considered, including but not limited to understanding competing priorities including unintended consequences to the WRRF or otherwise, establishing connections between better monitoring methods, and potential impacts on local communities.

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SECTION 1

Introduction

1 Introduction

The U.S. Environmental Protection Agency's (EPA's) 2022 Greenhouse Gas Inventory estimates the total greenhouse gas (GHG) emissions from water resource recovery facilities (WRRFs), previously known as either wastewater treatment plants (WWTPs) or publicly owned treatment works (POTWs) at approximately 44 million U.S. tons (Mtons) carbon dioxide equivalents (CO_{2eq}), slightly less than those from the cement industry (EPA 2022). The bulk of these direct emissions are comprised of nitrous oxide (N_2O) and methane (CH_4), as the Intergovernmental Panel on Climate Change (IPCC) considers carbon dioxide (CO_2) emissions from WRRFs as biogenic. The EPA's estimates conform to the requirements of the United Nations Framework Convention on Climate Change, which mandates that signatories (of which the United States is one) report estimates of their total GHG emissions annually (United Nations 1992). These estimates are based on emissions factors (EFs) produced by the IPCC, the recognized global authority for climate science, and the wastewater factors were most recently updated in 2019 (IPCC 2019).

While a tool such as emissions factors is necessary to produce annual GHG inventories, many authors have questioned their accuracy, applicability, and completeness for estimating WRRF-specific GHG emissions (Demir and Yapicioglu 2019; Li et al. 2022; Willis, Yuan, Murthy 2016). Among many other issues, they do not adequately account for variations in:

- The large variety of treatment trains in operation (Faragó et al. 2022; Nguyen et al. 2019; Yan et al. 2023).
- Seasonal factors and diurnal disparities (Vasilaki et al. 2019).
- Uncertainties introduced by measurement techniques and campaign durations (Marques et al. 2016; Thaler et al. 2017; Thorpe et al. 2012).
- Operational strategies, even for identical treatment trains (Kuokkanen 2021)
- Impacts of the introduction of novel treatment strategies (Ross et al. 2020; Schneider, Townsend-Small, and Rosso 2015; Yan et al. 2023).

These emissions factors also do not include emissions from the full WRRF life cycle. This is understandable in the context of producing national GHG inventories to avoid double counting, but it is not illustrative of the entire range of decarbonization opportunities potentially available to WRRFs. Emission factors are intended to support national GHG inventory accounting and are not intended to support life cycle carbon assessment and decision making. Decarbonization of WRRFs requires holistic assessment of carbon and wider value frameworks through application of life cycle carbon and wider life cycle assessment (LCA). Some, but not all, of the WRRF life cycle elements not included are:

- Emissions from collection systems, especially methane (Willis, Yuan, Murthy 2016).
- Indirect emissions from energy consumption drawn from fossil sources, particularly electricity.
- Downstream emissions from sludge disposal, especially CH_4 from landfills and N_2O from land application (Chen 2022; Liu et al. 2013; Obi-Njoku et al. 2022). The EPA/IPCC EFs do include N_2O emissions from water bodies receiving wastewater discharges.
- Diesel fuel consumption for sludge and biosolids transportation, which is growing in importance as land application and landfill regulations become increasingly stringent (CalRecycle 2020; NEBRA 2020; Yoshida, Gable, and Park 2015; Woo et al. 2022).
- The portion of direct CO_2 emissions from the fossil carbon component of wastewater, which can range from 5%–15% of total CO_2 releases from WRRFs (Law et al. 2013; Schneider, Townsend-Small, and Rosso 2015; Tseng et al. 2016).
- GHG emissions from the production of chemicals and other materials used in large quantities at WRRFs (e.g. sodium hypochlorite).

Some of these emissions are indirect, and not fully relevant to any possible measurement campaign, but they are part of the full WRRF life cycle. Figure 1 includes example activities that fit under Scope 1, 2, and 3 emissions categories at a WRRF under the Greenhouse Gas Protocol.

To address as many of these uncertainties as feasible in one workshop, the Industrial Efficiency and Decarbonization Office (IEDO) in the U.S. Department of Energy (DOE) sponsored a workshop at the Westin Washington, D.C., Center on Jan. 23–24, 2024. There were over 60 attendees from a diverse array of WRRFs, engineering firms, relevant nongovernmental organizations (NGOs), academic institutions, federal agencies (i.e., DOE, EPA), DOE national laboratories, and the private sector. The primary objectives of this workshop were:

- Sensing/measurement technologies and techniques, answering:
  - What are the current state-of-the-art sensing and measurement technologies and techniques?
  - What are the major challenges in implementing these technologies and techniques?

- Where might additional research and development (R&D) help to overcome these challenges?
- Measurement campaign design questions, answering:
  - How large would such a campaign need to be to provide credible data?
  - How long would it need to last, with what measurement frequency and specificity?
  - What kinds of variances need to be included in an optimal experimental design?
  - What would the chief challenges be in executing such a campaign?
- Execution considerations, answering:
  - What kinds of organizational characteristics, whether manifested by a single organization or a consortium, would be most critical to the success of such a campaign?
  - How might WRRF participation be most constructively mandated?
  - What kinds of evaluation metrics would be most appropriate to maximize the probability of producing public goods from such a campaign?
- Scope and objective questions, answering:
  - Should the measurement campaign target an improved dataset to support revised emissions factors?
  - If not, what should the objectives be?
  - How long should a putative campaign last?
  - What could be accomplished at various possible funding levels (within realistic congressional budgetary bounds)?

The balance of this report summarizes participant responses to the questions above as well as other issues that arose during the workshop. The overall goal is to inform possible future measurement campaigns that are specifically directed to informing mitigation strategies. Baselines are essential in monitoring the impact of any mitigations, and measurements are instrumental in making before and after comparisons. However, there is a tension between measurements designed to produce national emissions estimates and those required to achieve actual emissions reduction which seems inherent in many of the participant responses below.

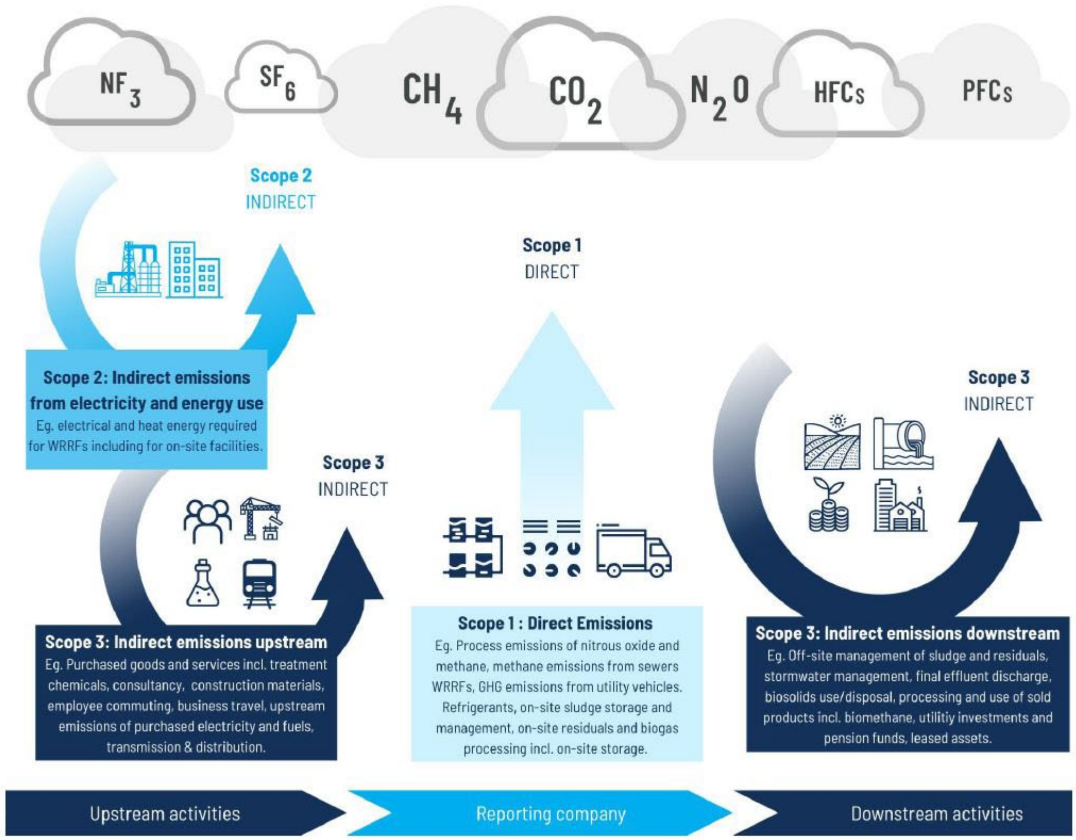

Figure 1. Possible activities defined under scope 1, 2, and 3 emission categories at a conventional WRRF under the Greenhouse Gas Protocol (IWA 2023)

SECTION

2

Water Resource Recovery Facilities Perspectives

2 Water Resource Recovery Facilities Perspectives

Specific concerns and opportunities for WRRFs were not explicit topics of this workshop. However, they were a consistent theme and should be incorporated into any future measurement campaign from DOE. Utility leaders and operators drive change at facilities responsible for waste resource recovery and, therefore, should be the champions of this work. Perspectives shared from utility leaders in attendance fell into two broad categories: (1) sensitivities and challenges (Section 2.1) and (2) opportunities that may come from a measurement campaign to fill the current gaps in WRRF emission measurements (Section 2.2). It is important to note that the outcome of this research will impact not only utilities themselves but the greater communities they serve.

2.1 Sensitives and Challenges

WRRFs are principally responsible for meeting their discharge permits while, to the degree feasible, minimizing rate increases to provide this service. GHG estimation and/or measurement is not required and therefore not part of the core business of WRRFs. As such, related efforts are perceived to cost money and time for something that is not currently needed. The operators of these plants are liable if the discharge permit is not met, making this industry extremely risk averse. Therefore, to address the gaps in emission measurements, it is imperative to address current problems facing the industry while working in the confines of how WRRFs operate. Specific concerns and sensitivities brought up during the workshop fall into three general categories: concerns about data sharing and dissemination of information; cost/execution considerations; and possible implications to the workforce and development.

2.1.1 Data and Dissemination of Information

The success of any campaign will be the quality and quantity of data provided by WRRFs on the ground. However, facilities already struggle with an unmanageable volume of data and no standard data ontology, even before considering the addition of GHG measurements. Currently, some facilities don't have the basic capabilities to track energy information. These data issues and the inability to openly share and collect data could complicate a large campaign's ability to function effectively.

Due to the relationship WRRFs have with the communities they serve, how information is shared and disseminated could potentially impact a WRRF's ability to operate business as usual and keep their credibility with rate payers. There is a perceived liability associated with quantification of GHG emissions from WRRFs, especially considering the mechanisms by which plants may be required to release data (e.g., public information requests). Several challenges exist with effective communication of results, including conveying technical information in layman terms for the public, using appropriate metrics, a current lack of benchmarks for comparison of results, and how impacts correlate to human health. A comparison was made to the challenges that per-and polyfluoroalkyl substances (PFAS) reporting/measurement faces; in one example, some utilities did not want to share PFAS data even with an understood “code of silence” as the WRRF may still face increased scrutiny if the information were to be leaked. Finally, it is important to realize and address the reality that trust in this research may be strained between facilities with easy- and hard-to-address emissions. A possible concern is if the ability of plants to address GHGs is not equitable, the credibility of the research could decrease.

2.1.2 Cost and Execution Considerations

When thinking about GHG measurements, WRRFs expressed concern over the potential cost and dynamics of utility funding. Associated costs include all required equipment (i.e., sensors and related infrastructure) and additional personnel and time necessary to train staff and maintain equipment. This increase in budget could be difficult to communicate and justify to ratepayers. Increases in operating costs may be an especially important consideration for WRRFs with limited resources as WRRFs tend to focus on funding improvements that help meet regulatory requirements and other competing priorities (e.g., prioritize pump replacement before implementation of costly GHG monitoring). However, it is important to acknowledge that inaction to address these challenges now could lead to even higher costs in the future.

WRRFs also require a high burden of proof when thinking about capital decisions. While direct off-gas monitoring coupled with process monitoring can provide quantifiable emissions information and aerial or mobile monitoring can provide overall footprint information, many WRRFs at this time do not have access to or face challenges implementing this technology. Two key categories of methods for direct GHG measurement are used by utilities at WRRFs globally—site-wide and process unit level. Each have their advantages and disadvantages and may range from $30,000 and upwards for capital and operational costs. No matter the direct monitoring method, other incentives may be required to justify capital decisions related to a measurement campaign. There could also be extended time requirements for utilities to approve capital decisions (e.g., suggesting amounts larger than $75,000 may require planning a year or more in advance). Such considerations will need to be incorporated in any measurement campaign.

2.1.3 Possible Implications to the Workforce and Development

Many participants at the workshop mentioned the need for significant technical expertise to understand the intricacies and corresponding needs of each treatment facility, support data collection and utilization for GHG measurement campaigns, and improve knowledge of current approaches to better control process operational parameters to reduce GHG emissions. Such expertise is not typically accessible to utilities due to their limited resources (though expertise does exist at some WRRFs). Additionally, the technology required for GHG monitoring is often not made for utility workflows, requiring contractors and/or service providers to fill the gap. However, buy-in from the WRRF is still essential due to the time requirements of the operations and management staff. Some workshop participants suggested that a cultural change may be required to support accurate GHG monitoring, potentially rethinking and upskilling a new generation of the workforce.

2.2 Opportunities

Despite these sensitivities and challenges, opportunities exist to help lead GHG measurements at WRRFs and accelerate the U.S wastewater industry toward a decarbonized future. One major discussion theme was the idea of co-optimization as a way of engaging WRRFs. For instance, a small WRRF needing to replace a pump to meet regulatory requirements may also see reductions in energy use, therefore decreasing emissions. Identifying synergies that advance knowledge about emerging issues, such as GHG monitoring, and address today's most pressing WRRF challenges is likely to gain support and buy-in from WRRFs at any level. Much of the information available is segregated throughout the water community and there is a need to coordinate networks for data and practice sharing. A coordinated campaign can also help limit duplication of work already being done both domestically (e.g., The Water Research Foundation [WRF] GHG measurement studies) and internationally (see plenary presentations in Sections A.5 and A.7). This includes fostering collaboration with existing programs or innovators and early adopters that voluntarily take a stake in emission improvements. For example, the IEDO Better Plants program can be leveraged to identify those who are voluntarily making GHG reduction targets early in the process. Additionally, there is an opportunity to inform stakeholders on the current status of emission measurement technology. Figure 2 shows the current methods used at scale to measure N_2O emissions at WRRFs; similar opportunities also exist for CH_4 measurement (UKWIR 2023).

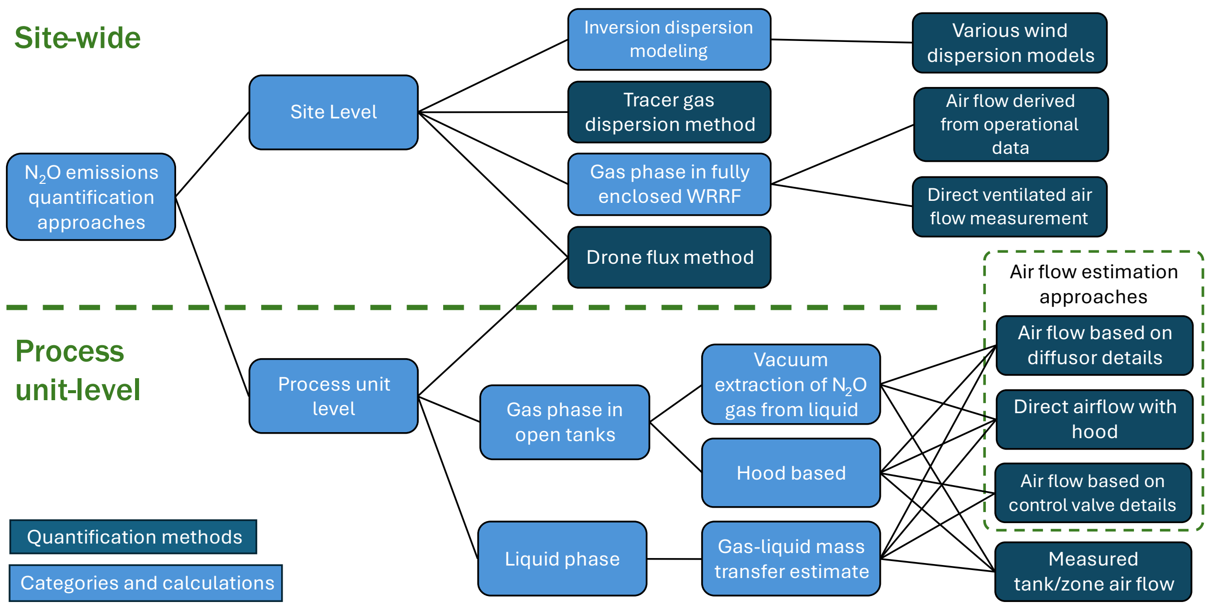

Figure 2. Current methods for measuring N_2O emissions at scale for both unit-level and sitewide approaches (Lake 2024)

Although the following list is not comprehensive, it suggests possible opportunities where GHG measurements could have lasting impacts, not only with filling current gaps but also informing sustainable operation of WRRFs into the future. Opportunities include:

- **Future planning**. As plants undergo expansions, upgrades, or master planning, WRRFs can utilize information from a measurement campaign to make more informed decisions (i.e., a major risk is that a utility may select an inappropriate technology to deploy, such as technologies with certain benefits but with increased direct emissions). Water infrastructure often lasts for decades and could jeopardize long term decarbonization goals.
- **Alignment with sustainability efforts**. Measurement campaigns could provide important insights into emissions at a WRRF, potentially allowing for: (1) engagement with carbon credit programs; (2) water, organic carbon, and nutrient recovery; and (3) biogenic CO_2 capture, utilization, and/or storage.
- **Cost reduction**. A campaign could introduce potential pathways for WRRFs to reduce costs through performance benefits in minimizing N_2O, CH_4, or other GHGs, typically lowering energy consumption, and potentially optimizing fossil derived carbon additions (e.g., chemicals like methanol, traditionally made from natural gas) to the treatment process. These performance benefits could be large enough to even offset the additional cost of new sensors and their operation at the facility. Additionally, some technologies may allow WRRFs to take advantage of carbon credits that could help economically justify monitoring or upgrades.

- **Present/future compliance**. There is potential to better understand sewer systems, biosolids handling, operational impacts to GHGs, handling of emerging contaminants, and other issues of emerging importance. Applying knowledge from these topics could help WRRFs regarding compliance with present and/or future discharge requirements and state/local government's net-zero goals before they are mandated.
- **Indirect benefits**. A whole-of-system approach would help illuminate the different and potentially unintended consequences of GHG mitigation strategies. For example, identifying issues, such as discouraging water reuse in water-scarce areas or higher energy demand in grids that cannot support it, will be possible.
- **Positive public perception**. By employing GHG monitoring/mitigation strategies, WRRFs can improve water quality in a more environmentally friendly way, which may help the facility to garner more public support and/or justify higher rates. It also provides an opportunity to broadly engage and educate communities about wastewater treatment while also increasing the treatment plants performance and longevity.
- **Establish new practices**. If facility-level equipment and infrastructure needed for a measurement campaign remain at the WRRF after conclusion of a campaign, there could be long-lasting effects on the industry beyond GHG monitoring. Facility-level emissions monitoring offers the opportunity for new operational techniques to be established which optimize WRRFs for quality, cost, and emissions.
- **Workforce development**. Although technical expertise is required to commission and implement GHG measurement campaigns at WRRFs, this has been widely undertaken in work globally, including in North America. Evidence to date suggests that existing process optimization routines are likely to support mitigation of GHG emissions. With the right training and support, there is evidence that the technical expertise for GHG measurement and mitigation exists already or can be fostered. Close working relationships between operators and researchers may be an enabling factor to make this happen.

Ultimately, it is crucial to include these WRRF considerations at the core of any measurement campaign. Close engagement with WRRFs and a systematic understanding that their primary concern is the service provided to their local communities will be necessary for any level of campaign undertaken. Potential opportunities of a measurement campaign or associated incentives for this work must outweigh WRRF concerns. The remainder of this report will cover specific considerations for a potential campaign and potential R&D needed to address identified gaps.

SECTION 3

Measurement Campaign Considerations

3 Measurement Campaign Considerations

3.1 Need for a Campaign

WRRFs face several competing factors in the operation and maintenance of their facilities, many of which present barriers to accurate and consistent GHG emission monitoring from wastewater treatment processes, as seen in Section 2.1 of this report. Often times, GHG accounting does not consider variations across treatment processes or technologies. WRRF emissions reporting guidance currently relies on EFs from the IPCC, which provides factors for centralized aerobic and anaerobic systems but does not further differentiate into the myriad of WRRF configurations that are currently implemented in the United States. This uncertainty in GHG emission calculations further complicates the ability of WRRFs to implement monitoring and mitigation. Figure 3 summarizes measurement and analytical methods for quantifying N_2O and CH_4 emissions at WRRFs today to highlight the complexity of GHG measurement and the need for alignment. Successful measurement campaigns require a good understanding of varied site typology and operational considerations as well as expertise in measurement methods and resulting data analysis. This requires application of the latest knowledge on operational procedures to minimize energy consumption and direct GHG emissions from various plant processes. A coordinated measurement campaign that convenes data and results from a diverse set of WRRFs can address this knowledge gap, and potentially inform both mitigation strategies and future on-site monitoring regimes.

Infrastructure related to wastewater and other waste resource recovery typically has a life expectancy of several decades, a coordinated campaign can help inform sustainable technology and infrastructure development to both meet GHG mitigation goals and help improve WRRF longevity through incentives for proper equipment maintenance and efficient operations. The timing of this information is especially critical, as plants undergoing expansions, upgrades, or master planning would greatly benefit from awareness around GHG implications of treatment options. By coalescing results and insights from a diverse set of facilities, a coordinated measurement campaign can provide risk mitigation for emission monitoring and mitigation to smaller and/or less advanced WRRFs that may not be able to implement experimental activities. Such champions will allow more WRRFs to have tools for more accurate emission estimation, especially for underserved communities.

The goal of a campaign needs to be well-defined to inform coordinated measurement protocol and develop accessible data—whether it is to implement sensing at every single treatment plant or to develop insights than can be scaled and potentially generalized. If the latter, there should be a minimum standard of limited data collection that can be scaled in practical situations.

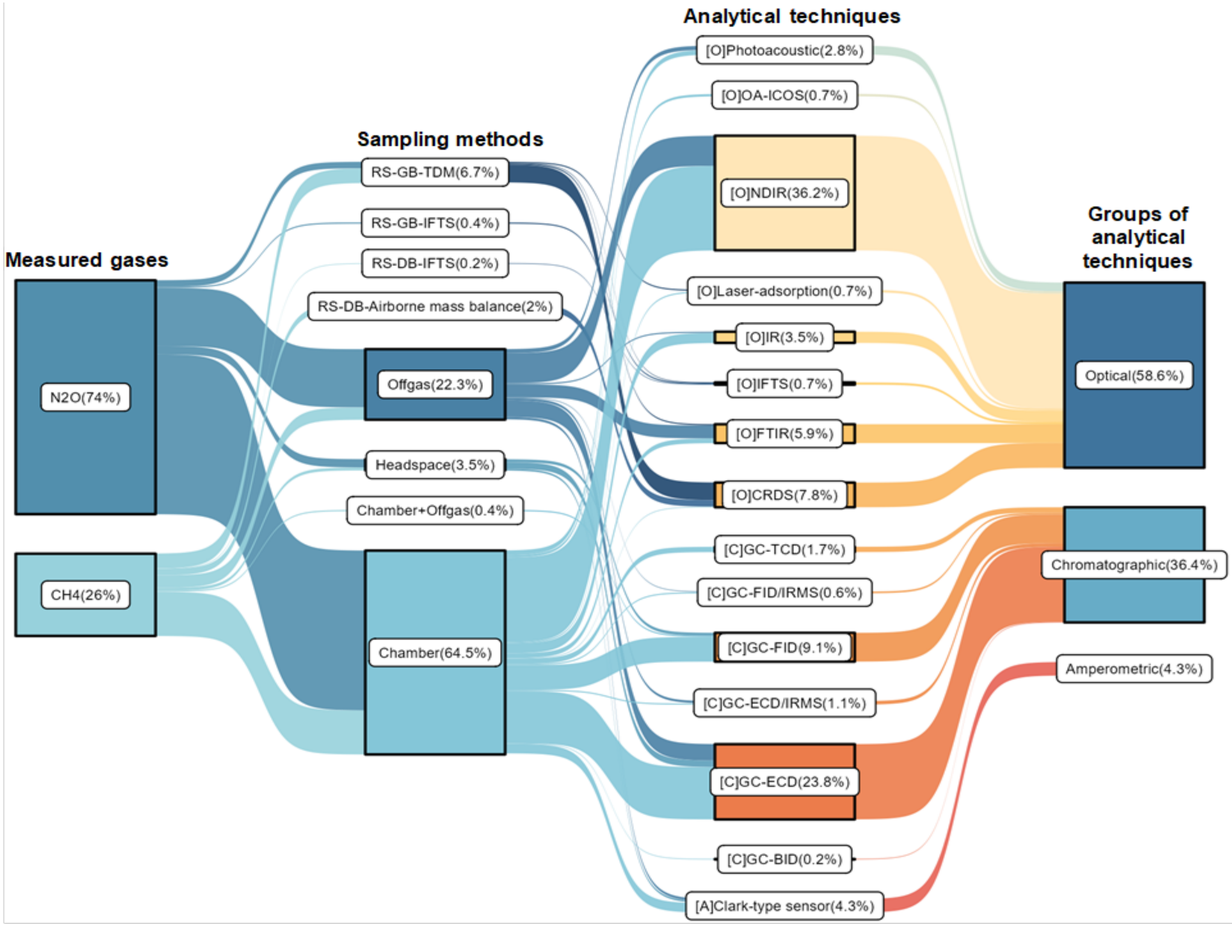

Figure 3. Current methods for measuring CH_4 and N_2O emissions from approximately 200 WRRFs, taken from 119 international publications, with RS-GB=gound-based remote sensing; IFTS=imaging Fourier transform spectrometers; TDM=tracer gas dispersion method; RS-DB=drone-based remote sensing; OA-ICOS=off-axis integrated cavity-output spectroscopy; NDIR=nondispersive infrared sensors; FTIR=Fourier-transform infrared spectroscopy; CRDS=cavity ring-down spectroscopy; GC=gas chromatography with various detection methods including TCD (thermal conductivity detector); FID=flame ionization detection; IRMS=isotope-ratio mass spectrometry; ECD=electron-capture detector; and BID=barrier discharge ionization detector. *Graphic from Ren 2024*

3.2 Optimizing Water Resource Recovery Facility Participation

Since only a fraction of WRRFs currently operating in the United States can participate in a measurement campaign, identification of a representative set of WRRF partners that can propagate results to the wider sector is vital. A prioritization exercise and/or research may be appropriate to define the most valuable variances. For ongoing measurements, diversity in WRRFs—not only in treatment and collection schemes/configurations but also spatiotemporal characteristics—is a challenge. A paper study that screens facilities and identifies variances of most value (e.g., “popular” and/or high-emitting process configurations) could lay the foundation for an initial, smaller measurement study on “archetypal” WRRFs. This study is discussed in further detail in Section 4. Results from emissions measurements in these archetypes could be used to inform emissions for other plants, incentivizing broader adoption of GHG monitoring and mitigation at WRRFs.

3.3 Standardized Methodology

While technological solutions are important, coordinated data collection and data sharing have significant impacts on large-scale communication and execution of these climate solutions. Accurate, complete, and comparable datasets will be crucial for the usability of data collected. Therefore, a standard methodology and approach will be required for data collection, reporting, and analysis, and a database will need to be maintained that can be easily accessed and shared by relevant stakeholders. The WRF conducts research with an eye towards standardizing methodologies for GHG measurements at sewers and WRRFs, and past methodologies already developed could serve as starting points. However, further analysis and coordination is needed. Standardization would be complex and challenging to execute but could have a material impact on the usefulness of a measurement campaign. Both the model and the analytical framework required to make sense of it will be critical components. A coordinated campaign provides the opportunity to harmonize efforts across multiple parties. While a lead institution may be needed to organize these efforts, the driving "voice" will be from a collective of stakeholders.

3.3.1 Data Collection Considerations

A standard methodology will need to consider:

- **Monitoring frequency**. Participants expressed that continuous monitoring is ideal and will be essential to a campaign. However, noncontinuous monitoring can still provide useful information. Higher resolution data will require more resources and should be strategically implemented. For example, one quarter of the campaign data collection may include electric car cataloguing, plantwide scans, inset sensors, hoods, and/or gas chromatography.
- **Experiment duration**. At a minimum, a one-year time frame is needed to cover all four seasons to support accurate quantification of emissions. In addition, evidence suggests year-to-year variation, highlighting the importance of continued measurement rather than stopping at 12 months (Chandran 2015). Notwithstanding this, shorter term campaigns may support prioritization, quantification, and mitigation measures by providing deeper data insights (e.g., more comprehensive analytical sampling) or a larger dataset (e.g., short-term measurements across eight sites which then support long-term continuous monitoring at one or two sites, where budget exists).
- **Sampling time of day, frequency, location in treatment train and within the unit**. Sampling details are important factors that influence GHG emission

production. In many cases (e.g., direct emissions from biological treatment processes) the monitoring plan must account for spatial and temporal variation in emissions from different areas within the treatment system and treatment process reactors.

- **Measurement techniques**. Measurement techniques must consider the wastewater recovery system in its entirety. Not just the accuracy of instruments or analyses should be considered but also extrapolation to site-level including associated modeling and calculations (e.g., inverse dispersion modeling method, liquid to gas, and process air flow assumptions). Collaboration and coordination on data collection from measurement techniques will help minimize the potential for major biases or inaccuracy in the results; there is currently a dearth of such cross-comparison studies.
- **Variation among systems**. Variation exists among and within WRRF typologies and operational conditions. One unique barrier is variation in N_2O and CH_4 emissions within and between different WRRF typologies and operational conditions. Evidence shows that similar treatment trains with similar water influent often do not exhibit similar conditions/performance when it comes to GHG emissions. Similar to the WRF project A Guide to Net-Zero Energy Solutions for Water Resource Recovery Facilities (project ENER1C12), which identified representative process flow configurations, this campaign can update and/or supplement these broader research efforts (WERF 2019).
- **Too much and too little data**. Many WRRFs struggle with too much data and a lack of standard ontology which makes using data for operational decisions difficult. If data cannot be managed efficiently, it complicates the ability for a large campaign to function. Alternatively, some facilities operate on one design variable and collect little data, sometimes even missing energy consumption data. These facilities will see a very large change in data handling if emission monitoring is included.
- **Data sharing**. Data sharing and analysis is the most critical part of this program, and confidentiality is vital, ensuring WRRFs can share data rather than compete with each other. Ideally, a central organization would manage this, and it is important to consider what could be subject to Freedom of Information Act requests. This data can also be seen as a liability if a plant’s emissions information is released. Sharing results across projects should also be standardized to maximize insights from several projects.

Additionally, it is more important to focus on how to measure emissions and how that knowledge may be used to mitigate emissions as well as supplement development of EFs rather than producing EFs themselves.

3.4 Lead Organizational Capabilities

Several participants asserted that a successful campaign would require a central, lead organization to serve as the organizer to help direct a coordinated effort. A lead will set a standard methodology and maintain the central data repository. The lead will coordinate collaboration, transparency, and consistent data collection and reporting across multiple parties throughout the WRRF life cycle and establish standard methods for data validation and analysis. Program oversight will require coordination amongst sites/utilities, centralized decisions around metadata, authorizations or support from boards/councils, political framework for GHG emphasis through constituent governments, and a data governance structure (e.g., database management, access, and analysis).

Breadth and depth of relevant technical expertise are critically important to a successful measurement campaign. This necessitates an independent, neutral organizing entity with experience in assessing the scientific and practical experience of the team, managing consortia and big data, and strategies for technological innovations that can impact industry. A single organizing force will be required to lead a campaign with elements of technical expertise in fundamental and practical research (e.g., WRRF partnerships, diversity of facilities).

Along with acknowledging the unique and crucial role utilities play, a technical advisory committee could assist in expanding the reach of the campaign without involving an unwieldy number of opinions and stakeholders in each discussion or decision. There should also be stakeholder engagement activities and an independent review panel that includes individuals with nontechnical expertise.

3.4.1 Expertise

There are different types of expertise needed to lead a campaign of this magnitude and focus, including:

- **Program/project management and grant and contracting experience**, including the ability to conduct tasks within scope; coordinate between multiple diverse stakeholders from academia, industry, and utilities (chief executive officers [CEOs]/directors, research teams, operators, technology vendors, sustainability team, and process engineers); communicate to varying audiences, including nonscientific audiences; negotiate and manage contracts with subcontractors and utilities; and provide a primary point of contact/project manager.
- **Data management**, including confidential sample/measurement procurement; the ability of the prime to pull and clean data; platforming open, anonymized access to data; implementation of proven quality assurance/quality control

procedures; and the ability to relate GHG data with influent water quality, climate/weather, and process data.

- **Process or operating staff**, crucial to safety and understanding the day-to-day operations of a facility with their familiarity of the processes that will allow for long-term impacts, through long-term, daily O&M of treatment systems.

3.4.2 Partnerships/Relationships

It is important for this campaign to have access to and establish relationships with utilities with diverse configurations and process instrument capabilities and that have the willingness to participate and share process GHG emission data. This could include having a primary “host” utility and establishing connections between this utility and other “secondary” or “nonhost” utilities to validate methodology in future phases of the work. It would be helpful to utilize in-depth understanding of the system being sampled (e.g., site selection, known temporal variabilities) and to be able to communicate with plant personnel to ensure high quality samples.

Other important relationships include connections to the global community of practice (which is ahead of the United States in many respects), site-specific relationships, contract labs and universities, industry, interest groups, and other stakeholders. Specifically, partnerships with academia or consultants experienced in measurements and data interpretation could be employed at diverse facility partners with support from national nonprofit organizations focused on water, DOE national labs, EPA Office of Water and other relevant federal agencies, and trusted vendors. Grid/electric utility providers are additional key players to include in the process.

3.5 Consortium

Several funding and organizational mechanisms exist to support the described endeavor, one of which is a consortium-like structure comprised of an association of entities organized by a central lead. In a GHG measurement campaign, a consortium would convene the unique skillsets and capabilities of diverse stakeholders including WRRFs, private industry, and academia to maximize quality, quantity, and accessibility of resultant data. The organizing entity would identify representative WRRF sites, standardize methodology, and evaluate R&D project funding.

WRRF participation is crucial to the success of direct measurement campaigns and should be included at a high level, such as a technical advisory committee. Industry organizations or consortia already have broad industry knowledge and experience working with WRRFs and hold credibility in the field. A diverse group of people need to be engaged and industry organizations should be leveraged to convene such groups.

3.5.1 Advantages of a Consortium

A consortium brings together various capabilities, including stakeholders from relevant industry organizations (e.g., WRF, U.S. Water Alliance, and others), research experts from academia, and technical expertise from engineering design firms (i.e., consultants). Such a structure could benefit this campaign by prioritizing collaboration among complementary skillsets and capacities to identify synergies, further validate results, and work towards standardizations for industry. A well-run, coordinated consortium has the potential to lend credibility to the effort and increase the reach and range of the campaign.

Although not an exhaustive list, advantages of a consortium include:

- Utilizing a **programmatic approach to conducting research**.
- **Capturing a greater volume of participants/facilities to provide more representative data**. Inclusion of multiple utilities can provide variability/diversity in treatment schemes, unit processes, spatiotemporal variabilities, climate, controls, and other aspects related to treatment plants (see Section 3.2), which will generally help verification and validation of the data or measurements. It will improve the potential for long-term benefits from the work.
- **Bringing together complementary skillsets and capacities along with diversity in expertise and perspective** (i.e., inclusion of national labs, academia, for-profit consultants, NGOs, and other stakeholders from around the country) in technical areas like the water energy nexus space, and with skills including project management, analysis, and data analytics.
- Potential to **collaborate with state regulatory agencies** to support monitoring requests/requirements.
- **Providing WRRFs with a level of shared risk**, as facilities can be anonymized more easily.
- Maintaining **consistency and standardization** in goal setting, narratives, and experimental aspects.
- Maximizing the benefit of resources by **avoiding overlap in scope and protecting against the duplication of work** or differing methodologies through adherence to data quantity and quality.
- Allowing for **collective learning, knowledge sharing** (via built-in distribution of learning and data), and **opportunities for synergies and shared access to resources**, which will help work towards standardizations for the industry and lower barriers to entry.
- Providing potential to **leverage cost share**.

- **Increasing credibility and trust**, promoting coordination with the global community of practice and other industries and leading to more utilities willing to participate, thus increasing impact.
- Providing solicitations for **R&D** and/or conducting the actual research.

3.5.2 Disadvantages of a Consortium

Though a consortium presents many benefits, the size of the group and its structure need to be considered. Due to its potential complexity, difficulties may arise in project management, especially in data synthesis and information sharing over time.

Although not an exhaustive list, disadvantages of a consortium include:

- Necessitating a high level of alignment from several diverse stakeholders, potentially leading to **the loss of diverse input**, especially for unaligned or dissenting parties.
- Requiring **overhead management of schedule and budget**, potentially leading to more personnel and larger overhead costs.

  Presenting **challenges in defining membership**, including openness to non-members, contractual flexibility if partners come and go, unintended exclusion of new members, and developing a sense of "team" and meaningful contribution of all players. If membership is metrics based (e.g., achieve 40% reduction by 2030), smaller facilities will be left out in favor of larger facilities that will have an overall larger impact.
- Delaying progress due to potential **challenges with communication and coordination** (e.g., data integration) across organizations and geographies, especially regarding data ownership and the protection of WRRF interests. If not handled well, this will be a significant barrier.
- **Demanding strong and cohesive leadership to avoid potential miscommunications** regarding interpretations of project objectives/misalignment, decision making (e.g., voting, consensus, prime contractor), lack of clear roles and responsibilities, poor management (e.g., meeting deadlines, quality assessment/quality control), potential for bias/personal agenda, less accountability, and overall slow processes related to bureaucracy.

3.6 Solicitation Evaluation Metrics

The potential impact to GHG mitigation from WRRFs is notable, making a measurement campaign ideal to lay the foundation for future monitoring and targeted mitigation strategies. Metrics to evaluate candidates for IEDO R&D resources are crucial to realizing this impact. Considerations should be given to practical outcomes and public benefit, technical expertise, and alignment with the campaign mission.

3.6.1 Practical Outcomes and Public Benefit

Utility leaders must play a central role in any campaign. The DOE's ultimate objectives are practical outcomes for facilities that result in community benefit. Utilities have the practical knowledge and a set of tools to sustainably execute long-term emissions solutions through a lens of "substantive impact for the public good." The main stakeholders to consider are the WRRFs and communities that want practical outcomes (i.e., justification to ratepayers), not necessarily a set of academic papers.

Community benefit plans should be included to uphold the commitment to building a clean, decarbonized water sector that puts communities at the forefront of its work, ensuring an equitable, healthier future for all Americans. Additionally, community benefit plans will ensure the communication of potential public benefit of emissions measurement work and the tangible impacts on the public good. These requirements could help ensure results from R&D last long after the campaign ends. This does, however, raise the question of whether there needs to be a direct benefit from the measurement project, or whether the benefit is to be realized in the future when measurements inform decisions.

3.6.2 Technical Expertise and Resources

Capabilities pertain to an organization's knowledge and expertise in the ability to undertake a project, while equally important is *capacity*, which, in this instance, is defined as human capital, time, availability, equipment, and other factors needed to complete a project outside of know-how. An organization's capacity is important as an organization with several ongoing projects may not be best suited to lead a measurement campaign like this.

An organization also needs to allow room for adaptability and flexibility to adjust project aspects as process information is made available, and this flexibility needs to be built into the structure of the agreement (e.g., allow for onboarding of new utilities if one utility is no longer able to participate in the project). Passion for the work is another key capability for an organization. Ways, or "proxies," to measure how passionate organizations and people are about the work could include subject matter expertise, relationships throughout the water sector, and commitment to goals. Furthermore, a utility focused on research that can spread knowledge to other facilities is important, but the challenge will be engaging small- and medium-sized facilities in the same way.

Each R&D team will require expertise from a diverse range of skill sets and advanced scientific resources. The executive director should have experience in project management, a background in the specific technology or system, and a commitment to the campaign mission. Team members should be experienced in the various technical aspects of the project along with the technoeconomic, life cycle, and community benefits aspects. Metrics to gauge expertise include academic qualifications, professional certifications, past research studies or development projects, and relevant industry experience. Access to both the appropriate waste facilities and proposed technological equipment are also determinative of potential for success.

3.6.3 Campaign Expectations

Access to and sharing results will be crucial to a measurement campaign that relies on the sum of results from GHG monitoring projects to provide true value. There needs to be coordination and an environment where successes and failures can be discussed. Disproving a hypothesis is a valuable research outcome. To assist with this, the campaign scope needs to be clear, with a method to track the unit process or operating practices. Having applicants provide realistic levels of effort based on key resources, including people and equipment, will further help achieve project outcomes.

The campaign also needs to recognize the importance of understanding the dynamics of utility funding (e.g., inability to obtain approval high levels of additional funding on short timeframes) and requiring costs to be planned out a year in advance. One consideration is creating a staged approach where teams get paid to do the necessary prework.

Applicants with established connections to WRRFs interested in participating in the campaign will help reduce delays and provide early indications on the level of diversity with regards to treatment. It is important, however, to provide equitable access to utilities considering applying, possibly with the help of the DOE. Questions to consider are: (1) if utilities should commit to DOE instead of the team applying; and (2) if perhaps DOE should provide a platform, along with standardization, for utilities to indicate interest in participating and provide a screening process for volunteer plants.

3.7 Levels of Funding

With its unique position at the nexus of water and energy, IEDO is well-positioned to study industrial decarbonization impacts of GHG monitoring at WRRFs in the United States. Funding will play a key role in the depth and breadth R&D will have to impact public good, and therefore will be foundational to the scope of a measurement campaign.

The number of representative WRRFs being measured will likely have the largest impact on the total cost. A paper study or multiphase/sequential funding process, where some money is distributed upfront to define measurements, scope, and data ontology, could be useful in defining these sites. A multiphase or sequential project would also allow the time necessary to get crucial input and support from WRRFs. When thinking about low-, mid-, and high-level funding for such a campaign, there are different costs to consider such as additional systems required for data collection and management, the points of measurement required, labor required to install and operate equipment, and lab testing. One important aspect to consider is the absence of existing relevant infrastructure, so there will need to be extensive investment in equipment, researchers, and operating costs for the duration of the project. Table 1 below summarizes some of the input gathered from attendees at the workshop.

Table 1. Levels of Funding

	$5 Million	$10 Million	$15 Million
Planning/Visioning	Produce basic planning document. Conduct literature review and limited sector engagement.	Produce detailed roadmap. More sector engagement.	Produce detailed roadmap. Revisit roadmap midway through the project.
Size of Team	Two to three research entities. Handful of utility partners. Limited diversity in type and representative sampling. Possible to monitor from three to eight WRRFs.	Three to five research entities. Quite a few more utilities with more configurations. Monitor up to 10–15 WRRFs.	Greater than five research entities. More diverse size, geographics, climate zones, etc. Monitor greater than 20 WRRFs, including greater than five each of micro-, small-, mid-, and large-sized.
Scale of Research	Focused on desktop/paper study. Inventory of facilities and relevant GHG sensing data, techniques, and technology. Limited funding toward physical experiments.	Initial paper study. More implementations of mitigation approaches with quantified benefits (pilot scale). Limited scale and/or sensitivity monitoring. Methodology and comparisons. Model development.	Initial paper study. Facility modifications to quantify and pilot improvements. Benchmark mitigation versus current practice. Multimethod monitoring at multiple locations.
Extent of Measurement	Limited measurement/collection strategies (e.g., on-site in-situ measurement, remote sensing like drive-by or drone based). Parallel sampling campaigns.	Sensor development, identification of surrogate analytes, using existing methods only. Focus on applying cross-cutting technology developed in other sectors.	High-fidelity sensors, approaching activity levels used for carbon credit accounting. Development of new analytical approaches. Representative sample with data logging (e.g., seasonal

	Interoperable database amongst team members; basic functionality.	Isotopic measurements to understand pathways. Calibration/validations and technology validations.	variation, geography, processes). Identify major sources of emissions. Measurement of downstream emissions from landfills and land application.
Stakeholder Engagement	Limited data dashboard. Consortium of utilities and researchers.	Public-facing dashboard with higher access, quality, ease of use, interactivity. Few in-person meetings/workshops.	Dedicated communication personnel. In-person meetings and workshops.
Emissions Scope	Focus on measuring direct emissions (Scope 1) only. Little to no effort on evaluation of mitigation options.	Focus on direct (Scope 1) and some evaluation of indirect emissions (Scope 2 and 3). Some evaluation of mitigation options.	Focus on both direct and indirect emissions (scopes 1, 2, and 3). Evaluation of commercial alternatives to mitigate emissions.
Complexity of Systems	Mostly subsystem level (e.g., biosolids, collection system), some treatment plant scale.	Treatment plant scale, with limited resources for “outside” the physical boundaries of the treatment plant.	More integrated systems (more complex, add subsystems). Entire WRRF life cycle (including collections and biosolids management).

3.8 Campaign Approaches

Tension exists between focusing funding on accurate measurement or steps toward mitigation. Measurement is the charge of this campaign, but related mitigation can also be achieved in tandem to meet U.S. climate goals (2030 and 2050). Accurate measurement can enhance mitigation effectiveness but should not limit action.

To ensure information can be derived from the data long-term, equipment and infrastructure need to be left in place at facilities. Co-benefits with GHG mitigation, such as improved local air quality or sludge volume reduction, need to be more clearly defined. Due to the complexity inherent in decarbonizing the wastewater sector, boundary definition will be imperative to campaign processes.

It is important to understand and prioritize the end-goal and the narrative DOE wants to communicate. The campaign should take a holistic approach to avoid unintended consequences of GHG monitoring and mitigation and avoid "the tunnel vision of carbon." Developing measurement techniques for these emissions is important, but the reduction potential needs to be paired or there could be a perception issue. Co-optimization will be a critical way of engaging WRRFs. If WRRFs can solve current problems by learning about new ones, they are more likely to support and engage in a measurement campaign.

Moreover, IEDO's work needs to be contextualized within the broader U.S. government/interagency environment. Similar and related efforts in different DOE departments and across federal agencies can be used to inform the management and reduction of GHGs. There may be existing campaigns doing similar work that could feed into this campaign. For example, the WRF has released a request for proposals (RFP) to develop a methodology for measurement of GHG emissions from WRRFs. This work is underway with WRF project, *Advancing the Understanding of Nitrous Oxide Emissions Through Enhanced Whole-Plant Monitoring and Quantification* (Project 5251), which will collect and collate N_2O data across 12 North American utilities and an additional 13 global utilities. Since different unit processes, even within subsystems, have different GHGs to target, once hotspots are identified, knowledge gained from past funding opportunities can be applied for optimization of GHG emission mitigation. For an effective measurement campaign, there are certain barriers to take into consideration, including more clearly defined components.

A long-term roadmap could involve early engagers and release updated versions at future intervals to show incremental steps. Increased engagement is important for continued R&D and providing direction on where to improve or simplify promising technologies as to not be a burden to operators. Guidance on how to break down the process into smaller sampling and data collection plans will increase participation. Facilities that have never engaged in GHG measurement or mitigation will need to be engaged to increase impact to public good, rather than continuing to primarily focus on those well-known facilities with progressive agendas and research budgets. There is a level of uncertainty surrounding smaller and less visible WRRFs that may contribute to large, unaccounted GHG impacts.

A phased approach would benefit a longer-term project (5–10 years) including a paper study, cross-validation of measurements, and narrowing of methods that work to deploy at other facilities or processes. A paper study in the first phase could help gather insights and validate methods valuable to the actual implementation of direct measurement. A phased approach can occur in tandem with other funding solicitations that focus on active GHG mitigation, employing interim lessons learned from the consortium. Current GHG inventories should be sourced into one repository.

Approaches should be identified that are appropriate to each respective GHG. CH_4 methodologies are well studied, whereas N_2O is less understood.

A standard operating procedure (SOP) for plant operators and involvement from independent specialty firms, including universities, are identified as campaign implementation tools. A SOP is structured in simple steps and includes a list of recommended equipment for leak detections, sniffer for gas imaging camera, and so on. At least two different methodologies should be employed for remote sensing by at least two independent teams on the same site to ensure data validation. This document should be revised as insights are gained from the campaign. A limited campaign in the lowest funding tier should establish protocols on data management, database administration, ease of communication, accessibility, collection, validation, and anonymization. Through midterm program assessments, failures and lessons learned will be shared without putting utilities in a compromised position.

SECTION

4

Specific Research and Development Needs

4 Specific Research and Development Needs

Regarding emissions monitoring throughout the life cycle of wastewater treatment, more research and development is necessary to answer the questions of: (1) where operators should be measuring greenhouse gases inside and outside of the facility; and (2) how they should be measuring them (Sections 4.1–4.2). For the latter, R&D needs are also provided to inform future standards development in GHG measurement for WRRFs. Additionally, technological R&D is necessary to allow for accurate and reliable measurements and provide affordable monitoring technologies to WRRFs (Section 4.3). Lastly, broader scale R&D needs are discussed for analysis that could inform a measurement campaign strategy that maximizes the breadth of the campaign's impact while conserving resources (Section 4.4).

4.1 Research and Development Needs in Emissions Measurements at the Facility

There is uncertainty in existing knowledge and literature on emissions related to wastewater treatment processes. Participants specifically noted the lack of understanding around fundamental N_2O emission generation throughout a WRRF and its different sources and sinks. This problem is exacerbated by the great variability that exists amongst the large number of WRRFs in the United States, namely facility size, specific treatment train, climate, influent quality, and state and local effluent regulations for wastewater. GHG emissions can also vary spatially *within* a treatment system, and even within a unit process itself. A deeper understanding of GHG sources, such as fugitive emissions and process N_2O emissions, is required to establish baselines for WRRF emissions that will play a role in future mitigation efforts. Within the three streams that leave WRRFs—liquid, solid, and air—air is less discussed compared to liquid and solid waste, but it is illustrated in odor, nitrous oxide (NO_x) pollution, and other hazards that are not well understood. R&D needs in emissions measurements at the facility include but are not limited to:

- Fundamental research of GHG emissions from wastewater treatment to enable a detailed accounting of emissions at the facility level.
- Deeper understanding of how GHG emissions at WRRFs vary depending on:
    - Facility size (designed capacity)
    - Climate and temperature variations by season
    - Influent quality and source (industrial, commercial, residential; direct or through a collection system)
    - Average influent flow
    - Operation conditions

  - Degree of nitrogen removal (carbon removal only, nitrification – seasonable and year-round, and biological nutrient removal)
  - Treatment trains with or without anaerobic digestion (AD) and types of AD
  - Type of aeration technology employed
  - Length to width ratio of tank dimensions
  - Diurnal peaking
  - Treatment trains with resource recovery
  - Emerging nutrient removal processes (e.g., shortcut nitrogen removal, denitrifying phosphorus removal)
  - Solids handling.
- Understanding of relationships between GHG emissions (at the unit process and facility level) and operational conditions (e.g., effect of dissolved oxygen adjustments in aeration tanks on N_2O emissions).
- Understanding of tradeoffs and possible burden shifting between mitigation strategies and total GHG emissions, as well as understanding of co-benefits from GHG mitigation efforts.
- Understanding of relationships between greenhouse gases and other constituents that could serve as "proxy" indicators for GHG measurements (e.g., nitrite in tanks preceding aerobic units used to estimate N_2O emissions).
- Development and/or validation of process models with real measurement data to improve model accuracy and credibility.
- Develop hybrid models to connect mechanistic understanding with machine learning (ML) tools to accelerate adoption of reliable measurement protocols.
- Development of digital twins to predict and reduce emissions.

Insights from R&D like those described above could point to areas of the WRRF from which significant GHG emissions originate and thus provide guidance on standardization for GHG measurements (the "how"). As previously mentioned, workshop participants agree the general lack of standard methodologies presents a barrier to implementation of this type of GHG measurement campaign. Methodologies for CH_4 measurement at WRRFs are well-understood by a subset of subject matter experts, but not broadly among WRRFs. To support and inform standards development, R&D is needed in both indirect and direct N_2O and CH_4 measurement techniques and analysis at the facility. Specific R&D needs discussed to inform measurement standards include:

- Identification of representative locations for GHG emissions at the unit process and facility level.
- Understanding the best practices for sampling frequency based on factors such as location within the facility/treatment train.
- Understanding of variability in emissions measurements between grab samples and continuous, real-time monitoring.
- Development of models that translate snapshot measurements and use them for continuous measurement predictions.
- Analysis of driving/flight routes and measurements to inform best practices for indirect GHG measurements at the facility level (e.g., drones, cars).
- Development of analysis and modeling tools (e.g., dispersion models) to process indirect emissions measurement data.
- Understanding the monitoring techniques and developing calibration equations and methods for quantification and reporting.

4.2 Research and Development Needs in Emissions Measurements Outside of the Facility

Consideration of aspects of the WRRF life cycle that fall outside of the facility fence line, such as the sewer system or biosolids applications is also merited. There is a particular need to better understand emissions at the end of the WRRF life cycle. These are more complex factors and are typically not included in emissions calculations. The benefits of carbon sequestration and carbon capture at this stage in the life cycle may not be accurately understood or reported. GHG baselines for effluent water body and land application settings also need to be established. Current default emissions estimates for effluent discharge in a tier system are based on receiving body water quality, but this is not well defined and needs to be better understood. Similarly, there needs to be further research on carbon impacts from land applications, as impacts from land application are believed to be net carbon sinks, but this is highly dependent on several factors of the land. Those studies are not entirely rigorous, and more work needs to be done. Table 2 summarizes the various R&D workshop participants identified for each location outside the WRRF.

Table 2. R&D Needs for Emissions Measurement Outside of the Facility

Locations Outside the Facility	R&D Needs (Knowledge Gaps)
Collection Systems	Techniques (and sensors) to measure GHG emissions to air in sewer collection systems.

Locations Outside the Facility	R&D Needs (Knowledge Gaps)
	Variance in emissions depending on the type of system and size (length, retention type), climate, composition of flow, and chemicals used for odor and corrosion control.
Land Application of Biosolids	Techniques to measure GHG emissions to air from land application of biosolids (e.g., studies utilizing a flux chamber). Understanding how GHG emission measurements change depending on temperatures, moisture, and other environmental variables. Detailed accounting of emissions from biosolids and appropriation of credits and/or burdens.
Biosolids Storage	Techniques to measure GHG emissions from biosolids storage.
Landfilling of Biosolids	Techniques to measure GHG emissions from biosolids in landfills (e.g., studies utilizing drones or other indirect measurement).
Incineration of Biosolids	More studies and/or use cases for continuous CH_4 and N_2O measurements from stacks. Detailed accounting of emissions coming from biosolids compared to fossil fuels in incinerators.
Effluent to Bodies of Water	Techniques to measure GHG emissions to air and water from WRRF effluent. Detailed accounting of carbon fates when emitted to a body of water and how these emissions vary depending on water body characteristics.

4.3 Technological Research and Development Needs

Research is necessary to develop the technology that will enable accurate and reliable GHG measurements. These R&D needs primarily focus on the development of affordable and reliable sensors and improvement of hardware specifications related to the measurement of GHGs. The development of new materials, manufacturing processes, and innovative sensor designs may help address the upfront cost of sensing equipment. However, R&D is also necessary in auxiliary technologies, both in terms of hardware and software. There is a lack of research in the application of remote and soft sensors in a cost-effective way. Research is needed in coupling remote monitoring with artificial intelligence (AI)/ML to process data and aid in identifying flaws, inconsistencies, and/or spikes in data (e.g., use of AI for gas phase sensors to accurately measure N_2O or CH_4 despite interferences from other gases). With research and development of these technologies, they can be adapted to measure GHGs from wastewater treatment to inform emissions baselines. R&D needs identified in the workshop include:

- Development of sensors that:
  - Have lower detection limits for gas phase measurements (especially to measure CH_4 in collection systems).
  - Can measure dissolved CH_4 in the liquid phase.
  - Allow for real-time continuous N_2O measurements within a facility for both gases and liquids.
  - Measure dissolved N_2O with reduced frequencies required for re-calibration due to wastewater temperature changes.
  - Can be used in various aeration methods (e.g., fine bubble, spray aerator).
  - Withstand variations in temperatures and other environmental factors.
  - Last longer and have lower lifetime costs, including manufacturing cost and associated labor and maintenance.
- Development of standards for validating sensor's effectiveness before and during operation to ensure accurate sensor performance.
- Development of “proxy” sensors that use related markers to predict emissions (e.g., nitrite for N_2O).
- Development of auxiliary equipment alongside sensors that can provide accurate and reliable measurements in various temperatures/climates.
- Development of low-cost, simple, and disposable sensors to prohibit operators from using sensors past expiration (and thus improving confidence in measurements).
- Coupling hardware with software to inform, calibrate, and enhance process models.
- Coupling hardware with software using AI/ML techniques to ensure accurate and reliable measurements are being obtained (e.g., development of soft sensors).
- Development of remote technology, such as drones and satellite technology, to minimize costs in emissions measurements.
- Evaluating the GHG implications of emerging solutions like partial denitrification, Annamox, and others in the context of broader tradeoffs.

4.4 Research and Development Needs for Broader Scale Analysis

As previously mentioned, participants highlighted a potential analysis that could allow for optimization of a measurement campaign through identification of representative WRRFs in the United States. There was consensus that a smaller measurement study should be conducted on archetypal WRRFs based on an initial paper study, screening plants, and to identify the most common and/or highest emitting process configurations to address knowledge gaps about metrics and variances that are the most critical to establish a select number of plants required to complete a measurement campaign.

Participants identified two primary approaches to consider when identifying archetypal WRRFs. One approach involves mostly large WRRFs (e.g., archetypes from the top 100 largest plants), whereas another approach is to include archetypal facilities for smaller plants. Smaller plants can be easier to model as they are typically less complex (e.g., no anaerobic digestion, no sidestream, possibly less regulations, smaller staff/resources) and often have less process variability. An 80-20 rule, which purports that 80% of emissions come from 20% of WRRFs, could provide a helpful baseline in quickly establishing high-impact archetypes to begin to generate meaningful results early on in a campaign.

Some of the most important variances identified by participants included geographic diversity of WRRF locations, range of unit processes (and performance/efficiency thereof), and treatment approaches for solids management. Additional variances include plant performance and associated GHG emissions, such as facility size/capacity and plant configuration; seasonal and temporal variations; influent water quality and composition; and effluent limitations. Operations and maintenance can affect emissions, including sensor calibration and cleaning as well as controls strategy. Single events, such as an influx of industrial waste, can greatly affect influent mix and are critical parameters as they can put a strain on the operational capacity of WRRFs. The WRRF life cycle is generalized into three categories: collection systems, treatment processes, and solids management.

For collection systems, variations that should be prioritized include:

- The size of the network (length/retention time)
- Local climate
- Composition of flow (industrial/commercial/residential) and inflow
- Characterization of flow (especially single events) from industry
- Composition of inputs from direct discharge and/or collection system
- Type and age of system
- Chemicals used for crown corrosion and odor control.

For treatment systems, variance priorities should include:

- The type of collection system
- The type of treatment process(es)

- Seasonal variations (weather/climate)
- Diurnal peaking
- Treatment capacity
- Average treatment flow
- Geography
- Influent characteristics
- Relationships with energy use/efficiency
- Dimensional ratios of tanks influent biochemical oxygen demand strength
- Use of external carbon for denitrification or anaerobic co-digestion
- Inclusion of specific emitting process (e.g., AD, biological nutrient removal)
- Dewatering operations (e.g., frequency of sidestream returning to the headworks)
- Sampling types, locations, and frequency.

For biosolids management, variations that should be prioritized include:

- The ultimate use/disposal of solids
- Polymer usage
- Types of landfill management and climate
- Access to resource recovery systems
- Carbon sequestration from land application and landfilling.

Participation from as many facilities as possible under a standard data collection methodology could begin to reveal trends quicker than a limited dataset focused on a set number of representative plants. Special attention should be paid to the most common unit processes. A phasing approach could allow lessons learned from each stage of the campaign to be implemented as more facilities join in subsequent stages.

In a measurement campaign, accurate measurements at representative sites should be priority. While frequent and/or continuous monitoring meets this need, its expense presents a technoeconomic challenge. While expensive, insights from these studies may allow assumptions that could be applied to larger scale applications. Representative types of sewers and collection systems (closed or combined sewers) and land application scenarios, like treatment processes, also need to be defined and included in a measurement campaign.

SECTION 5

Remaining Gaps

5 Remaining Gaps

During the workshop, participants discussed additional gaps and needs when designing and implementing a measurement campaign. Such topics warrant further discussion but are outside the scope of this current workshop and report.

When designing a measurement campaign, additional considerations include but are not limited to:

- Leveraging experience from other industries and groups that intersect with water, where a campaign can "plug in" to existing reports and campaigns, technologies, databases, platforms along with "lessons learned." This includes having presentations on LCAs that have been conducted for various WRRFs.
- Understanding competing priorities and unintended consequences within a system. For example, efforts to decrease effluent nitrogen could increase Scope 2 emissions. Obtaining understanding of emissions and potential tradeoffs or burden shifting could be obtained through previous LCA studies of WRRFs.
- Establishing connections between better monitoring methods, such as plant-type specific EFs, with IPCC protocols and local protocols would help when determining monitoring, methodology, and adoption.
- Determining how mitigation of GHGs at WRRFs comes into play with a measurement campaign.
- Considering the dilemma between perfect versus practical, which presents a challenge for WRRFs.
- Understanding the potential impact a measurement campaign may have on communities–the potential short and long-term benefits a community may receive and the most efficient methods to track these benefits.
- Identifying whether the campaign's end goal is widespread adoption of measurement methods or individual measurement studies. This will impact the ultimate deliverable, functionality, and scope of a potential campaign. For example, a market transformation plan could be included, but if the campaign is for one-off measurement studies, such a plan may not be needed.
- Discussing whether secondary/ongoing measurement campaigns will continue after the first campaign and how lessons learned from the campaign can be realized after its conclusion.
- Considering that decentralized systems are an understudied part of the WRRF ecosystem and pose various challenges, however, emissions from these

systems are almost entirely unknown and introducing them into a measurement campaign would be difficult due to their volume and size.

There are also considerations for implementation of a measurement campaign.

- Determining the correct balance among: (1) unit-specific and plant-wide measurements; (2) liquid, gas, and combined liquid-gas measurements; and (3) perfecting measurement accuracy and implementation of actual measuring, sensing, and mitigation.
- Supporting accurate GHG monitoring requires a cultural change, potentially rethinking and upskilling a new generation of the workforce.
- Identifying how to learn from analogous nationwide measurement campaigns, such as fugitive methane measurement in the oil and gas industry, point source carbon emissions monitoring, or less directly connected events like PFAS quantification/reduction where treatment plants all of the sudden needed a way to measure and then address PFAS in water.

Furthermore, there could be additional discussions regarding why a measurement campaign is needed, such as:

- A decision support framework is needed in the short term to facilitate decision making around treatment processes and in the long term to determine updates to EFs.
- Emerging contaminants of concern, namely PFAS and microplastics, present an unknown future and have not yet impacted all utilities but will need to be considered in a campaign.
- It is important to understand the endpoint for EF evolution from a regulatory perspective and provide useful EFs to plants without overcomplexity. For example, a table/tool that plants can use to estimate their emissions could be the end goal. These EFs would need to account for spatiotemporal variations and show plant managers how they can reduce their emissions. It is also important to include confidence intervals and ranges based on plant characteristics (e.g., if a plant has AD, the CH_4 emissions factor may be twice that of a non-AD plant).

SECTION 6

Plenary Presentation Summaries

6 Plenary Presentation Summaries

There were seven plenary presentations throughout the course of the two-day workshop. This appendix provides a short summary of each presentation, including the presenters and their topics.

6.1 U.S. Department of Energy Measuring Life Cycle Greenhouse Gas Emissions From Water Resources Recovery Facilities Workshop

David Ponder, Director of Climate Action, U.S. Water Alliance

David Ponder emphasized the critical need for partnership and action for understanding and mitigating emissions from WRRFs. Amidst intensifying climate challenges, such as intense storms, rising sea levels, and droughts, water utilities face increasing strains on infrastructure and resources, requiring a proactive approach to emissions reduction. Ponder advocated for immediate alignment within the U.S. water sector to achieve net-zero GHG emissions by 2050, stressing the sector's pivotal role in climate resilience and mitigation.

The water sector holds a unique position to tackle both direct and indirect emissions, with strategies like embracing OneWater approaches, nature-based solutions, and resource circularity. Ponder explained the co-benefits of these initiatives, in which achieving ambitious climate goals can also present opportunities for cost savings, additional revenues, and operational efficiencies. By implementing energy management, process optimization, methane management, and investing in upstream quality, emissions can be significantly reduced while supporting business objectives.

Highlighting the significant emissions output of water utilities, Ponder underscored the necessity for transparent and comprehensive emissions accounting. Current methodologies often underestimate emissions, failing to include various sources such as sewer methane emissions, energy consumption, and biosolids use and disposal. In effect, Ponder called for a paradigm shift towards life cycle emissions analysis and improved accounting practices to accurately measure progress and prioritize mitigation efforts. In addition to improvements in estimation methods, he said that immediate actions, such as repairing methane leaks, optimizing energy efficiency, and controlling process emissions can be implemented now. To conclude, Ponder advocated for proactive measures to address both direct and indirect emissions, emphasizing the availability of cost-effective opportunities for emissions reduction.

6.2 Greenhouse Gas Emissions From Wastewater Sector

Jason Ren, Professor in Department of Civil and Environmental Engineering and Associate Director of Research at Andlinger Center for Energy and the Environment, Princeton University

Jason Ren explained the significant contribution of wastewater to industrial GHG emissions, noted as 14% of total GHG emissions in the latest IPCC report. He highlighted discrepancies between estimated and actual CH_4 and N_2O emissions and included that the 2019 IPCC emissions factor is orders of magnitude higher than its 2006 emissions factor, which tripled the estimates of WRRFs' N_2O emissions. He explained that current inventories are based on limited literature and studies and don't represent diverse emission scenarios. Not every utility is created equal, and a single national-level emission factor oversimplifies the estimated emissions. Ren emphasized that additional data is needed for an enhanced and representative EF.

On measurement and analytical methods, Ren mentioned that despite the availability of diverse monitoring tools such as ground-level sensors, liquid sensors, infrared, and drones, the lack of coordination among these measures across utilities poses a challenge. He emphasized the need for guidance and coordination from organizations, such as DOE, to better align monitoring efforts and ensure consistency in data interpretation.

Ren shared a project that involved partnering with air quality monitoring groups utilizing sensors anchored on electric vehicles (EVs) to conduct drive-by emissions monitoring. Results indicated that data points obtained from 100 drive-by monitoring samples were two times higher than IPCC numbers commonly used by utilities for their inventories, highlighting potential discrepancies in emissions estimation. He concluded that increased monitoring and quantification are needed, in which technology development, policy making, and net-zero emission plans should be guided by such data.

6.3 An Artificial Intelligence/Machine Learning Approach for Assessing, Reducing, and Monitoring N_2O Emissions

Jose Porro, Chief Executive Officer and Founder of Cobalt Water Global

Jose Porro outlined the metabolic processes within WRRFs that lead to N_2O emissions, primarily from nitrification and denitrification in aerobic zones with forced aeration. Operational parameters such as DO and nitrite levels serve as indicators of N_2O production, allowing for risk assessment.

Porro explained that by leveraging AI and ML, a knowledge base is developed to assess N_2O risks and predict emissions based on process data. This predictive capability is particularly useful in situations where continuous N_2O measurement may not be feasible. Historical data and ML algorithms help identify sites with the highest emissions and opportunities for reduction, guiding mitigation efforts. The necessary data for accounting and assessment includes Supervisory Control and Data Acquisition (SCADA) data, DO levels, and ammonia and nitrite concentrations. The AI/ML platform helps identify risks such as low DO conditions, which are significant drivers of N_2O emissions. With this information, it can be determined if a site is N_2O reduction ready, depending on age and size of blowers and other factors.

Various measurement methods were highlighted, such as microsensors and floating hoods, each with its advantages and limitations. The choice depends on factors like technical capabilities and available funding, Porro explained. After method selection, placement of sensors and hoods is critical, requiring continuous monitoring, as N_2O emissions can fluctuate over time. He stated how essential it is to validate measurements across different lanes at a particular WRRF site or at multiple WRRF sites to ensure accuracy in data collection. Action needs to start now while the industry continues to learn from practice, in parallel to research.

6.4 Sewer CH_4 as an Example of a Tough Greenhouse Gas Nut To Crack

John Willis, Vice President of Wastewater Solutions at Brown & Caldwell

John Willis emphasized that methane production in sewer collection systems is not primarily from sediment, but rather from biofilms, also called slime, on pipe walls. Force mains, lacking oxygen transfer, are significant methane producers due to their fully wetted perimeter, allowing biofilm for long residence time to support methanogens in deeper layers. Willis shared his adjusted initial assessment on the level of significant sewer methane in the U.S. centralized wastewater treatment industry's Scope 1 emissions, which was reduced from 55% to 45% of Scope 1 GHG emissions.

In a study comparing DC Water facilities, Willis found that the East Headworks emitted approximately 4.6 times more methane per million gallons of flow compared to the West Headworks, hypothesizing that differences in ventilation and stripping processes may have been responsible. The methodology used in DC Water, which subtracted the calculated methane emissions from the headworks from the total sewer methane emissions, was solely based on foul-air fluxes and ignored the liquid phase. He highlighted that the findings raise questions about the underlying reasons for the observed variations in methane emissions between the two headworks, emphasizing the need for further investigation.

Willis highlighted the WRF project 5220, aiming to refine sewer methane estimation methodologies and apply them to 40–50 sewer sheds. By developing a simplified methodology, he explained the project aims to encourage widespread adoption of sewer methane estimation practices, ultimately reducing the oversight of sewer methane emissions.

6.5 What Ontario's Experience Tells Us To Measure After We've Decarbonized Energy

Jeremy Kraemer, Wastewater Technical Director Waterloo, Ontario, Canada and Chair of the Joint Climate Change Committee between the Water Environment Association of Ontario and Ontario Water Works Association

Jeremy Kraemer delved into Ontario's unique GHG accounting and mitigation framework, emphasizing the province's progress in decarbonizing its electric grid. He highlighted Canada's grid decarbonization average as the top 10% globally and Ontario's average specifically is down to a third of the Canadian average (30 grams per kilowatt-hour).

The WEAO/OWWA Climate Change Committee issued a GHG inventory tool developed by and produced for the water sector. Kraemer shared that the tool is free, simple to use, and publicly available and emphasizes the education of methane and nitrous oxide emissions. The inventory tool integrates the Biosolids Emissions Assessment Model and includes Scope 3 emissions to avoid having a narrow focus. He stated that in Ontario there's an expansion in the scope/extent of analysis for GHG emissions within the tool, including contracted biosolids disposal, considered under Scope 3 emissions.

In Ontario, the emphasis remains on N_2O and CH_4 emissions, with efforts in the City of Toronto to procure lower carbon chemicals. He stressed the importance of research programs to ensure accurate GHG inventories, highlighting the need for collaboration among various entities and researchers. In terms of execution considerations, Kraemer provided a comprehensive list including factors such as experimental design, quality control, project management, and value optimization, with a focus on knowledge dissemination and leveraging resources effectively to share data with other areas of the industry.

6.6 Measuring Life Cycle Greenhouse Gas Emissions From WRRFs

Harry Zhang, Research Program Manager at the Water Research Foundation

Ashwin Dhanasekar, Research Program Manager at the Water Research Foundation (Formerly)

Harry Zhang provided an overview of WRF's purpose and research coordination role. He explained that research on efficient resource use and recovery provides best practices, methods, processes, and tools for effective planning and operational management to cost-effectively reduce and mitigate GHG emissions by water utilities and municipalities. Collaboration with stakeholders beyond the water sector focuses on GHG accounting and emission reductions, decarbonization strategies, carbon capture associated with water utilities, and possible carbon emission trading.

Zhang discussed some of WRF's ongoing research on GHGs and climate mitigation. *Project 5188: Establishing Industry-Wide Guidance for Water Utility Life Cycle Greenhouse Gas Emission Inventories* involved the development of a utility-facing guidance document and a supporting spreadsheet tool that captures current best practices for developing a utility GHG inventory over the life cycle of capital and operational emissions. He also highlighted *Project 5251: Advancing the Understanding of Nitrous Oxide Emissions Through Enhanced Whole-Plant Monitoring and Quantification*, which aims to provide accurate whole-plant N_2O emissions estimates for WRRFs by employing continuous online monitoring and developing guidance on related process conditions.

\Ashwin Dhanasekar presented on *Project 5220: Sewer Methane Methods for Everyone*. The project objective is to develop methodologies with progressively increasing accuracy and local infrastructure specificity for estimating collection system methane emissions. Sources of CH_4 represent a sizeable chunk of utility emissions and this project aims to enhance knowledge of this hard-to-measure GHG source. To conclude, he emphasized collaboration, specifically on how to connect the dots with IPCC, which could be achieved by having a cohort or mediator for organizations.

6.7 Measuring Life Cycle GHG From WRRF Facilities Workshop

Amanda Lake, Head of Carbon and Circular Economy for Europe at Jacobs

Amanda Lake provided an overview of various R&D projects, including an International Water Association Masterclass series on Scope 1 emissions (2022), *A Review on the Measures To Reduce Greenhouse Gas (GHG) Emissions From the Wastewater Treatment Sector, Including the Benefits and Costs – WT15130* (2023) published by the United Kingdom government, and *Quantifying, Reducing Direct Greenhouse Gas Emissions From Waste and Water Treatment Process – Phase 2* (2023) published by UK Water Industry Research. Lake explained that the recommendations from these research projects draw attention to the importance of national monitoring programs, improved sector level guidance, emissions mitigation through CH_4 leak fixes and process optimization for N_2O, R&D to reduce emissions, incentives for mitigation, and limitation in abatement costs.

To address process emissions, Lake underscored the importance of mitigation and measurement efforts. For example, measurement characteristics for a site-wide level can include capturing all emissions (that day/week), campaign based (not continuous), limited granularity, and more CH_4 work compared to some N_2O. On the process unit level, she explained that these measurement characteristics can be discrete (CH_4 leak detection), continuous (liquid/gas N_2O), capturing seasonal/operational variation, and supporting process understanding, root cause, and mitigation.

Lake spotlighted several European national monitoring campaigns, including results from the National N_2O Monitoring Campaign in France, which led to recommended EFs for three typologies, a coordinated approach using consistent methods, and robust research institute oversight. Harnessing the momentum of these national monitoring programs is key, Lake stated. Utilizing the best practices of existing monitoring programs can assist with establishing the framework, processes, and technical objectives for national monitoring program design and implementation.

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