“Evaluation and Reduction of Greenhouse Gas Emissions from Austrian Biogas Plants”

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Preface

Over a period of 6 months, I have been working abroad in collaboration with the University of Natural Resources and Life Sciences. My Fulbright year has proven to be incredibly beneficial with regards to gaining experience in scientific research, project management and expanding my cultural awareness while living abroad in Austria. I am so thankful to have had this opportunity, which has advanced my skill base, knowledge and allowed me to gain a newfound sense of independence and tenacity. It has been a pleasure to work in such a high caliber research environment with such dedicated colleagues. A special thank you to Viki, who I have learned so much from. Thank you to Dr. Marion Huber-Humer, ABF-BOKU's department head who has supported my project and to Dr. Marlies Hrad who approved my proposal to work with her group. Without both of you, I would have never been able to come to Vienna in the first place. A huge thank you to the rest of my colleagues at ABF-BOKU, the Fulbright Austria Staff, and my fellow peers for your continuous welcoming demeanor and kindness. I have appreciated the guidance, offers of help, and teachings that have led to my growth over these past months. You all have made this year an incredible experience, and for that I cannot thank you enough. While the COVID-19 crisis disrupted many aspects of my project it could never undo the importance of my work, nor the unrelenting and continuous kindness that I have seen within my network during this time.

Abstract

Biogas is becoming an important alternative energy resource within the world. However, it's growth as an industry is being stunted due to the lack of standardization which causes misinformation regarding environmental impact. As such, the European Union is creating an overarching quantification system to standardize fugitive emissions sources in the industry. This is being done through intensive on-site / off-site measurements and instrumentation studies. As such voluntary groups made up scientific institutes and universities are among the few qualified to conduct this research. Two of the primary gases of concern are methane and nitrous oxide. These Greenhouse Gases (GHG) can be accidently released during the biogas process into the atmosphere. This huge issue as such impacts the environment, economics, as well as health and human safety.

In this scientific report, several processes are recorded in order to better understand how biogas emissions are created, measured, recorded and analyzed. That section will mostly focus on fugitive methane emissions. The second purpose of this report is a study concerning data quality and optimization of various instrumentation used to gather nitrous oxide emissions. Lastly, this report also summarizes the primary differences between the American and Austrian biogas communities, as well provides recommendations for the biogas industry as a whole. This is done with the overall goal of increasing knowledge from an American perspective.

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Introduction

1.1 Motivation

Biogas is one of the newer and cleaner energy alternatives, and can be easily converted into bio-methane, replacing the need for fossil fuels.[1] It is produced from the anaerobic decomposition of organic waste and is used for electricity, heat, and gas.[2] As a result, many countries have been researching and taking advantage of the biogas sector. However, because biogas production is a relatively new industry, there are no standard emission regulations in place. Hence, the concern that a lack of regulation will lead to safety and environmental issues.

Two leading problems in Austria are air pollution, and global warming, especially from greenhouse gases such as methane and nitrous oxide. Biogas itself contains around 50-65% methane as well as trace amounts of nitrous oxide, which is 10-15 times more potent than methane. As such emission rates are a considerable concern to the Austrian government, whose population has accordingly suffered from destructive flooding, heat waves, and reduced snow. Austria is continuously trying to maintain current sustainable practices in both their infrastructure and policies. To implement corrective procedures, it is critical to establish a standard to measure the impact of the emissions. In January of 2018, the European Environment Agency created a collaborative project titled the "Evaluation and Reduction of Methane Emissions from different European Biogas Plants Concepts" (EvEmBi).[3] The purpose of thus effort is to have voluntary groups from specific EU member countries measure, analyze and report their biogas emission rates.[4] The data will be used to create the first greenhouse gas emissions inventory for the biogas sector, in order to design and implement emission reduction strategies.[5] As such, this project is critical to human health, energy and waste management

1 *"Biomethane fueled vehicles the carbon neutral option". Claverton Energy Conference Bath, UK. 24 October 2009.*
2 Webdesign, Insyde. "How does biogas work?". *www.simgas.com*. Archived from the original on 10 May 2018. Retrieved 28 November 2019.
3 "Projects." *European Biogas Association*, www.europeanbiogas.eu/project/evembi/. Retrieved 24 January 2020.
4 Anonymous. "EU Member Countries in Brief." *European Union*, 23 July 2020, europa.eu/european-union/about-eu/countries/member-countries_en.
5 Events. (n.d.). Retrieved March 6, 2020, from https://www.europeanbiogas.eu/biogas-plant-operator-workshop-quantification-of-ghg-emissions-from-biogas-plants/

standards in Austria.[6]

This technical report will serve as a point of reference to the American biogas community, who are in the process of developing their quantification system. The professional organization, ASABE (the American Society of Agricultural and Biological Engineers)[7] is currently sharing the responsibility of overseeing this undertaking. As an active member, I have an obligation to contribute to this endeavor any way I can.

Additionally, Austria, and particularly Vienna is renowned for its innovative waste management systems, while boasting a population of 1.8 million.[8] This feat, in addition to the opportunity to learn alongside esteemed experts within the biogas field made Austria a unique country to work on this project in. This practical experience will be used to foster and create stronger initiatives in the waste management, renewable energy and biogas field. This goal includes bridging the knowledge and cultural gap between the American and Austrian biogas community through close collaboration.

1.2 Problem Statement

Even as climate change becomes one of the forefront issues in the world today, scientists have begun to come up with ways to try to retract its effect on the world. Greenhouse gases (GHG) are one of the largest contributors to climate change, and are largely produced during the combustion of various energy sources, including biogas.[9] In the European Union, approximately 54% of GHG emissions are produced from the energy sector.[10] It is important to note that biogas only contributes to Greenhouse Effect through fugitive emissions. Fugitive emissions are

6 Holmgren, M. A., Nørregaard Hansen, M., Reinelt, T., Westerkamp, T., Jørgensen, L., Scheutz, C., & Delre, A. (2015). Measurements of methane emissions from biogas production – Data collection and comparison of measurement methods: Energiforsk report 2015:158. Energiforsk AB. http://www.energiforsk.se/SiteAssets/rapporter/2015_158.pdf

7 American Society of Agricultural and Biological Engineers Home. (n.d.). Retrieved March 13, 2020, from https://www.asabe.org/

8 STATISTIK AUSTRIA. *"Bevölkerung zu Jahres-/Quartalsanfang"*. statistik.at. *Retrieved 12 February 2020*.

9 Sources of Greenhouse Gas Emissions. (2020, April 11). Retrieved from https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions#:~:text=Human%20activities%20are%20responsible%20for,over%20the%20last%20150%20years.&text=The%20largest%20source%20of%20greenhouse,electricity%2C%20heat%2C%20and%20transportation.

10 Greenhouse gas emission statistics - emission inventories. (2020, June 18). Retrieved from https://ec.europa.eu/eurostat/statistics-explained/pdfscache/1180.pdf

considered gases that escape the airtight digesters and other parts of the plants during the anaerobic digestion process.[11] They arise from bad plant upkeep or poor design, and are often neglected by operators due to lack of awareness. Additionally, while two methods of recording, measuring and accessing fugitive emissions exist, they are not standardized or quantified. Contributing to this issue is the limited and unreliable data that makes it extremely difficult to quantify greenhouse gas losses from the biogas plants. Most studies have found the reason behind this is the differences in feedstocks, sizes, location and costs. Therefore, the emission quantity and quality varies highly. As such experts are needed in order to properly begin this standardization process.

As biogas becomes a more utilized fuel within the 21st century, the lack of quantified emission data from the process has become a greater problem. Quantification systems provide bases for measurement.[12] Due to the numerous variables that consist within the biogas plant measurement method process it is hard to create a standard system. Therefore, it is vital for many entities to work together to tackle this issue. One example of this type of collaboration occurred a couple years ago. Several countries from the EU collaborated to make a guideline to help professionals determine how to achieve continuous reliable methane emissions from biogas plants. The guideline was written under a project, which was known as MetHarmo[13], succeeded in preparing different methods to quantify methane emissions and compare them to one another. After this success, a second measurement campaign was launched. Funded by an ERA-NET Bioenergy project, they are currently working towards a set of 5 goals, with the overarching goal of completing the quantification system within the EU. The Evaluation and Reduction of Methane emissions from different European Biogas plant concepts (EvEmBi) project, which began in 2018, will evaluate methane emissions from European biogas plants to develop a voluntary system for greenhouse gas (GHG) emission mitigation. The team is made up of 11

[11] Desjardins, R. L., Flesch, T. K., Worth, D., Gao, Z., Li, X., & Martin, T. (n.d.). *Quantifying Fugitive Methane Emissions from Biodigesters*. Speech presented at Agriculture & Agri-Food Canada. Retrieved December 7, 2019, from https://www.globalmethane.org/expo-docs/india10/postexpo/ag_desjardins.pdf
[12] The Importance of Standards . (n.d.). Retrieved November 7, 2019, from https://www.cencenelec.eu/research/tools/ImportanceENs/Pages/default.aspx
[13]Clauß, Tina & Reinelt, Torsten & Vesenmaier, Angela & Reiser, Martin & Ottner, Reinhold & Huber-Humer, Marion & Flandorfer, Claudia & Stenzel, Sirma & Piringer, Martin & Yngvesson, Johan & Holmgren, Magnus Andreas & Fredenslund, Anders & Scheutz, Charlotte & Innocenti, Fabrizio & Hrad, Marlies & Liebetrau, Jan. (2019). Recommendations for reliable methane emission rate quantification at biogas plants.

different project partners from within the European Union.[14] The project will also be supported by the European Biogas Association who is fully advocating for both EU wide and national voluntary systems.[15] As such there are several goals and objectives of this project, which have been listed below.

1. Gather more data based upon agreed upon criteria set by all parties on the team
2. Create modeling software that can accurately calculate applicable life cycle-cost analyses
3. Identify/Reduce fugitive methane emissions in biogas plants and see how prevalent they are in Austria in comparison to other countries in the EU
4. Grow the current voluntary system and create training workshops for plant operators so that they are trained to keep fugitive emissions low
5. Reach the EU methane reduction rates within the biogas industry as required by the 2021 and the 2025 mandates

Once all these goals are successfully met, it will be easier to create a final, official guideline. The team is also hoping that by fulfilling the above goals there will simultaneously be a natural reduction in fugitive emissions due to their efforts.

The above goals and efforts will lead to the correction of inaccurate emission data, which in turn would provide regulatory parties with better information. This would allow the government to implement more solid emission mitigation strategies. That would lead to positive economic, health, safety, energy, environmental and lifestyle changes. The ultimate goal is to reduce the GHG production in the energy sector as well as slowly shift it to depend more and more on renewable energy. As a result, biogas should become a safer, more frequently used and a better understood energy source that can be successfully incorporated into daily life.

1.3 Objective and Research Questions

[14] EvEmBi – Evaluation and reduction of methane emissions from different European biogas plant concepts. (n.d.). Retrieved from https://www.best-research.eu/en/competence_areas/biogas_en/projects/view/556
[15] EvEmBi Voluntary action for GHG emissions control in the biogas sector. (n.d.). Retrieved from https://www.europeanbiogas.eu/project/evembi/

The objective of this work is to create a technical report outlining the EU methane quantification project and to provide insight for American and non - EU researchers on how this process works. It also seeks to highlight the biogas industry as a whole. This will be achieved by working with an international team to test for fugitive emissions at biogas plants across Austria. Tasks include performing data analysis, investigating published literature and data concerning biogas methane emissions, learning the software Windtrax[16] and getting a better understanding the methodology, equipment, collaboration and experimentation techniques. It is also an opportunity to look at current government policy concerning the limitations involving methane emissions as well as the future of biogas within both America and Austria. For this analysis I will consider the renewable energy politics and biogas regulatory policies in both countries.

As such, I have three main research questions/needs that I will answer during my Fulbright fellowship at BOKU in Vienna, Austria in order to help stream-line my technical report and to better understand the process of how the European Union quantification system is being developed.

1. Understanding and documenting the current methods for testing and analyzing fugitive methane emissions from biogas plants through hands on experience.

The goal is to learn from and accompany the Austrian biogas team during their emission monitoring days. My affiliation, the University of Natural Resources and Life Sciences (BOKU), who is a part of the EvEmBi voluntary team to gather data for the EU, has agreed to help facilitate my travel to the biogas plants and provide any additional training that I might need.[17] I also will be reviewing past works and documentation in order to gain a better understanding of the overall process.

2. Working with instrumentation in the lab to see how different devices work as well as how they could be optimized so data quality could be improved.

[16] Thunder Beach Scientific. (n.d.). Retrieved from http://thunderbeachscientific.com/.Windtrax Publisher
[17] The University of Natural Resources and Life Sciences, Vienna (BOKU). Retrieved from https://boku.ac.at/en/

The goal is to compare the data gathered with the N2O/CO LGR Device[18] at the field in Stuttgart, Germany with a set of lab tests and field tests in Austria in order to test the devices flushing time. Flushing time refers to the amount of time it takes the device to start up and begin to accurately gather data. This will be done through point measurements using the inverse dispersion modeling method (IDMM). As seen at the Stuttgart testing site, the LGR Device takes 6-10 minutes longer to set up. Since the voluntary team is using various instrumentation, this fact could affect the comparison studies. Therefore, the goal of this side project is to reduce the flushing time to less than 5 minutes.

3. Creating recommendations by understanding the primary differences between the American and Austrian biogas communities, with an overall goal of increasing knowledge from an American perspective.

The goal for this last objective is to create a set of recommendations for the American Biogas Community. The European Union is in possession of far advancing technologies, processes and standardization proposals than the U.S. within this industry. [19] Currently the agency in charge of organizing this is the American Society for Agricultural & Biological Engineers (ASABE), which I currently am a member of. In their most recent 2019 International Meeting paper, the organization discusses the importance of the US creating a system to monitor anaerobic fermentation processes and data. [20] As of now, they are focusing on a three-part biogas monitoring system, intent to measure emissions from large and medium sized projects.

2.0 Background

2.1 The Process

[18] N2O/CO Analyzer (nitrous oxide, carbon monoxide). (n.d.). Retrieved April 2, 2020, from https://www.lgrinc.com/analyzers/overview.php?prodid=20#:~:text=LGR's N2O/CO,Hz with optional external pump).

[19] Dang, F., Bi, Y., & Liu, Y. (2014). Analysis of the large-and-medium-sized biogas projects in europe and comparisons with our country. Chinese biogas, 32(1), 79-83.

[20] 2019 ASABE Annual International Meeting, Paper No. 1901017, pages 1-16 (doi: 10.13031/aim.201901017). St. Joseph, Mich.: ASABE.

Biogas production is a form of renewable energy that was officially credited with discovery in the 17th century.[21] However, the oldest first known use of biogas was by the Assyrians in 900 BC, as a bath water heater.[22] It is created through anaerobic digestion, a natural biological process which uses the lack of oxygen in a closed system in combination with microbes to decay organic matter. A high temperature, high acidity, mixing, feeding and bacterium is required for this operation to work correctly.[23] This airtight process produces fumes which contain 50-70% methane as well as lesser amounts of carbon dioxide and other gases.[24] Biogas plants are extremely versatile as any sort of biodegradable materials can be used to create fuel. This includes but is not limited to plant waste, food waste, sewage, animal byproducts, manure etc., All these feedstocks have different benefits and disadvantages depending on how much or little they are used. For example, a study conducted by the U.S. Department of Energy, found that biodiesel produced from tallow plants should be blended or require additives to ensure they hold their form during colder temperatures.[25] These findings have led to various comparative analysis studies to better understand how both pure feedstocks and the co-digestion of multiple feedstocks can improve biodiesel.

After the feedstocks have been chosen, gathered, prepared and properly screened for containments, the next step is treatment. In order to create a digester influent that can be effectively handled by the anaerobic digester it needs to have a smooth consistency. To achieve this ideal consistency, the total solids content of the influent needs to be modified. Multiple measures may include adding water, mixing, separating, or heating. After this step, the product is transferred into the plant's anaerobic digester. There are several digester designs based upon the plant's location, cost, the digester influent and feedstock source. Several designs include covered

21 A Short History of Anaerobic Digestion. (2020, August 01). Retrieved from https://extension.psu.edu/a-short-history-of-anaerobic-digestion

22 Why biogas? (2020, May 06). Retrieved from https://www.worldbiogasassociation.org/why-biogas/

23 Biogas Plant Development Handbook • BiogasWorld. (n.d.). Retrieved from https://www.biogasworld.com/biogas-plant-development-handbook/

24 Usda.gov/oce/reports/energy/Biogas_opportuities_roadmap_8-1-14.pdf_page6

25 U.S. Energy Information Administration - EIA - Independent Statistics and Analysis. (n.d.). Retrieved from https://www.eia.gov/todayinenergy/detail.php?id=36052

lagoons, plug flow, complete mixes, batch digesters, induced blanket reactors, and fixed film digesters.[26]

Covered Lagoon

In a **covered anaerobic lagoon** design, methane is recovered and piped to the combustion device from a lagoon with a flexible cover. Some systems use a single cell for combined digestion and storage.

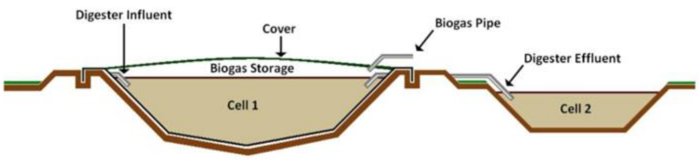


Diagram of a covered anaerobic lagoon showing 2 cells, where the first cell collects the digester influent and traps the biogas and the second cell collects the digester effluent

Figure 1

Complete Mix

Complete mix digesters are designed with an enclosed, heated tank with a mechanical, hydraulic or gas mixing system. Complete mix digesters work best when there is some dilution of the excreted manure with water (e.g., milking center wastewater).

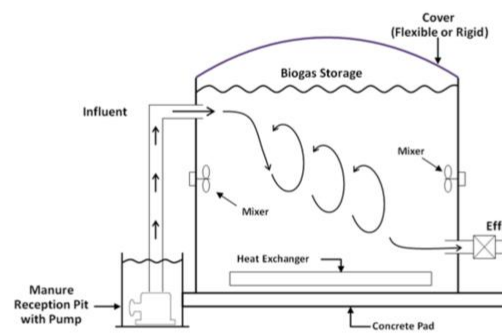


Diagram of a complete mix digester illustrating the process of adding manure into the digester; mixing, heating and storing the biogas within the digester; and extracting the resulting effluent

Figure 2

Plug Flow

Plug flow digesters are primarily used at dairy operations that collect manure by scraping. Mixed plug flow systems have been used at a wider variety of operations because they can tolerate a broader range of solids concentrations.

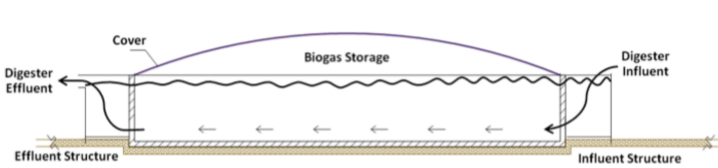


Diagram of a plug flow digester showing digester influent entering and flowing through the digester with the biogas being captured and stored beneath a cover [27]

Figure 3

There are four main steps of the anaerobic digestion process. These are as follows: hydrolysis, acidogenesis, acetogenesis and methanogenesis.[28]

The first essential step is called hydrolysis. In this stage, water in the digester (made up of biomass) goes through a chemical reaction fueled by microbes, breaking down to form H+ cations and OH- anions[29]. This is important because the large polymers which are prevalent in the biomass slurry such as proteins, fats and carbohydrates are unusable unless they

26 How does anaerobic digestion work? (2019, March 18). Retrieved from https://www.epa.gov/agstar/how-does-anaerobic-digestion-work#:~:text=Anaerobic digestion is a process,primary component of natural gas.
27 How does anaerobic digestion work? (2019, March 18). Retrieved from https://www.epa.gov/agstar/how-does-anaerobic-digestion-work#:~:text=Anaerobic digestion is a process, primary component of natural gas.
28 S. (2017, May 11). The illustrated step-by-step guide to anaerobic digestion. Retrieved from https://www.opusenergy.com/blog/illustrated-step-by-step-guide-to-anaerobic-digestion/
29 Biomass to Biogas: E Instruments. (n.d.). Retrieved from https://www.e-inst.com/training/biomass-to-biogas/

are broken down into smaller molecules.[30] Small molecules such as sugars, fatty acids and amino acids are needed so the cells can assimilate the various materials in the influent in preparation for the next step [31].

Acidogenesis occurs when the products created by hydrolysis are fermented by microbes to continue to break down. These microbes are known as acidogens, and consist of certain strains of bacteria produced within an acidic environment. During this process the sugars, fatty acids and amino acids, which are still too large to produce methane, are converted further into long chain fatty acids and intermediates. Long chain fatty acids and intermediates are made up of products such as ammonia, alcohols, H2, CO2, H2S etc.

In the next step, acetogensis, the recently created long chain fatty acids and intermediates are further broken down into acetate, H2 and CO2. This process is done by microbes known as acetogens. This is needed in order to make use of any material that is leftover that could help to create methane as a biofuel.

The final step, known as methanogenesis is when acetate, H2 and CO2 are converted into biogas by methanogens. The end biogas makeup consists of 60% methane, 38% carbon dioxide and 2% trace gases.[32]

This process is considered renewable since biogas systems run on various waste materials which are used to create a product that will provide heat and energy. These systems also are able to capture potential fugitive methane sources to use as fuel. This is extremely vital as it reduces the greenhouse effect and allows for a suitable replacement for fossil fuels. Biogas can easily be used and converted to heat, power and energy which makes it an extremely renewable valuable energy source.[33]

There are two types of anaerobic digestion processing technology which both mostly concern waste feedstocks; wet and dry. Wet digestion refers to systems that digested diluted

[30] Franke-Whittle, I. H., Walter, A., Ebner, C., & Insam, H. (2014). Investigation into the effect of high concentrations of volatile fatty acids in anaerobic digestion on methanogenic communities. *Waste management (New York, N.Y.)*, *34*(11), 2080–2089. https://doi.org/10.1016/j.wasman.2014.07.020

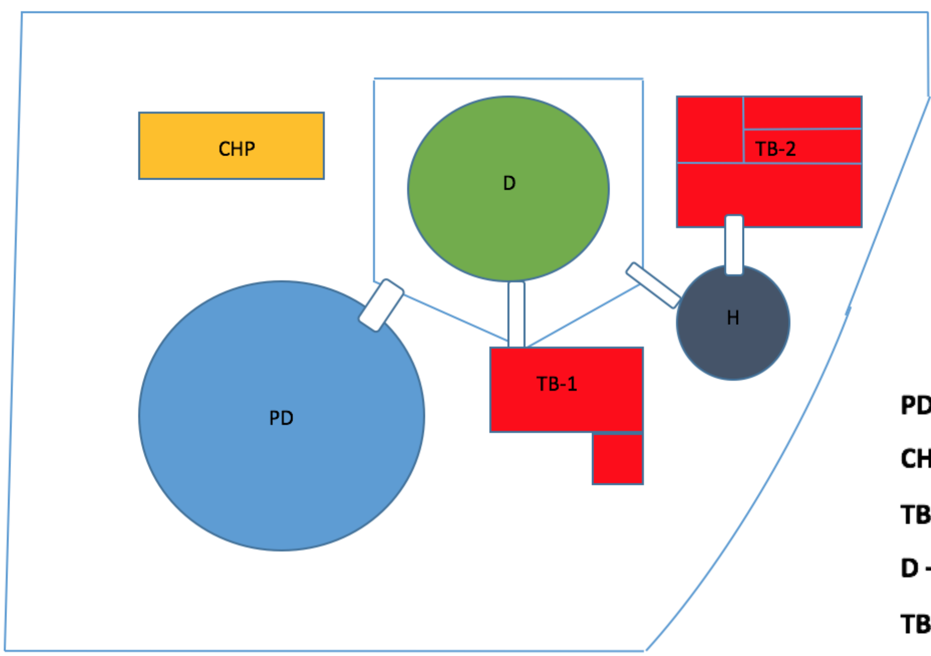
[31] *Anaerobic Digestion: Microbiology and Biochemistry*. (n.d.). Lecture. Retrieved June 7, 2020, from https://biogas.ifas.ufl.edu/Internships/2012/files/AD 1.pdf

[32] Rep. No. EPA/600/R-15/304 at 18 (2015). Retrieved June 7, 2020, from https://www.epa.gov/sites/production/files/2016-07/documents/ad_and_applications-final_0.pdf

[33] About biogas and biomethane. (n.d.). Retrieved from https://www.europeanbiogas.eu/about-biogas-and-biomethane/

organic slurry which has less than 15% total solids content. Dry digestion on the other hand, has a higher total solid slurry which is between 15-40% and does not need to be diluted before it is handled.[34] Knowing whether you are working with wet or dry slurry will differ the system you are using. It will also change the process the waste feedstock will need to go through to be converted to biogas.

The complexity of a biogas plant depends on several variables, and as such the plants have several variations. The schematic below is loosely based upon the structure of one of the simpler biogas producing plants I have seen.



PD – Post Digester

CHP – Combined Heat and Power

TB-1 – Technical Building 1

D – Digester

TB-2 – Technical Building 2

H – Hydrolysis

Figure 4

As shown by the key above, there are six important processes that allows this plant to produce biogas. The first stage of the process that occurs is in the first smallest tank, on the middle left labeled hydrolysis. This is where the biological degradation of the feedstocks occurs. Microbes breakdown the various organic structures, perform precondition and mixing as well as buffering substrate. In order to perform the main and basic anaerobic digestion practices, the

[34] (n.d.). Retrieved from https://www.walesadcentre.org.uk/ad-information/technologies/wet-dry-systems/

plant needs a digester. [35] This is where the previously broken down influent is fully mixed. Simultaneously the temperature controlled vessel allows microbial organisms to convert the solid product to a gaseous one which is made up of methane, carbon dioxide and other vapors. During this time the technical buildings house systems that support this process. In technical building 1, a central pumping station is held which controls the heating and cooling of the fermentation tanks. This is critical to ensure a specific quality of biogas. In technical building 2, this is done through additive preparation. Iron hydroxide is incorporated for the precipitation of sulfur and trace elements are optimized to ensure the highest biological performance possible.

The largest dome is known as the Post-Digester. During this final degradation stage, homogenization and biological desulfurization of biogas occurs. This ensures the quality of the other product of anaerobic digestion known as digestate. Digestate which is produced during the acidogenesis and methanogenesis is often used by farmers as a fertilizer. The top of the Post-Digester, known as the “hood”, also serves as a storage tank for the newly generated biogas, until it is processed.[36] If the user wants to generate heat and electricity, then the biogas is burned as fuel for the combustion engine and electrical generator in the Combined Heat and Power (CHP) plant.

2.2 The Biogas Industry in Austria/EU vs. the USA

As a member of the European Union, Austria must follow all laws created and approved by the panel of countries (including itself), that make up the organization. One of those is the Renewable Energy Directive which was created in 2009. It states that by the end of 2020 all members must have renewable fuels make up for 10% of their transport sectors.[37] This was done in part to minimize greenhouse gas emissions and to observe with the Kyoto Protocol to the United Nations Framework Convention on Climate Change. Unfortunately, due to the lack of standardization and unmet sustainability criteria, the biogas sector has not been able to meet the

[35] Biogas Process. (2008). Retrieved June 7, 2020, from https://www.integratedenergyindustries.com/biogas-process.html
[36] Biogas Process. (2008). Retrieved June 7, 2020, from https://www.integratedenergyindustries.com/biogas-process.html
[37] European Union, DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL. (2009, April 23). Retrieved June 7, 2020, from https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0016:0062:EN:PDF

specific criteria needed as of this time. Since the sustainability criteria mostly concerns the fugitive emissions being produced from biogas plants, the voluntary action team (EvEmBi)[38] are working at this time to fulfill this.

Austria, as of 2019, has 368 biogas producing sites and an annual biogas production around 1.5-2.5 TWh.[39] Most biogas plants use animal manure, wooded material, wastewater treatment sludge, fatty plant material, food waste or a combination of the above in order to produce high quality biogas. The EU has over 10,000 biogas producing sites.[40] This is due to the European Union's commitment to green energy and sustainability, which has increased greatly in the last 30 years. Additionally, most countries within the EU, have different electricity prices depended on types of energy (wind, biogas, solar) etc., used. This as well as secure, guaranteed access to the electricity grid with minimal to no fees has encouraged the diversified use of green energy.[41]

Some of biogas systems in Austria are also highly integrated with advanced technologies, which are known as "BioRefiniers". As of 2017, there are four in Austria.[42] These plants are built specifically for high quality energy and product creation. The majority of the biorefiniers in Austria use wood-based materials (excl. pulp for paper only), with only one using sugar/starch based products including bioethanol and other chemicals. As just stated, in Austria, there are two sets of rules and regulations that the country must meet. The first is the ones set by the European Union, and the second are those set by the country themselves. It is also very common that local

38 Anonymous. "EU Member Countries in Brief." *European Union*, 23 July 2020, europa.eu/european-union/about-eu/countries/member-countries_en.

39 Holmgren, M. A., Nørregaard Hansen, M., Reinelt, T., Westerkamp, T., Jørgensen, L., Scheutz, C., & Delre, A. (2015). Measurements of methane emissions from biogas production – Data collection and comparison of measurement methods: Energiforsk report 2015:158. Energiforsk AB. http://www.energiforsk.se/SiteAssets/rapporter/2015_158.pdf

40 Diaz, A. (2019, March 21). Biogas Market Snapshot. Retrieved from https://americanbiogascouncil.org/biogas-market-snapshot/

41 Electronic -only Sixth International Dairy Housing Conference Proceedings of the 16-18 June 2007, (Minneapolis, Minnesota, USA), eds J. Zulovich, B. Holmes, J. Harner. St. Joseph Michigan: ASABE. ,16-18 June 2007. ASAE Pub #701P0507e

42 Mapping European Biorefineries. (2017, November 11). Retrieved from https://biconsortium.eu/news/mapping-european-biorefineries

municipal agencies often have input in where the biogas plants can be built, what digestate they use, as well as it's pasteurization and management.[43]

In the United States, the biogas community is also conducting research on biogas plants, though it is more limited in comparison to their European counterparts. Most current data and articles discussing GHG emissions from energy sources are either from natural gas or coal facilities. Yet this does not mean biogas is not utilized in America, and the last ten years have seen growth within the anaerobic digestion and biogas industry. Some groups encouraging the continued growth of biogas include the United States Department of Agriculture (USDA) and the American biogas association. Collaborative documents such as the Biogas Opportunities Roadmap are proof of that progress.[44]

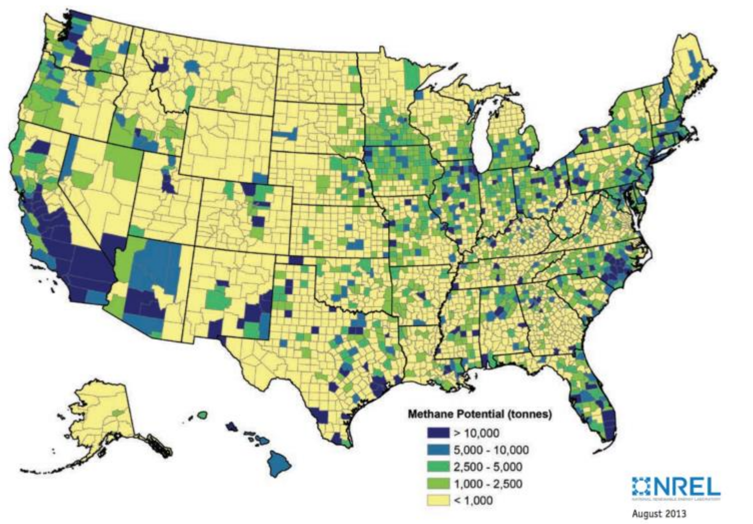
One main concern that is encouraging the implementation of alternative energies such as biogas is Greenhouse effect and Greenhouse Gases. Methane emissions in the United States, while reduced since the 1970's, were still around 600 metric tons (CO2 equivalent) in 2017.[45] According to the USDA, the methane emissions from the current livestock operations in the US alone provide enough to power around 70,000 homes. Additionally, the U.S. National Renewable Energy Libationary estimated in 2013, how many tones of methane generation potential for select biogas sources for the entire country. A schematic of their analysis is included below.

43 Electronic -only Sixth International Dairy Housing Conference Proceedings of the 16-18 June 2007, (Minneapolis, Minnesota, USA), eds J. Zulovich, B. Holmes, J. Harner. St. Joseph Michigan: ASABE. ,16-18 June 2007. ASAE Pub #701P0507e

44 American Biogas Council, Biogas Opportunities Roadmap (USDA, EPA, DOE, 2014), EPA AgSTAR 2016, EPA LMOP 2017, Water Environment Federation "Enabling the Future"

45 Overview of Greenhouse Gases. (2020, May 28). Retrieved April 29, 2020, from https://www.epa.gov/ghgemissions/overview-greenhouse-gases#methane

Figure 5



[46] Estimated methane generation potential for select biogas sources by county

Overall, the United States of America, is currently not as supportive in green energy initiatives as the European Union, due in part to the politicization of sustainable and climate change projects. Coupled with the fact that many anaerobic digesters needed for the creation of biogas plants have high startup costs, many health regulatory policies to meet and a lack of return on investment, have led to less biogas production in the country as a whole.[47] As such, research concerning fugitive emission standards as well as the process of developing such a quantification system is very limited. As the United States continues to progress in renewable energy development, they will need to look to their international counterparts for guidance.[48]

One of the main organizations leading the effort to continue increasing knowledge and supporting the biogas supply chain is a profit organization called the American Biogas Council.

[46] United States Department of Energy, N. (n.d.). Energy Analysis Biogas Potential in the United States. Retrieved from https://www.nrel.gov/docs/fy14osti/60178.pdf

[47] CD-Rom of the International Symposium on Air Quality and Waste Management for Agriculture Conference Proceedings, 16-19 September 2007, (Broomfield, Colorado, USA) Editor, L. Moody, St. Joseph Michigan: ASABE. ,16, September 2007 . ASAE Pub #701P0907cd

[48] *Anaerobic Digestion Market Report United states of America* (Rep.). (n.d.). Retrieved http://www.worldbiogasassociation.org/wp-content/uploads/2018/07/AD-Market-Report-America.pdf

The American Biogas Council is the first trade association that represents the U.S. biogas industry, and includes over 200 companies.[49] The American Biogas Council understands that while the current number of sites are low in the US, there is huge potential for expansion. The organization has found that a little under 15,000 sites are available for biogas plant site development and that these systems could produce 103 trillion kilowatt hours of electricity each year.[50] Our country is a huge untapped resource when it comes to biogas as a clean energy source. Progress from the addition of more sites would directly lead to reduced emissions from transportation, increased construction contracts which in turn would produce more temporary and permeant jobs. Other indirect benefits would be vast and include environmental, waste treatment, economic and energy gains.[51] However, progress is not easy and still on the slower side. As of 2018, the U.S. only has around 2,200 sites that actually produce useable biogas.[52]

2.3 Greenhouse Gases: Methane (CH_4) & Nitrous Oxide (N_2O)

Greenhouse Gases are molecules made of three or more atoms that are loosely held together and vibrate when they absorb heat. During this vibrating stage they release radiation which can be absorbed by other molecules. Our atmosphere is mostly made up of nitrogen and oxygen, which are both two atom molecules. Since two atom molecules are unable to vibrate, they can't absorb the heat that the greenhouse gas molecules are giving off.[53] As such, the heat being given off by the three atom greenhouse gas molecules stay trapped near the Earth's surface, within the atmosphere.[54] This contributes to the Earth's greenhouse effect which leads to the warming of our planets climate. While this is a natural occurrence, the increase within the last 200 years of industry and technology across the world has amplified this effect.

As stated previously in this report, the two Greenhouse Gases that were focused on were Methane (CH_4) and Nitrous Oxide (N_2O). When anaerobic digestion facilities produce biogas as

49 Admin. (2018, December 22). Leadership. Retrieved from https://americanbiogascouncil.org/about/leadership/
50 American Biogas Council, Biogas Opportunities Roadmap (USDA, EPA, DOE, 2014), EPA AgSTAR 2016, EPA LMOP 2017, Water Environment Federation "Enabling the Future"
51 Admin. (2018, December 22). Why Biogas? Retrieved August 7, 2020, from https://americanbiogascouncil.org/resources/why-biogas/
52Admin. (2018, December 22). Why Biogas? Retrieved August 7, 2020, from https://americanbiogascouncil.org/resources/state-profiles/
53 The Greenhouse Effect. (n.d.). Retrieved from https://scied.ucar.edu/longcontent/greenhouse-effect
54 Overview of Greenhouse Gases. (2020, May 28). Retrieved from https://www.epa.gov/ghgemissions/overview-greenhouse-gases

a renewable energy source, these gases are often unintentionally emitted into the atmosphere. The frequent loss of these gases during production impacts not only the environment, but causes great economic, as well as health and safety concerns.

Methane (CH4) is the most focused upon Greenhouse Gas within the biogas community. This is due to the fact that around 40-60% of biogas consist of methane.[55] Methane is an extremely potent gas, that has about 20-30 times that heat-trapping capability of carbon dioxide (CO2). [56] Due to this heat-trapping capability, methane contributes directly to global warming. Though methane is produced by several other industries (natural gas, landfills, etc.,) in order for biogas to become a more mainstream alternative energy, the loss of the gas must become more accounted for. This should be done in order to properly create standardization, improve operational efficiency and enable more precise regulatory enforcement.

Nitrous Oxide (N2O) is another important Greenhouse Gas which is created and can be emitted during the biogas production process.[57] While methane is 20-30 times more potent than CO2, nitrous oxide is way worse at 250-300 times.[58] Studies have found that the continued expelling of nitrous oxide into the atmosphere has also led to the rapid thinning of the ozone layer.[59] As such, researchers are also working on reducing nitrous oxide emissions from biogas facilities as well.

55 "Biomass Explained: Landfill Gas and Biogas." *Energy Information Administration*, www.eia.gov/energyexplained/biomass/landfill-gas-and-biogas.php#:~:text=Biogas is composed mostly of,water vapor and other gases.

56 Dumont, M., Luning, L., Yildiz, I., Koop, K., 2013. Methane emissions in biogas production. 248-266. Biogas handbook: Science, production and application, edited by Wellinger, A., Murphy, J., Baxter, Woodhead Publishing Series in Energy No. 52, Oxford, Cambridge, Philadelphia, New Dehli. 512 pages

57 Carter, M. S.; Hauggard-Nielsen, H.; Heiske, S.; Jensen, M.; Thomsen, S.; Schmidt, J. E.; Johansen, A.; Ambus, P. Consequences of field N2O Emissions for the Environmental Sustainability of Plant-Based Biofuels Produced Within an Organic Farming System. *Global Change Biol. (CBG) Bioenergy* 2012, *4*, 435–452. DOI:10.1111/j.1757-1707.2011.01132.x. [Crossref], [Web of Science ®], [Google Scholar]

58 "Climate Change & Sustainable Development." *World Biogas Association*, www.worldbiogasassociation.org/goals/climate-change-sustainable-development/.

59 *Ravishankara, A. R.; Daniel, J. S.; Portmann, R. W. (2009). "Nitrous Oxide (N_2O): The Dominant Ozone-Depleting Substance Emitted in the 21st Century". Science.* ***326*** *(5949): 123–5. Bibcode:2009Sci...326..123R. doi:10.1126/science.1176985. PMID 19713491.*

3.0 Field Testing across Austria using varying Methods

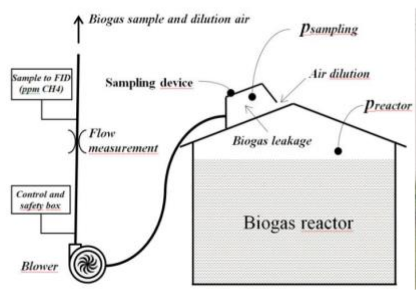
3.1 On Site vs. Remote Sensing Methods, Modeling Practices & Quantification

There are several types of methods that have been established and are used at biogas plants all over Europe. [60] One of the best sources that compares the varying methods in terms of their strengths and weaknesses, has been written by the project partners of MetHarmo.[61] I will be reposting their general findings and comparisons in this section. This information is extremely accurate and was published in June of 2019.

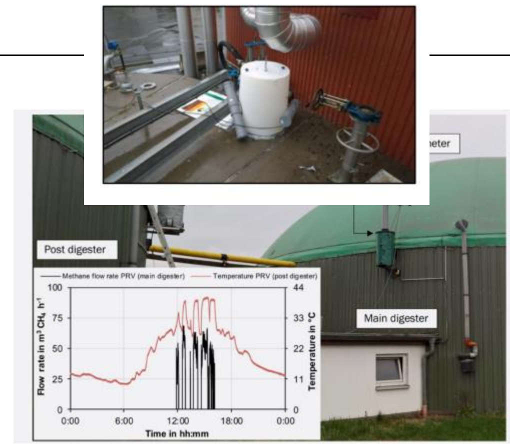
There are two ways measurements for biogas emission are gathered; on the biogas plant site and downwind of the biogas site. These are more commonly referred to as “on-site” and “off-site”. Based upon first-hand knowledge, literature reviews and the Met Harmo project recommendations, in general on-site method are recommended to be conducted the following way. It is first recommended to create a questionnaire, go on pre-visits and thoroughly research the biogas site in order to understand the scope of the measurement before starting. An initial leakage detection should be performed, and recorded using a scaled site map of the premises. All emission leakages should be noted, and later assessed to see if they will be further investigated as part of the official measurement campaign. Additionally, the emission rate from each individual potential leakage source needs to be determined separately. In order to properly calculate this emission rate, both volume flow and concentration must be determined. On-site measurements have several methods available in order to properly quantity the leakage which are depended upon the source they arise from.

[60] *(PDF) Methane Emissions from Biogas Plants. Methods for* ... www.researchgate.net/publication/323174976_Methane_Emissions_from_biogas_plants_Methods_for_measurement_results_and_effect_on_greenhouse_gas_balance_of_electricity_produced.

[61] Clauß, Tina & Reinelt, Torsten & Vesenmaier, Angela & Reiser, Martin & Ottner, Reinhold & Huber-Humer, Marion & Flandorfer, Claudia & Stenzel, Sirma & Piringer, Martin & Yngvesson, Johan & Holmgren, Magnus Andreas & Fredenslund, Anders & Scheutz, Charlotte & Innocenti, Fabrizio & Hrad, Marlies & Liebetrau, Jan. (2019). Recommendations for reliable methane emission rate quantification at biogas plants.

62	**Method**	**Images / Examples**
Channeled Sources (off-gas from gas utilization units, encapsulated emission sources with ventilation etc.,)	Air Extraction[63]	64 
Leakages (all that are categorized as being a part of the encapsulated emission sources)	High Flow Sampling[65] (the Dynamic Chamber Method can be substituted)	  Figure 5. High volume sampler.
Area Sources (open storages and non-gas-tight covered storages)	Air Injection Method and Static (Closed) or Dynamic (Open) Chamber Method[66]	 67

62 Clauß et al. (2019).
63 Clauß et al. (2019).
64 Wechselberger, V. (n.d.). [Author performing measurements].
65 Holmgren, M. A., Nørregaard Hansen, M., Reinelt, T., Westerkamp, T., Jørgensen, L., Scheutz, C., & Delre, A. (2015). Measurements of methane emissions from biogas production – Data collection and comparison of measurement methods: Energiforsk report 2015:158. Energiforsk AB. http://www.energiforsk.se/SiteAssets/rapporter/2015_158.pdf
66 (Rochette and Mc Ginn, 2005)
67 Holmgren et al. (2015)

Pressure Relief Valve (a type of safety valve used to control and/ or limit pressure in a system)	Permanent Online Monitoring[68]	[69] 

Unlike on-site sensing, the remote sensing approach is not based upon specific sectors of the biogas plant, but serves to measure the entire plant as a whole. This is done by measuring a proper distance from the site, and it can be monitored by the measurement team for whatever period they wish.

There are three remote sensing methods; Differential Absorption Lidar (DIAL), Tracer Dispersion Method (TDM), and lastly, Inverse Dispersion Modeling Method (IDMM).

DIAL is laser-based technique, and allows emissions to be measured via an open path, which uses a far range to capture resolved gas concentration measurements. There are two adjacent wavelengths created by the laser; one is tuned to the target gas line and the other minimizes the absorption. The far reaching radius of the laser enables measurements to be made along various lines on a vertical plane, which is later displayed on a 2-D map.

68 Clauß et al. (2019).
69 T., T., & J. (n.d.). Monitoring of methane emissions from biogas plants. Retrieved from https://www.gas-for-energy.com/fileadmin/G4E/pdf_Datein/g4e_2_17/02_fb_Liebetrau.pdf

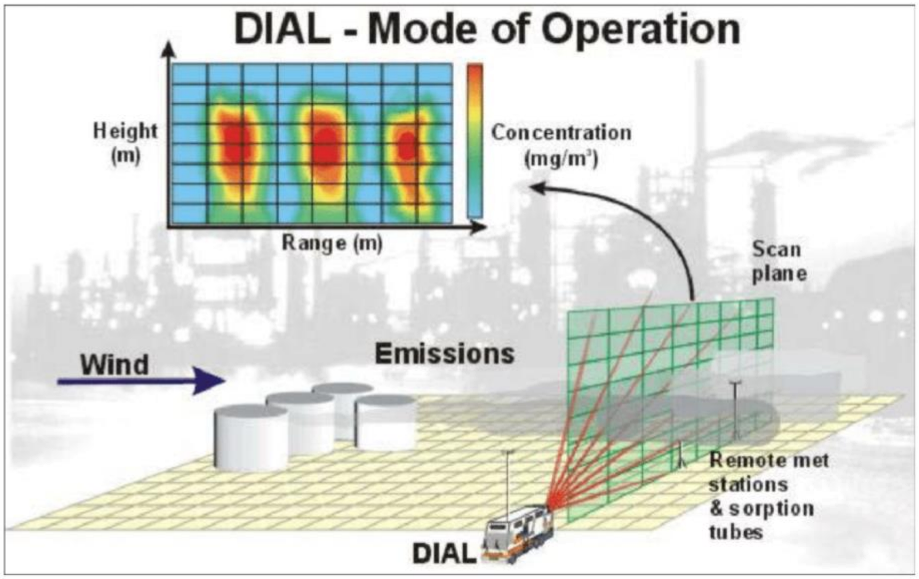
[70] 

Figure 6

TDM, as the name suggests, uses a tracer gas called acetylene, which is released controllably near the biogas plant replicating the real released emissions. The reasoning behind this method, is that the acetylene will follow the same dispersion flow from the biogas plant into the atmosphere. Therefore, while this release is occurring, the measurement team can easily identify the wind direction, as well as other factors needed to calculate the emission rate.

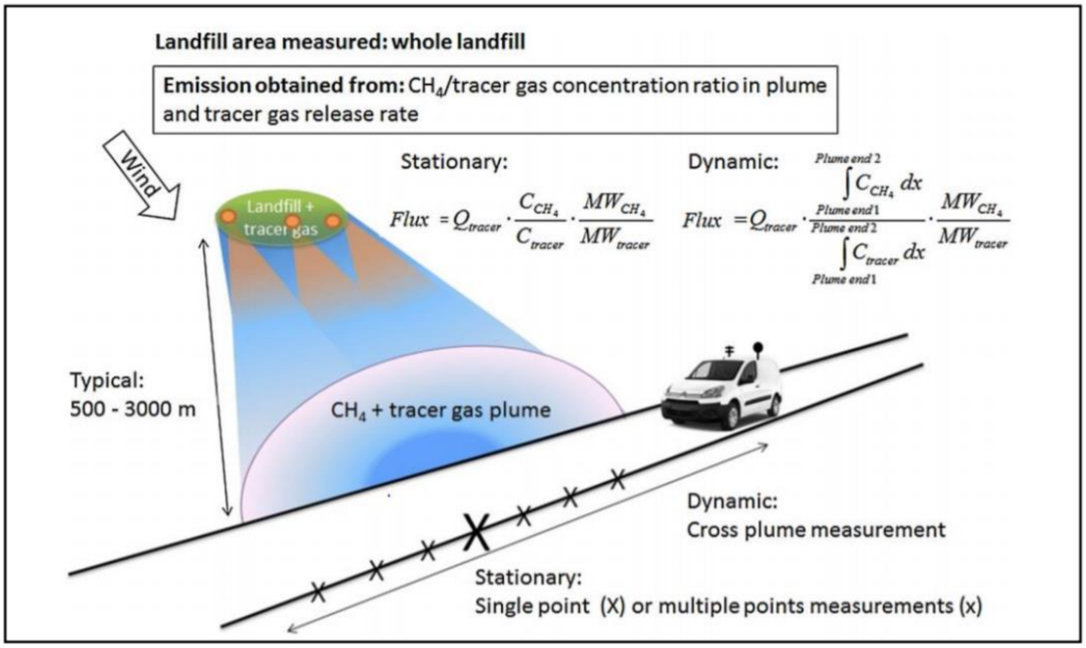
[71]

$$E_{gas} = Q_{tracer} \cdot \frac{\int_{Plume\ end\ 1}^{Plume\ end\ 2} C_{gas} dx}{\int_{Plume\ end\ 1}^{Plume\ end\ 2} C_{tracer} dx} \cdot \frac{MW_{gas}}{MW_{tracer}}$$

This process occurs downwind of the biogas plant, and is measured using a mobile high-analytical measurement instrumentation. [72]

[70] Mikel, Dennis & Merrill, Raymond & Colby, Jennifer & Footer, Tracey & Crawford, Philip & Alvarez-Aviles, Laura. (2011). EPA Handbook: Optical Remote Sensing for Measurement and Monitoring of Emissions Flux.
[71] Mønster, J., & Scheutz, C. (2015). Quantification of the methane emission from Masons landfill - Part II. Department of Environmental Engineering, Technical University of Denmark (DTU).
[72] Mønster et al., 2015

[73]



Mønster, J., Kjeldsen P., Scheutz C. 2018

Figure 7

The last off-site measurement method is called IDMM. It also uses an open path in order to measure an integrated emission concentration. However, the difference is that it takes the difference of two concentrations (measured from two different sides of the biogas plant simultaneously). This is done with an open path tunable diode laser absorption spectrometer (OP-TDLAS). These two concentrations are used together with pressure senor, temperature sensors and an ultrasonic anemometer to obtain wind direction and speed allow are needed to gain final readings.[74]

[73] Vechi, N. T., Scheutz, C., & Delre, A. (2020, May 6). *Assessment of methane emissions from Danish livestock production practices using the tracer gas dispersion method*. Speech presented at EGU2020: Sharing Geoscience Online 1. Retrieved from https://presentations.copernicus.org/EGU2020/EGU2020-20405_presentation.pdf.

[74] Hrad, M., Piringer, M., & Huber-Humer, M. (2015). Determining methane emissions from biogas plants – Operational and meteorological aspects. *Bioresource Technology, 191*, 234-243. doi:10.1016/j.biortech.2015.05.016

[75]

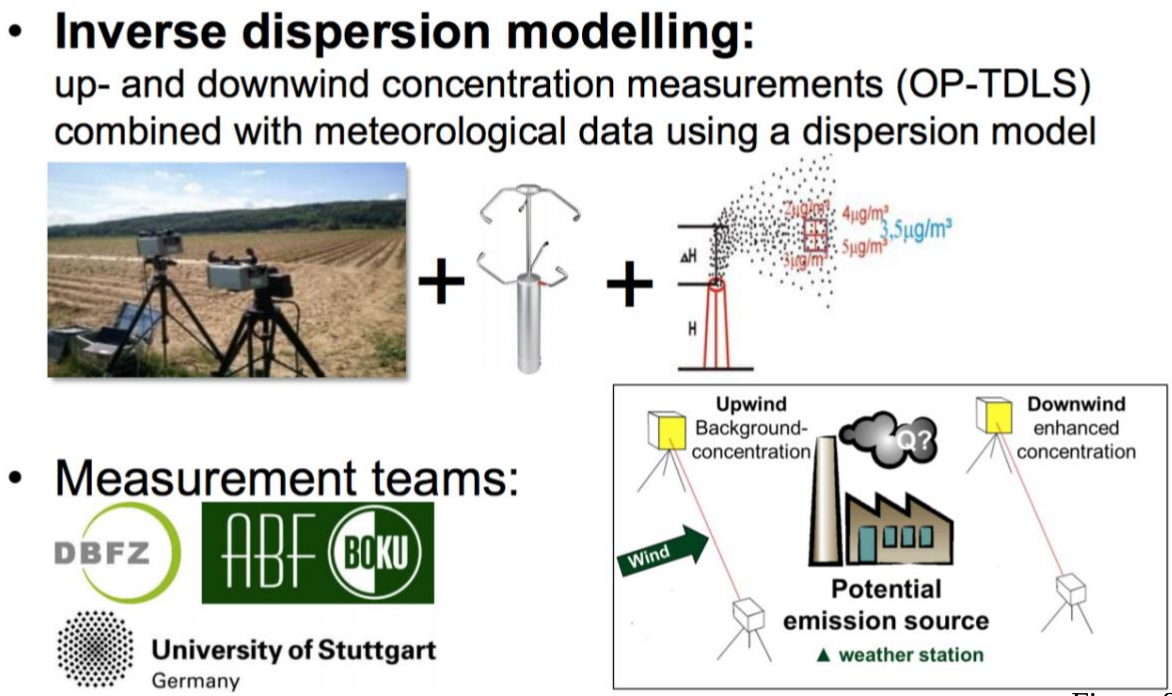


Figure 8

Met-Harmo recently complied an extensive list of the strengths and limitations of each measurement approach, which has been citied below. This is extremely helpful when trying to access the biogas plants individual specifications while meeting other constraints such a research budgets, locations, length of the project and amount of measurements needed. [76]

3.2 Instrumentation, Tools and Methods Used

During my time working with BOKU, our measurement campaign consisted of 7-8 biogas plants. They were stationed throughout Austria, with most requiring 1-2 days of measurements. Our team ranged from 2-4 people at any given time. The measurement campaign started officially in late fall due to some initial setbacks. When measuring emissions from biogas plants using the IDMM method it is important to consider factors such as the weather, wind, light intensity etc., that need to be accounted for. This measurement method is very dependent on

[75]Hrad, M. (2017). *European harmonization of methods to quantify methane emissions from biogas plants*. Speech presented at 5th CEBC 2017. Retrieved from https://nachhaltigwirtschaften.at/resources/iea_pdf/events/20170120_cebc/14_Hrad_CEBC.pdf?m=1484851858&.

[76] Clauß, Tina & Reinelt, Torsten & Vesenmaier, Angela & Reiser, Martin & Ottner, Reinhold & Huber-Humer, Marion & Flandorfer, Claudia & Stenzel, Sirma & Piringer, Martin & Yngvesson, Johan & Holmgren, Magnus Andreas & Fredenslund, Anders & Scheutz, Charlotte & Innocenti, Fabrizio & Hrad, Marlies & Liebetrau, Jan. (2019). Recommendations for reliable methane emission rate quantification at biogas plants.

weather conditions. This plus human factors (operation capacity of the plant, seasons, operator schedules, travel) lead to fluctuating travel plans. All pre-assessments, contact and visits were done before my arrival, as BOKU had already established relationships with the above biogas plant operators in question.

During most of the biogas plant site investigations a combination of on-site leakage detection approaches as well as the off-site IDMM measurement technique was used.

[77]

Measurement approach	Device	Manufacturer, type	Comment
On-site	IR camera	FLIR, GR 320	For leak search
On-site	Methane laser	CROWCON, LaserMethane mini Gen2	For leak search
On-site	Heated gas sample probe	M&C	For gas sampling (off-gas of cogeneration or biogas upgrading units)
On-site	Gas sample probe	M&C	For gas sampling (off-gas of cogeneration or biogas upgrading units)
On-site	Gas cooler	M&C	For gas sampling
On-site	Gas sampler	Sarstedt, GS312	For gas sampling
On-site	Blower	Elektor Air Systems GmbH, D 060	For open chamber method (leakage quantification)
On-site	Gas chromatograph equipped with a flame ionization detector	Agilent Technologies, Agilent 7890A	Third party analyses
Off-site	Open path tunable diode laser absorption spectrometer (OP-TDLS)	Boreal Laser Inc., GasFinder 2.0	
Off-site	3D ultrasonic anemometer	R.M. Young Company, Model 81000	

Figure 9

IDMM was chosen due to the availability of the needed equipment, overall expense, that it was a non-intrusive method to the plants normal operation and because we were able to determine emissions from the whole plant with limited data points. This method is usually conducted over a few days including the analysis and modeling phases. The path-integrated methane concentrations were measured up- and downwind of the plant using the OP-TDLS in combination with several distant reflectors. Meteorological data were collected using a portable 3D ultrasonic anemometer at a measuring frequency of 10 Hz and a height of 3 m above the soil surface.

3.3 Measurements

[77] Wechselberger, V. (n.d.). Retrieved March 29, 2020.

Depending on the emission source, different methods were applied in order to quantify on site methane emissions from individual sources. Due to the limited number of possible measurements the team made the decision to focus on major sources such as the gas utilization units and major leakages for on-site measurements. Gas sampled were collected discontinuously using evacuated glass vials (20 mL) and analyzed in the laboratory by a gas chromatograph equipped with a flame ionization detector/ Air flows were measured according to EN 15259:2007 (2007)[78] and ISO 16911-1 (2013)[79] using a hot wire anemometer.

For emissions from leakages released from the biogas-producing plant components (on-site) the following technique was used. First, a leakage survey was conducted at each plant. Biogas-bearing plant components which include digesters, biogas storages and piping were investigated with both an infrared (IR) camera and a portable methane laser. An IR camera can detect and localize difficult to find emission sources by visualizing biogas emitted from a source for the human eye. The discovered leakages were verified via the portable methane laser. Afterwards, based on the results of leakage survey, major sources were quantified by a dynamic chamber method. The chamber which consisted of a gas-tight foil as well as an in- and output, is able to contain the leakage. The output was connected to a blower and the exhaust air flow was measured over a time period of 30 minutes. In order to assess the influence of the blower (suction) on the emission, two different air velocity settings were applied for each leakage. Gas was collected through the in- and output flows and as such methane concentrations were determined. The equation for emission rate is:

$$E = Q\,\rho\,(C_{out} - C_{in})$$

where E is the emission mass flow (mg CH_4 h^{-1}), Q is the volume air flow (m_{Air}^3 h^{-1}) under normal conditions (0°C, 101325 Pa), ρ is the gas density of methane (mg mL^{-1}) and C_{out} and C_{in} are the exhaust and background methane concentrations (ppmv). For on-site emissions that were

[78] B. (2007). *Air Quality. Measurement of Stationary Source Emissions. Requirements for Measurement Sections and Sites and for the Measurement Objective, Plan and Report*. EN 15259 : 2007
[79] I. (2013). *Stationary source emissions — Manual and automatic determination of velocity and volume flow rate in ducts — Part 1: Manual reference method* [2020]. Retrieved from https://www.iso.org/standard/57947.html. ISO 16911-1:2013

produced from the off-gas released from the cogeneration unit, gas samples were taken using a heated gas sample probe. This process is called air extraction. Note that due to lack of measurement points, the off-gas volume flow was calculated on the basis of operational data. The equation for emission mass flow is:

$$E = Q\,\rho\,C$$

where E is the emission mass flow (mg CH_4 h^{-1}), Q is the volume air flow (m_{Air}^3 h^{-1}) under normal conditions (0°C, 101325 Pa), ρ is the gas density of methane (mg mL^{-1}) and C represents the exhaust concentration of the methane (ppmv).[80]

The determination for the emission rate for IDMM off-site data is done via the surface-specific methane emission rate, known as QCH4. It is calculated according to the equation below:

[81]

$$Q_{CH4,spec} = \frac{(C_{CH4} - C_{CH4,BG})}{(C/Q)_{sim}} \qquad \text{Equation 2}$$

$Q_{CH4,spec}$	Surface specific emission rate of methane in kg $h^{-1}m^{-2}$
C_{CH4}	Measured downwind concentration of methane in kg m^{-3}
$C_{CH4,BG}$	background concentration of methane in kg m^{-3}
$(C/Q)_{sim}$	Prediction of ratio of methane concentration at the sensor to the methane emission rate in h m^{-1}

To analyze off-site IDMM data, a backward Lagrangian stochastic (bLs) model[82] is needed. All models that take IDMM data this information in order be able to accurately determine the unknown source emission rate [83]:

80 Wechselberger, V. (n.d.). Retrieved March 29, 2020.
81 FLESCH, T. ; WILSON, J. ; HARPER, L. ; CRENNA, B.: Estimating gas emissions from a farm with an inverse-dispersion technique. In: Atmospheric Environment 39 (2005), Nr. 27, S. 4863–4874
82 (Flesch et al., 2004)
83 Clauß, Tina & Reinelt, Torsten & Vesenmaier, Angela & Reiser, Martin & Ottner, Reinhold & Huber-Humer, Marion & Flandorfer, Claudia & Stenzel, Sirma & Piringer, Martin & Yngvesson, Johan & Holmgren, Magnus Andreas & Fredenslund, Anders & Scheutz, Charlotte & Innocenti, Fabrizio & Hrad, Marlies & Liebetrau, Jan. (2019). Recommendations for reliable methane emission rate quantification at biogas plants.

1. gas concentrations (upwind and downwind) in either units of µg m-3 or mg m-3 (CCH4, BG and CCH4), (if measured in units of ppm or ppb conversion is needed)

2. meteorological data (this includes the wind direction, wind speed, wind statistics, friction velocity u*, and Obukhov length L, as well as the standard deviations δu1, δu2, and δu3, of the wind velocity components u1, u2, u3)

3. the surrounding terrains roughness height (z0)

4. source location and configuration (area, line, point or volume)

5. concentration sensors of the height and location (line-averaging or point)

6. Any additional software model-specific data processing and filtering changes

This model is suitable for any well-defined area sources, can estimate both point sources and area sources.[84] The software the team uses to implement bLs models is called Windtrax.[85] Windtrax is made to simulate short-range dispersion models and has been designed to serve as graphical interface for the bLS models. WindTrax's input data is prepared in a time series of 10-min average. For each interval, Windtrax calculates the emission rate by simulating 50,000 air parcels backward in time, starting from the measurement path. As such the sensors to emission rates simulated ratio of concentration is referred to as (C/Q)sim. It's calculated according to the equation below during the final stages:

$$\left(\frac{C}{Q}\right)_{sim} = \frac{1}{\mathrm{P_{sim}}} + \sum_{i=1}^{P_{sim}} \left(\frac{1}{N_{sim}} \sum \left| \frac{2}{u_3^0} \right| \right)$$

$(C/Q)_{sim}$	prediction of ratio of concentration at the sensor to the emission rate in s m^{-1}
P_{sim}	number of points along the measurement path
N_{sim}	the total number of gas particles released at the measurement site
$u_{3,0}$	vertical velocity at "touchdown" in m s^{-1}

84 Mcbain, M., & Desjardins, R. (2005). The evaluation of a backward Lagrangian stochastic (bLS) model to estimate greenhouse gas emissions from agricultural sources using a synthetic tracer source. *Agricultural and Forest Meteorology*, *135*(1-4), 61-72. doi:10.1016/j.agrformet.2005.10.003

85 Thunder Beach Scientific. (n.d.). Retrieved from http://thunderbeachscientific.com/.Windtrax Publisher

3.4 Analysis

Due to confidentially agreements, I am unable to show you what the specific data looks like from the visited biogas plants during the measurement campaign. Instead the images below are ones that replicate the technique based upon exercises conducted that very closely mimic the raw data. These exercises were created by the VU Emission Monitoring of Biological Processes in Waste Management.[86] The goal is to use the information normally obtained by off-site measurement methods in the field to calculated the R value. The R value refers to the modeled emission rate or the actual value for the complete time series of CH_4 and CO_2. As such, both R values should equal 1.

The given information for the first part of the exercise is as follows:

- The aerial view of the biogas plant
- The CH_4 and CO_3 concentrations measurements of the OP-TDLAS laser
- The meteorological measurement data
- The Output file 1 which is initially empty
- The coordinates of the source
- The distance from the top right corner of the aerial photo (red point 3) to the lower right corner (point 4) is 700 m and 1.3 m pixel
- Laser / reflector location in the Line Concentration Sensor 1, the x/y coordinates are Start (761 / -262), end (707 / -639), measuring height: 2 m
- Anemometer location (instrument tower) (x/y) = (566 / -206)
- Surface roughness (z0) = 15 cm
- Target value for the emission rates (Q) = 28.36 kg CH_4 /h; 6,303 kg CO_2 / h

The additional information needed for second part of the exercise are:

- CH_4 and CO_2 concertation measurements of the OP-TDLS lasers
- Meteorological measurement data for 2
- Output File 2 which is initially empty

86 Exercise: Determination of CH_4 and CO_2 emission rates of a biogas plant using the Lagrange dispersion model "Windtrax" Retrived through VU Emission Monitoring of Biological Processes in Waste Management (813.344), Univeristy of Natural Resources and Life Sciences (BOKU). file:///Users/Alex/Downloads/Anleitung_Modellierung.pdf

Exercise A

Column	Legend:												
	1:00	Input	Data	File	1:00	Column	1						
	2:00	Lime	Area	Source:	CH4	Emission	Rate	(g/m^2/min.)					
	3:00	Lime	Area	Source:	CH4	Standard	Deviation						
	4:00	Lime	Area	Source:	CH4	Area-integrated	Emission	Rate	(g/min.)				
	5:00	Lime	Area	Source:	CO2	Emission	Rate	(g/m^2/min.)					
	6:00	Lime	Area	Source:	CO2	Standard	Deviation						
	7:00	Lime	Area	Source:	CO2	Area-integrated	Emission	Rate	(g/min.)				
	8:00	Lime	Area	Source:	Area	(m^2)							
	9:00	Lime	Area	Source:	Fraction	covered	by	touchdowns					
Time	**CH4 emission rate (g/m^2/h**	**CH4 standard deviation**	**CH4 area integrated ER (g/min)**	**CO2 emission rate (g/m^2/h**	**CO2 standard deviation**	**CO2 area integrated ER (g/min)**	**Area (m^2)**	**Fraction covered by touchdowns**		**CH4 area integrated ER (kg/h)**	**CO2 area integrated ER (kg/h)**	**CH4 Ist/Soll**	**CO2 Ist/Soll**
11:40	2.00E-02	6.89E-03	525.8	4.456	1.532	116972	26248	0.8876		31.55	7018.32	1.11	1.12
11:50	2.00E-02	6.67E-03	524.8	4.447	1.483	116713	26248	0.8819		31.49	7002.78	1.11	1.11
12:00	2.03E-02	7.28E-03	531.9	4.495	1.615	117995	26248	0.8683		31.91	7079.70	1.13	1.13
12:10	1.98E-02	7.20E-03	519	4.4	1.603	115497	26248	0.7954		31.14	6929.82	1.10	1.10
12:20	2.00E-02	7.04E-03	525.7	4.439	1.56	116505	26248	0.8331		31.54	6990.30	1.11	1.11
12:30	1.54E-02	3.21E-03	405.4	3.444	0.7154	90388	26248	0.7794		24.32	5423.28	0.86	0.86
12:40	1.54E-02	3.42E-03	403.6	3.406	0.758	89412	26248	0.8509		24.22	5364.72	0.85	0.85
12:50	1.51E-02	3.46E-03	396.2	3.355	0.7695	88057	26248	0.8893		23.77	5283.42	0.84	0.84
13:00	1.81E-02	3.62E-03	473.9	4.007	0.8028	105181	26248	0.8778		28.43	6310.86	1.00	1.00
13:10	1.78E-02	3.34E-03	467.5	3.951	0.7409	103708	26248	0.8902		28.05	6222.48	0.99	0.99
13:20	1.81E-02	3.75E-03	474.6	4.01	0.8314	105259	26248	0.8755		28.48	6315.54	1.00	1.00
13:30	1.68E-02	2.54E-03	442.1	3.748	0.5641	98391	26248	0.7174		26.53	5903.46	0.94	0.94
13:40	1.68E-02	2.47E-03	440.4	3.74	0.55	98170	26248	0.7443		26.42	5890.20	0.93	0.94
									R	**28.30**	**6287.30**	**1.00**	**1.00**
									Soll	28.36	6303		

Figure 10

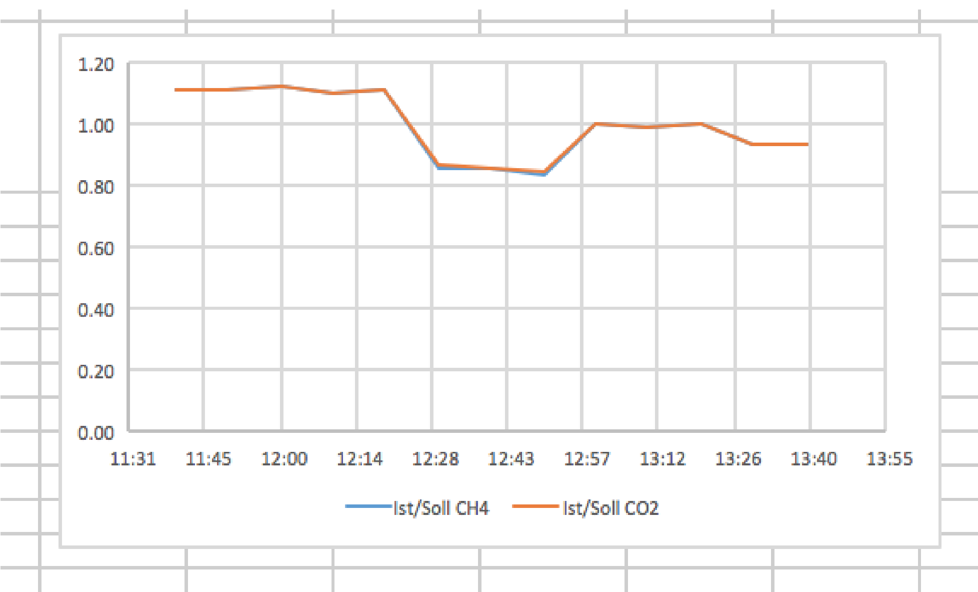


Figure 11

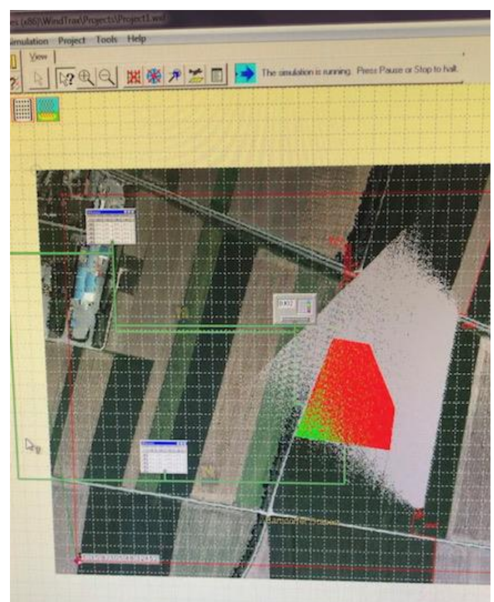


Figure 12

Exercise B

Column	Legend:												
	1:00	Input	Data	File	1:00	Column	1						
	2:00	Lime	Area	Source:	CH4	Emission	Rate	(g/m^2/min.)					
	3:00	Lime	Area	Source:	CH4	Standard	Deviation						
	4:00	Lime	Area	Source:	CH4	Area-integrated	Emission	Rate	(g/min.)				
	5:00	Lime	Area	Source:	CO2	Emission	Rate	(g/m^2/min.)					
	6:00	Lime	Area	Source:	CO2	Standard	Deviation						
	7:00	Lime	Area	Source:	CO2	Area-integrated	Emission	Rate	(g/min.)				
	8:00	Lime	Area	Source:	Area	(m^2)							
	9:00	Lime	Area	Source:	Fraction	covered	by	touchdowns					
Time	**CH4 emission rate (g/m^2/h**	**CH4 standard deviation**	**CH4 area integrated ER (g/min)**	**CO2 emission rate (g/m^2/h**	**CO2 standard deviation**	**CO2 area integrated ER (g/min)**	**Area (m^2)**	**Fraction covered by touchdowns**		**CH4 area integrated ER (kg/h)**	**CO2 area integrated ER (kg/h)**	**CH4 Ist/Soll**	**CO2 Ist/Soll**
11:40	1.38E-02	5.05E-03	363.1	3.108	1.135	81578	26248	0.1902		21.79	4894.68	0.77	0.85
11:50	3.89E-02	1.25E-02	1022	3.088	0.9879	81060	26248	0.2781		61.32	4863.60	2.16	0.85
12:00	1.55E-02	4.68E-03	407.4	3.435	1.035	90167	26248	0.2911		24.44	5410.02	0.86	0.94
12:10	1.66E-02	5.70E-03	434.9	3.665	1.26	96199	26248	0.3656		26.09	5771.94	0.92	1.01
12:20	5.00E-02	1.83E-02	1.31E+03	2.841	1.038	74560	26248	0.1902		78.84	4473.60	2.78	0.78
12:30	1.36E-02	5.71E-03	357.2	3.098	1.301	81321	26248	9.59E-(2		21.43	4879.26	0.76	0.85
12:40	1.79E-02	9.77E-03	469.7	3.988	2.177	104684	26248	0.2934		28.18	6281.04	0.99	1.10
12:50	1.40E-02	8.62E-03	366.9	3.188	1.967	83681	26248	0.1364		22.01	5020.86	0.78	0.88
13:00	2.26E-03	1.45E-03	59.23	5.665	3.634	148708	26248	0.2693		3.55	8922.48	0.13	1.56
13:10	2.61E-02	1.73E-02	686	5.806	3.832	152397	26248	0.248		41.16	9143.82	1.45	1.59
13:20	5.87E-03	2.89E-03	154.1	4.215	2.075	110636	26248	0.4095		9.25	6638.16	0.33	1.16
13:30	1.48E-02	1.91E-02	389.1	3.3	4.25	86611	26248	9.33E-02		23.35	5196.66	0.82	0.91
13:40	4.94E-02	2.06E-02	1.30E+03	1.95	0.812	51178	26248	0.1883		77.76	3070.68	2.74	0.54
									R	**33.78**	**5735.91**	**1.19**	**1.00**
									Soll	28.36	6303		

Figure 13

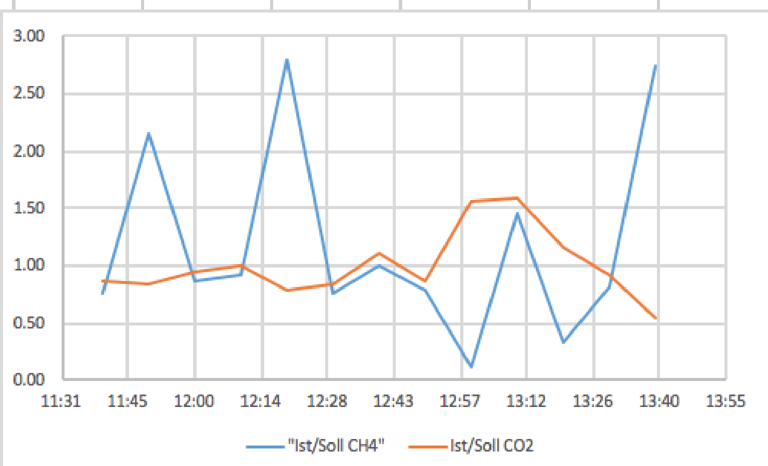


Figure 14

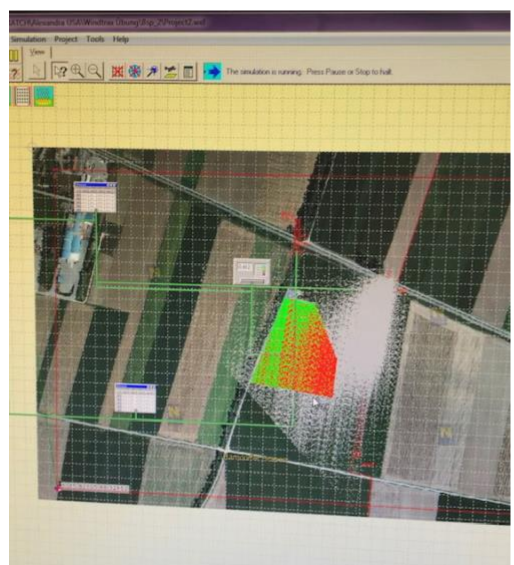


Figure 15

3.5 Conclusions

As you can see by figure 12 and 15, the points along the measurement path (P), the gas particles released at the measurement site (N), as well as the modelled vertical velocity at the "touchdown" are combined to show how the particle touch-down the ground within the emission source area.[87]

Refer to the modeled emission rates for methane (CH4) and carbon dioxide (CO2) (which are representative of the R values) in exercise A and B which have been calculated and displayed in both Figure 1 and Figure 4. While exercise A is a possible real life scenario that could occurred and is correctly calculated, part B is not due to the impossible R value for the methane emission time series (CH4). As such, this information is either unreliable and cannot be used or an error was made, either by the user or by Windtrax. If the secondary case applies, it is important to ensure all conversion have been done correctly, as stated by the Windtrax introductory manual or by contacting the publisher.

4.0 In-Lab Experimentation to reduce flushing times

4.1 Previous Studies & Aim

The data instrumentation part of this project was conducted in part to gain a stronger understanding of in lab emissions testing, as well as to get more familiar with the data analyzation process in Microsoft Excel and Windtrax. Secondly, it was also implemented as a continuation of a previous study, conducted in the summer of 2019. Using the same equipment, researchers optimized and developed an air sampling method to simulate an open path for the cavity method OA-ICOS N2O/CO analyzer. While most inverse dispersion modelling methods (IDMM) are based on concentration measurements in the up and downwind area of an emission source, meteorological data and an inverse dispersion model, point measurements can also be performed the same way. However, the validity of point measurements is more difficult to obtain (see filter criteria in Clauß et al. (2019)).[88] For that, two different air sampling setups were tested

87 Flesch, T. & Wilson, J. & Harper, Lowry & Crenna, B. & Sharpe, R.. (2004). Deducing Ground-to-Air Emissions from Observed Trace Gas Concentrations: A Field Trial. Journal of Applied Meteorology - J APPL METEOROL. 43. 487-502. 10.1175/1520-0450(2004)043<0487:DGEFOT>2.0.CO;2.
88 Clauß, T.; Reinelt, T.; Liebetrau, J.; Vesenmaier, A.; Reiser, M.; Flandorfer, C.; Stenzel, S.; Piringer, M.;

performing preliminary tests in the laboratory. The results of the study found one sampling setup to be far superior than the other, due to its branched inlet system. This system allows for the simultaneous measurement of 4 measurement points.

[89]

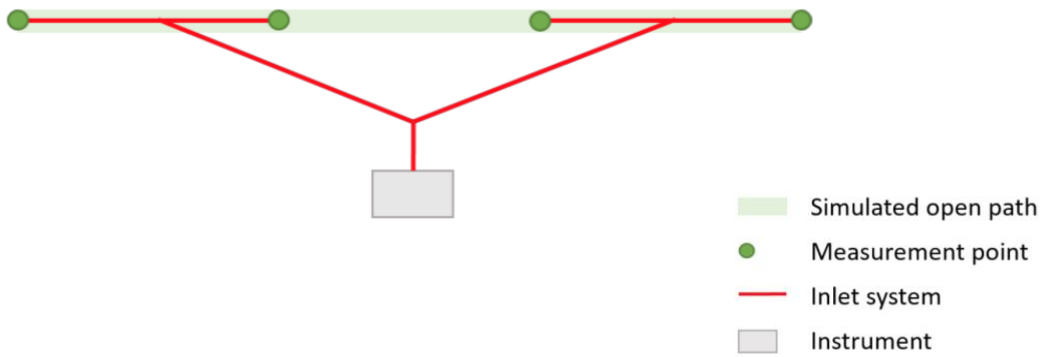


Figure 16

Based upon the results of this previous study, the current experiment methodology was created. This time we were tasked if seeing if concentration changes of N2O emission would affect the flushing. The goal was to see if the flushing time would reduce from 6-10 minutes to less than 5 depending upon variables such as the concentration.

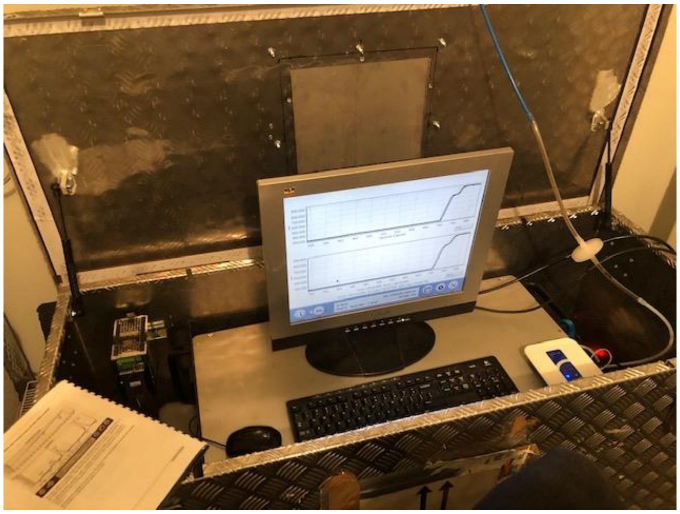
4.2 Instrumentation & Materials

The OA-ICOS LGR N2O/CO analyzer is a device that continuously and simultaneously measures ambient levels of nitrous oxide and carbon monoxide in real time. It also is able to measure water vapor within the air, which prevents the need for further empirical corrections that is needed to report N2O and CO on a dry moil basis. This is extremely useful, as it allows data to be recorded and analyzed easily. The device is known throughout the industry as a reliable measurement instrument, that reports over a wide range of temperature, without cross-sensitivity and up to concentrations 20 times higher than typical ambient air levels. It can be used both for

Fredenslund, A. M.; Scheutz, C.; Hrad, M.; Ottner, R.; Huber-Humer, M.; Innocenti, F.; Holmgren, M.; Yngvesson, J. (2019): Recommendations for reliable methane emission rate quantification at biogas plants. DBFZ-Report No. 33. Leipzig, DBFZ

[89] Wechselberger, Viktoria, and Florian Mouillard. *SIMULATION OF AN OPEN-PATH FOR THE INVERSE DISPERSION MODELLING METHOD (IDMM) USING AN OA-ICOS INSTRUMENT - PRLELIMINARY TESTS.* 2019, file/download/2019-11-28_N2O_Simulation-open-path_preliminary-tests.

in-lab experimentation as well as field studies. [90]

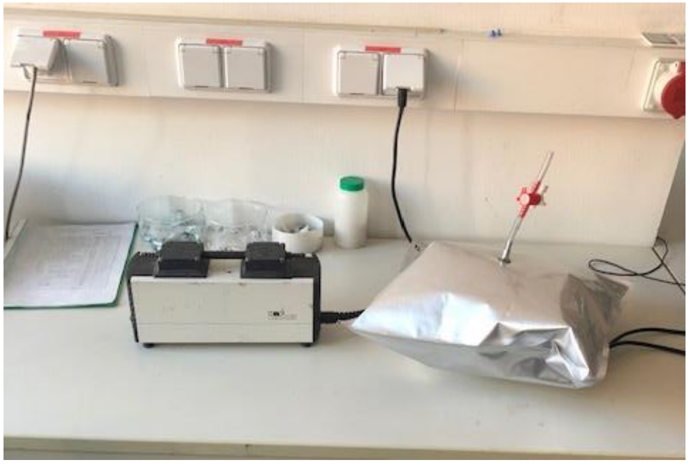


4.3 Methodology

Like the previous studies, the samplings and instrument were connected by a 60 m long open path line. Blue PA tubing which measured an 6mm outer diameter and 4 mm inner diameter were used. The instrument itself was operated within a temperature controlled space at 22 °C at all times. The same four gas bags were used during this experimental process, which were labeled and placed in the same location corresponding to their labels throughout the entire experiment. Gas bags were filled with either 6 liters of ambient air or N2O gas from a reference gas bottle (1000 ppb ± 5%) using the Ritter Bochum-Langendreer pump depending on the trial.[91] After the measurement period was finished, any remaining volumes were measured by a RITTER gas meter to assess if the suction flow was the same at each measurement point. Due to the long standing length of the experimentation, remaining volume in the gas bags were 0.

90 "N2O/CO Analyzer (Nitrous Oxide, Carbon Monoxide)." *Los Gatos Research - N2O/CO Analyzer (Nitrous Oxide, Carbon Monoxide)*, www.lgrinc.com/analyzers/overview.php?prodid=20.

91 Wechselberger, Viktoria, and Florian Mouillard. *SIMULATION OF AN OPEN-PATH FOR THE INVERSE DISPERSION MODELLING METHOD (IDMM) USING AN OA-ICOS INSTRUMENT - PRLELIMINARY TESTS.* 2019, file/download/2019-11-28_N2O_Simulation-open-path_preliminary-tests .

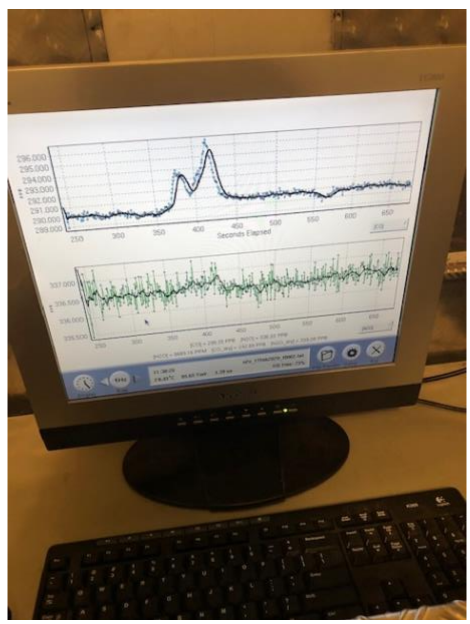


Pump used to remove either ambient air or N2O gas from

Ritter Bochum-Langendreer pump

N2O Reference gas canister

Branched inlet with gas bag set up outside of the temperature controlled room



Real time readings from the LGR N2O/CO device taken in the temperature controlled room

4.4 Experimental Methods (parameters, measurement intervals)

For this experiment there were a total of planned 4 measurements, which each measurement being performed three times for data accuracy. The first two measurements were performed in lab, while the final two were scheduled to be conducted in the field. However, due to the effects of COVID-19, only the were two measurements were able to be conducted.

During measurement 1, 4 gas bags were filled with 6 liters of reference gas and connected to the measurement points. For measurement 2, two of the gas bags were filled with 6 liters of reference gas (bag 1 and 2) and ambient air (1000 ppb ± 5%) (bag 3 and 4), respectively. After the device went through its initial warm up period as well as calibration, the filled gas bags were measured for a period of 20 minutes and then ambient air was provided to the instrument for another 20-minute period. These consecutive 20 minute periods continued until the gas bags emptied. A more detailed overview of the tests and their trials has been listed below:

	Date	Start Time	End Time	Room Temp	Notes
Test 1; run 1	Feb 28th	10:57	15:08	22-24 °C	File 0-3;
Test 1; run 2	March 4th	10:14	15:26	22-24 °C	File 0-3
Test 1; run 3	March 5th	10:04	17:10	22-24 °C	File 0-2
Test 2; run 1	March 6th	9:18	14:42	22-24 °C	File 0-2; TO*
Test 2; run 2	March 9th	10:16	17:10	22-24 °C	File 0-2
Test 2; run 3	March 13th	12:02	17:21	22-24 °C	File 0-1; TO*

*Technical issue occurred for a slight time frame

Like the previous studies, tests such as , assessment of suction behavior and flushing time calculations were based on tests performed by Lebegue et al (2016).[92]

4.5 Data Retrieval & Analysis

Data retrieval was a very simple process, as the OA-ICOS LGR N2O/CO analyzer has a built internal computer that stores the data on its internal hard drive until it's ready to be accessed. It can also be remotely accessed via the internet provided you set up a connection beforehand. This connection is secure and password protected. A secure external jump drive was used to transfer data from the analyzer to a PC workstation for further analyzation. The initial data analysis was done via Microsoft Excel, which converted the original text files into spreadsheet form in order to properly organize and format the raw data. Next, standard

92 Lebegue, B.; Schmidt, M.; Ramonet, M.; Wastine, B.; Kwok, C. Y.; Laurent, O.; Belviso, S.; Guemri, A.; Philippon, C.; Smith, J.; Conil, S. (2016): Comparison of nitrous oxide (N2O) analyzers for high-precision measurements of atmospheric mole fractions. Atmospheric Measurement Techniques 9: 1221-1238.

deviations of the averaged data (which consisted of the last 5 minutes of each trial) of the continuous measurement were calculated.

4.6 Results

	Measurement	Final Value (ppm)	Cell temperature ©
Feb 28th	1a	1.01	22-24
	1b	0.998	22-24
	1c	1.01	22-24
	1d	1	22-24
	1e	0.992	22-24
Mean		**1.002**	
Std		**0.007874008**	
March 4th	2a	1.01	22-24
	2b	0.999	22-24
	2c	0.995	22-24
	2d	0.75	22-24
	2e	1.01	22-24
Mean		**0.9528**	
STD		**0.113563639**	
March 5th	3a	1.01	22-24
	3b	1.01	22-24
	3c	1.01	22-24
	3d	1.01	22-24
	3e	1.01	22-24
Mean		**1.01**	
STD		**0**	
March 6th	4a	1.01	22-24
	4b	1.01	22-24
	4c	1.01	22-24
	4d	1.01	22-24
	4e	1.01	22-24
Mean		**1.01**	
STD		**0**	
March 9th	5a	0.989	22-24
	5b	0.693	22-24
	5c	0.688	22-24
	5d	0.694	22-24
	5e	0.689	22-24
Mean		**0.7506**	
STD		**0.133294036**	
March 13th	6a	0.708	22-24
	6b	0.708	22-24
	6c	0.708	22-24
	6d	0.698	22-24
	6e	0.709	22-24
Mean		**0.7062**	
STD		**0.004604346**	
Total Mean	0.905266667		
Total STD	0.043222671		
Total Mean (ppb)	**905.2666667**		
Total STD (ppb)	**43.22267134**		

the short term repeatability assessment test results

The N2O reference gas filled bag (1000 ppb ± 5%) experiments were conducted 30, with 6 total trial runs. Each measurement within these runs lasted for 20 minutes, alternating with ambient air. During the last 5 minutes of each N2O analysis, a final value was accessed and calculated. Additionally, the repeatability is expressed as the standard deviation (1σ) of these runs as previously done in other literature.

4.7 Conclusion

The stabilization time would have been calculated over the last 5 min of the 20-minute measurement at ±2σ ppb of the final value. The stabilization time refers to the average over both measurements (N2O reference gas and ambient air). The stabilization time is needed in order to understand how long it takes for the device to reach the final value. This also occurs with the flushing time experiments as well, which is calculated when using a branched inlet system. The flushing time refers to the assessment of the suction strength at the various measurement points. It would have been the final test conducted for the above experiments. Had this test occurred, the gas bags would have been filled with half ambient air and half reference gas (1000 ppb ± 5%). After a period of time, the user would see how much remaining volume was left in the gas bags after the measurements were complete. Then a comparison of the actual and target N2O concentration value would be drawn up.[93] As I had just started this section of my research in late February, I had only conducted early, preliminary tests. At the time, I was testing various timing methods and gas bags, as well as learning through experimentation how to operate the LGR N2O / CO device. As such, there are some data reliability issues in these initial experiments and they would have been redone. However, since my experimentation was cut 3 months short due to COVID-19 this unfortunately was not possible.

After these would have been completed, complimentary field tests would have occurred during April. Then the results from both the laboratory and field tests would have been compared to the tests done with a partner team in Stuttgart, Germany in May. Both the original data and the Windtrax analyzation would have been accessed to see if there were any major differences in variables, and impact on the flushing time of the device. Additionally, other variables besides N2O concentration levels were discussed being tested to see if they could impact the devices flushing time. This includes but is not limited to temperature, amount of liters, open path lengths etc.,

In conclusion, the preliminary results of the above experimentation show varying errors. For example, even though all trial runs used the same amount of liters of gas within each bag, some ambient air trials ran longer than 30 minutes due to constraints and other responsibilities that needed to be attended to by the user.

93 Wechselberger, Viktoria, and Florian Mouillard. *SIMULATION OF AN OPEN-PATH FOR THE INVERSE DISPERSION MODELLING METHOD (IDMM) USING AN OA-ICOS INSTRUMENT - PRLELIMINARY TESTS.* 2019, file/download/2019-11-28_N2O_Simulation-open-path_preliminary-tests .

4.8 Future Studies

If funding allows and the effects of COVID-19 dissipate, future studies include redoing the laboratory tests. The associated field studies which would follow the same methodology as the laboratory ones would also be conducted. Secondly, the LGR N2O/CO device had some technical issues that occurred and had to be resolved during the lab testing period, which could have possibly impacted some data points. One of the gas bags was also loosened during the March 6th and 9th trials. As such, a rerun this initial experiment should be conducted to ensure that those technical issues did not affect the emission measurements. This should also happen due to time lapses in the experimental process. The 20-minute ambient air measurements caused some inconsistency in reporting for the overall time process. While the data was not effected as the ambient air levels stayed stable even past the 20-minute time frame, it still would have been redone for clarity sakes. Lastly, testing other interesting variables should also be explored, such as the open path lengths, temperature and other gas bag sets up as potential influencers on the reduction of the flushing time.

5.0 Recommendations for the American Biogas Community

5.1 Detailed Recommendations

Based upon this 7-month experience working heavily as a visiting member of the biogas EvEmBi project group, in both the field and lab, the following recommendations have been made for the American biogas community as a whole.

The first recommendation would be to start a similar, interdisciplinary voluntary group for a project such as EvEmBi in the United States, with the goal to use on-site and off-site measurement methods to gather data from the current 2,200 biogas producing plants in the US. All plants should be encompassed including smaller facilities. This should be possible due to current data and information regarding plant locations, sizes and other details. It is recommended that the team include industry professionals, professors, primary investigators (PI's), as well as national and university labs. Key funding partners could include the US Environmental Protection Agency (EPA), the US Department of Agriculture (USDA) or US Department of Energy (DOE). Other partners could include the American Biogas Council and the World Biogas Association which have goals rooted in reducing climate change and improving both economic and sustainable development. The group should include experts in greenhouse gases, air quality, air monitoring and the biogas field as a whole. Lastly, a small internship program should be attached to it to get American college students involved in the process as well. It is recommended that the voluntary group measure and analyze with one method first in order to more easily control the data outputs and analysis.

The second recommendation would be that professional organizations such as the American Society of Agricultural and Biological Engineers (ASABE) create training courses to teach people how to use and understand Windtrax. While quite popular and well known in the European biogas field, few Americans have produced technical reports or published papers that mention working with the software. There are alternatives to Windtrax that can also be taught in its stead such as LASAT or NAME.[94] However Windtrax is recommended due to its ease of use, popularity and that it is available for users at no cost.

The third recommendation is to continue to advocate on capitol hill for policy support, that will assist biogas plant operators with fees or provide other benefits that could improve biogas as a marketable source of alternative energy within the U.S. economy. Additionally, continuing to provide current biogas industry and university labs with research money, so they can start internship programs, research experiences for undergraduates (REU's) and shadowing programs. This will facilitate interest in the biogas industry for future generations, especially for those that are unable to get into the industry without this initial financial support and experience.

The final recommendation is to involve and educate the U.S. public about biogas and the bioenergy field through museums, plant tours and other initiatives. One way Austria, in particular Vienna ingrains waste to energy practices such as biogas within citizen's daily life is through the beautification and education of plants. One example of this is Spittelau, the main plant that performs waste-to-energy functions in the city. In the 1970's conflicts regarding the safety and cleanliness of the plant arose, and the people of Vienna began wanting to shut the whole plant down. In order to prevent this from happening the current mayor at the time, Helmut

[94]Holmgren, M. A., Nørregaard Hansen, M., Reinelt, T., Westerkamp, T., Jørgensen, L., Scheutz, C., & Delre, A. (2015). Measurements of methane emissions from biogas production – Data collection and comparison of measurement methods: Energiforsk report 2015:158. Energiforsk AB. http://www.energiforsk.se/SiteAssets/rapporter/2015_158.pdf, page 17.

Zilk asked famous artist Freidensreich Hundertwasser to redesign the plant. [95] The results led to a beautiful, iconic landmark which adds to the tourism trade, and a renewed sense of confidence in alternative energy by the Viennese.[96] Today, tours of Spittelau as well as its sisters plants Flötzersteig, Simmeringer Haide and Pfaffenau are offered to students, professionals and the general public at no cost. Spittelau also has a children's museum on site which highlights how renewable energy fuels daily life using fun, informative games, displays and activities.[97] If major U.S. cities could encourage similar museums, initiatives and field trips for children, this could make a huge difference of people's opinions of biogas in the future while simultaneously educating future generations about energy uses. The beautification of plants could also add to local tourist trades, especially in this age of social media blogging, branding and partnerships.[98]

6.0 Final Word

I really enjoyed my time in Vienna, Austria and feel that this experience has really changed my life. Even though the global health crisis caused my grant to end prematurely, I am glad that I was still able to obtain some data and learn a lot about conducting measurement campaigns as well as the biogas industry as a whole. I am hoping that the work that I've done over the past six months will be of some interest to the American Biogas Community and my affiliation as well. I am proud of having completed work that will be useful to both counterparts. Due to this experience, I have a better understanding of the process behind creating a quantification system. Being exposed to the environmental compliance and monitoring side as well as optimizing the instrumentation used to gather that data in the first place simultaneously was incredibly beneficial. Thank you again to everyone who helped to contribute to making my time abroad worthwhile.

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