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A Techno-Economic Model of Continuous Versus Intermittent Methane Monitoring Programs

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Abstract- Methane emissions from industrial and natural sources pose significant environmental challenges due to their high global warming potential. Effective monitoring is essential for timely leak detection and mitigation, yet monitoring programs vary widely in their technical approaches and economic implications. This paper presents a comprehensive techno-economic model that systematically compares continuous and intermittent methane monitoring strategies. The model integrates key technical parameters, such as detection sensitivity, monitoring frequency, and response time, with economic factors including capital expenditures, operational costs, and potential savings from emission reductions. Results highlight critical trade-offs between upfront investments and detection effectiveness, demonstrating that continuous monitoring provides superior leak detection and environmental benefits but at higher costs, whereas intermittent monitoring offers lower initial expenses with potential delays in leak identification. The model's flexibility allows adaptation across diverse operational contexts, supporting tailored decision-making for methane mitigation investments. By bridging technical and economic considerations, this framework informs both industry stakeholders and policymakers on optimizing methane monitoring programs to balance environmental goals with financial feasibility. Future research directions include incorporating dynamic emission profiles and emerging technologies to enhance model precision and applicability.

Index Terms : Methane monitoring, Techno-economic model, Continuous monitoring, Intermittent monitoring, Emission detection, Cost-effectiveness

I. INTRODUCTION

1.1 Background

Methane is a potent greenhouse gas with a global warming potential significantly higher than carbon dioxide over a 20-year horizon. It is primarily released from natural gas production, agriculture, landfills, and other anthropogenic activities (Howarth, 2015, Balcombe et al., 2018). Because of its high heat-trapping capacity, mitigating methane emissions is critical for climate change strategies and achieving near-term environmental targets (Dean et al., 2018). However, methane emissions are often intermittent and spatially heterogeneous, making detection and quantification challenging (McKercher et al., 2017). Traditional methods rely heavily on periodic manual inspections and intermittent measurements, which may miss episodic leaks and underestimate emissions (Gatland et al., 2014, Balcombe et al., 2017).

The rise of advanced monitoring technologies offers new opportunities for more comprehensive methane detection. Continuous monitoring programs employ fixed or mobile sensors providing real-time data, enabling rapid leak identification and repair (Gbabo et al.). In contrast, intermittent monitoring uses periodic sampling or surveys, which are less resource-intensive but may delay detection (Mchale et al., 2019, Knobelspies et al., 2016). This creates a need to rigorously evaluate these approaches not only on technical merits but also from an economic perspective to guide decision-making in industry and policy (Molnár, 2018, Reay et al., 2010).

Developing a techno-economic model that compares continuous and intermittent methane monitoring can fill this knowledge gap (Alkadi et al., 2019, Siebenaler et al., 2016). Such a model helps stakeholders understand the trade-offs between cost, detection performance, and operational feasibility, facilitating more informed investment and regulatory strategies in methane mitigation efforts (Whiting and Chanton, 2001).

1.2 Importance of Methane Monitoring

Effective methane monitoring plays a vital role in environmental management and regulatory compliance. Methane emissions contribute significantly to atmospheric greenhouse gas concentrations and directly impact air quality (Majumdar et al., 2006). Monitoring programs provide critical data needed for emission inventories, helping quantify sources and prioritize mitigation efforts. The ability to detect leaks early is essential for minimizing emission volumes and reducing the overall climate impact. (Ogunnowo, Okuh et al., Okuh et al.)

Beyond environmental benefits, methane monitoring has economic significance for operators. Unchecked leaks represent a loss of valuable product and potential regulatory penalties. Continuous monitoring enables proactive maintenance, reduces leak duration, and thus limits financial losses. Furthermore, regulatory frameworks worldwide are increasingly mandating stricter methane controls, making reliable monitoring an operational imperative (Gbabo et al.).
Given the variability in monitoring approaches, understanding the effectiveness and costs associated with each method is essential. This ensures that methane mitigation investments are optimized, balancing financial constraints with environmental responsibilities. Consequently, robust methane monitoring supports not only sustainability goals but also operational efficiency and regulatory adherence (Howarth et al., 2012).

1.3 Objectives

This paper aims to develop a comprehensive techno-economic model to compare continuous and intermittent methane monitoring programs. The primary objective is to quantify the cost-effectiveness of each approach by integrating technical performance metrics with economic considerations. This includes evaluating detection capabilities, operational costs, and potential financial savings from avoided emissions.

The model advances prior research by systematically incorporating key parameters influencing monitoring outcomes, such as detection frequency, sensor accuracy, and response times, alongside cost drivers like installation, maintenance, and data management. Unlike many existing studies focusing solely on technical or economic aspects, this integrated framework provides a balanced perspective relevant to both operators and policymakers. By offering a clear comparison of monitoring strategies, the study contributes to the field by informing decision-making on methane mitigation investments. It highlights trade-offs and practical considerations that influence monitoring program design, ultimately supporting efforts to reduce methane emissions more efficiently and effectively.

II. LITERATURE REVIEW

2.1 Methane Emission Monitoring Techniques

Methane emission monitoring techniques have evolved significantly, driven by the need for accurate and timely detection to mitigate environmental impacts. Traditional methods include manual inspections using handheld detectors and periodic surveys conducted by aircraft or drones equipped with optical gas imaging cameras (Wen et al., 2018). These intermittent approaches provide snapshots of emission levels but can miss transient leaks or those occurring between inspection intervals. Consequently, they may underestimate total emissions and delay leak repair (Balafoutis et al., 2017, Golston et al., 2018).

In response, continuous monitoring technologies have gained prominence. These systems employ fixed sensors deployed at strategic locations, providing near real-time data on methane concentrations. Advances in sensor technology, including laser-based spectroscopy and low-cost electrochemical sensors, have improved sensitivity and affordability. Continuous monitoring allows operators to detect leaks promptly, reducing emission duration and enabling rapid response. Additionally, networked sensor arrays facilitate spatial localization of leaks, improving repair efficiency (Ventrella and MacCarty, 2019, Davies, 2012).

Emerging techniques also integrate machine learning and data analytics to enhance detection accuracy and filter false positives. While continuous monitoring offers clear advantages, it often involves higher upfront costs and infrastructure requirements compared to intermittent methods. Understanding these technical distinctions is essential for developing models that fairly compare monitoring strategies and their practical implications (Adegboye et al., 2019).

2.2 Economic Evaluation in Environmental Monitoring

Economic evaluation is critical for assessing the viability and impact of environmental monitoring programs. Cost-benefit analysis, life-cycle costing, and techno-economic assessments are commonly used methodologies to quantify financial implications alongside environmental outcomes. These approaches evaluate installation, operational, and maintenance costs against benefits such as avoided emissions, regulatory compliance, and product recovery (Van Dael et al., 2014, Milousi et al., 2019).

In methane monitoring, economic evaluation considers not only the direct costs of sensor deployment and maintenance but also the indirect costs associated with data management, personnel, and leak remediation. Benefits include reduced methane loss, potential carbon credits, and avoidance of penalties. The challenge lies in accurately quantifying these factors given variability in emission patterns and monitoring performance (Shafiee et al., 2016, Isa et al., 2016).

Recent studies emphasize the need to incorporate uncertainty and variability in cost-effectiveness assessments. Sensitivity analyses and probabilistic models help capture dynamic conditions and operational realities (Buchner et al., 2018, Ferreira et al., 2012). Despite advances, economic evaluations often focus on singular technologies or isolated cost factors, limiting a comprehensive understanding of trade-offs between continuous and intermittent approaches (Van Nijen et al., 2018).

2.3 Gaps in Current Techno-Economic Models

Existing techno-economic models for methane monitoring have made important strides but reveal several gaps that limit their practical application. Many models focus predominantly on either technical performance, such as detection limits and response times, or economic factors like capital and operating expenses, rarely integrating both dimensions comprehensively. This fragmented approach can obscure true cost-effectiveness and operational feasibility (Ahmed et al., 2017).

Another notable gap is the limited treatment of temporal variability in emissions and monitoring schedules. Methane leaks can be sporadic and variable in magnitude, affecting detection probabilities differently in continuous versus intermittent monitoring frameworks. Current models often assume static emission profiles or fixed inspection intervals, which may not reflect real-world complexities.

Additionally, many studies overlook the operational context, including site-specific factors and regulatory drivers, that influence monitoring program design and economics. There is also insufficient exploration of how emerging sensor technologies and data analytics impact cost-benefit dynamics. Addressing these gaps requires developing flexible, integrated models that incorporate technical, economic, and operational variables to guide more informed decision-making in methane monitoring strategies (Tomei et al., 2016).

III. METHODOLOGICAL FRAMEWORK

3.1 Conceptual Model Development

The development of a conceptual model is foundational to comparing continuous and intermittent methane monitoring programs in a techno-economic context. This model serves as an abstract representation that captures the essential elements influencing detection effectiveness and economic performance. The framework integrates both the technical characteristics of monitoring systems and the economic factors that affect their deployment and operation.

The conceptual model delineates two primary monitoring strategies: continuous systems characterized by real-time data acquisition and intermittent programs defined by periodic inspections or measurements. Each strategy involves distinct operational workflows, sensor configurations, and data processing requirements. By structuring these elements, the model provides a systematic approach to evaluate how monitoring frequency, sensor sensitivity, and response capabilities influence overall performance.

Furthermore, the model incorporates cost components including capital expenditures, operational expenses, and indirect costs such as labor and data management. This dual focus allows the comparison to extend beyond technical feasibility to include financial viability. The conceptual framework is designed to be flexible and adaptable, accommodating various technological setups and operational scenarios, which is critical for its applicability across different methane emission sources and regulatory environments.

3.2 Key Parameters and Variables

A critical aspect of the methodological framework is the identification and definition of key parameters and variables that influence both the technical and economic dimensions of methane monitoring. On the technical side, parameters include detection sensitivity, sensor accuracy, monitoring frequency, and leak response time. These variables determine how quickly and reliably a monitoring system can identify methane emissions, directly impacting the potential for emission reductions (El Haggar, 2010, Shindell et al., 2017).

Economic variables encompass initial capital investment, installation costs, ongoing maintenance, operational labor, data handling, and potential savings from reduced methane loss or avoided penalties. Additionally, factors such as sensor lifespan and replacement frequency affect the total cost of ownership. The interaction between technical performance and cost parameters is complex, as improvements in detection capability often come at increased expense (Galitsky, 2008).

Temporal factors are also essential; for example, the duration and frequency of emissions and monitoring activities influence detection probabilities and cost efficiency. Incorporating stochastic or time-varying emission profiles allows the model to reflect real-world conditions better. By clearly defining these parameters and their interrelations, the model facilitates quantitative comparisons that are both rigorous and relevant to decision-makers.

3.3 Comparative Metrics for Continuous vs Intermittent Monitoring

To objectively evaluate and compare continuous and intermittent methane monitoring programs, the framework employs a set of well-defined comparative metrics. These metrics capture both performance and economic outcomes, enabling a balanced assessment of each approach's strengths and limitations. Key performance metrics include detection rate, time to detection, false positive/negative rates, and coverage completeness, which reflect the ability of the monitoring system to identify leaks reliably.

On the economic side, metrics focus on total cost of ownership, cost per detected emission event, and return on investment. These indicators consider capital, operational, and maintenance costs alongside benefits such as recovered methane value and regulatory compliance savings. Additionally, metrics assessing cost-effectiveness incorporate factors like the emission reduction per unit cost, providing insight into how efficiently resources are allocated.

Integrating these metrics allows for multi-criteria decision analysis, where trade-offs between cost and detection performance can be quantified. This approach supports stakeholders in identifying optimal monitoring strategies tailored to specific operational goals and budget constraints. Ultimately, the comparative metrics facilitate transparent, data-driven choices in designing methane monitoring programs.

IV. TECHNO-ECONOMIC MODEL ANALYSIS

4.1 Cost Components and Drivers

Understanding the cost structure is fundamental to evaluating methane monitoring programs. The total cost of a monitoring system comprises capital expenditures, operational costs, and ancillary expenses, each influenced by different drivers (Hest, 2013). Capital expenditures typically include the purchase and installation of sensors, communication infrastructure, and integration with existing systems. Continuous monitoring systems often require a larger initial investment due to the deployment of multiple sensors and real-time data platforms (Kalina Capdevila, 2019, Shindell et al., 2017).

Operational costs encompass regular maintenance, calibration, data processing, and personnel needed to manage monitoring activities (GCR, 2004, Robinson et al., 2009). For continuous systems, these costs can be substantial because of constant data flow and the need for dedicated monitoring staff or automated analytics platforms. In contrast, intermittent monitoring usually incurs lower ongoing costs but may require higher labor intensity during inspection periods (Paranhos et al., 2015).

Ancillary costs, such as training, software licensing, and compliance reporting, also contribute to overall expenses. Factors driving these costs include technology maturity, sensor lifespan, site complexity, and scale of deployment. Additionally, indirect costs related to downtime during sensor maintenance or false alarms can impact operational efficiency. Identifying and quantifying these cost drivers is essential to accurately assess the economic implications of continuous versus intermittent methane monitoring (Lazarus et al., 2011).

4.2 Performance and Effectiveness Considerations

The effectiveness of methane monitoring programs is primarily measured by their ability to detect leaks promptly and accurately. Continuous monitoring systems typically offer superior temporal resolution, enabling rapid identification and localization of methane emissions. This advantage reduces leak duration, limiting total emissions and enhancing environmental benefits. Their ability to generate real-time alerts also supports proactive maintenance, minimizing operational disruptions (White et al., 2005, Ajayi et al., 2019).

Intermittent monitoring, while less frequent, may still provide valuable data, especially when strategically timed or combined with other detection methods. However, the longer intervals between inspections increase the risk of undetected leaks persisting, potentially leading to larger cumulative emissions. Performance is also influenced by sensor sensitivity, false positive and false negative rates, and environmental conditions that affect measurement accuracy (Ho et al., 2001, Siebenaler et al., 2016).

Balancing these performance factors with economic constraints is critical. High-sensitivity sensors may reduce emissions more effectively, but increase costs. Conversely, lower-cost sensors or less frequent inspections may be economically attractive but risk missing significant leaks. Therefore, evaluating effectiveness involves assessing detection probability, timeliness, and reliability in the context of operational requirements and cost considerations (Wilson, 2012, Ganesan et al., 2019).

4.3 Economic Trade-offs and Decision Criteria

The choice between continuous and intermittent methane monitoring involves complex economic trade-offs that must consider both costs and benefits (Tiwari et al., 1999). Continuous monitoring demands higher upfront and operational investments but can lead to greater emission reductions and potentially lower long-term costs associated with lost product and regulatory penalties. Intermittent monitoring offers lower initial costs but risks delayed leak detection, potentially resulting in higher cumulative emissions and associated financial impacts (Dean and Tucker, 2017, Neumann et al., 2017).

Decision criteria often include cost-effectiveness, measured as the cost per unit of methane detected or avoided, and return on investment, reflecting financial benefits relative to expenditures (Khalili and Duecker, 2013, Soltani et al., 2015). Other important considerations include risk tolerance, regulatory requirements, operational complexity, and site-specific characteristics. For example, high-risk or sensitive sites may justify continuous monitoring despite higher costs, while lower-risk areas may be suited for intermittent approaches (Dusseault et al., 2014).

Multi-criteria decision-making frameworks can integrate these factors, allowing stakeholders to weigh technical performance against economic constraints. Sensitivity analyses further support understanding how changes in key parameters impact outcomes. Ultimately, selecting the optimal monitoring strategy requires a tailored approach balancing economic viability with environmental and operational goals (Oliveira et al., 2019, Tiwari, 2000, Si et al., 2016).

CONCLUSION

This paper has developed a comprehensive techno-economic model comparing continuous and intermittent methane monitoring programs. The analysis highlights that continuous monitoring, while more capital-intensive and operationally demanding, offers superior detection capabilities by providing real-time data, enabling prompt leak identification and repair. This results in reduced methane emissions and greater environmental benefits. Intermittent monitoring, characterized by periodic inspections, presents a more cost-effective option upfront but risks delayed leak detection, potentially leading to higher cumulative emissions and lost methane volumes.

Cost components such as sensor installation, maintenance, data management, and labor were identified as critical drivers influencing total expenditures in both monitoring types. The model emphasizes that economic outcomes depend not only on absolute costs but also on performance factors like detection sensitivity and monitoring frequency. Trade-offs between detection effectiveness and cost efficiency are central to decision-making in methane mitigation programs. Overall, the framework demonstrates that neither approach is universally optimal; rather, selection depends on site-specific priorities, regulatory pressures, and financial constraints.

Theoretically, this study advances methane monitoring research by integrating technical and economic factors into a unified model, addressing gaps in prior literature that often considered these elements separately. This holistic approach facilitates a nuanced understanding of how performance metrics and cost drivers interact, supporting more informed evaluation of monitoring strategies. The model's flexibility allows application across diverse contexts, improving its relevance to different industries and regulatory regimes.

Practically, the findings inform operators and policymakers by elucidating the economic trade-offs inherent in methane monitoring decisions. Operators can better assess investments based on their operational needs and risk profiles, optimizing resource allocation. Regulators may use insights to design more effective policies and incentives that encourage the adoption of appropriate monitoring technologies. By balancing environmental benefits with economic realities, the model supports sustainable methane management that is aligned with climate goals and industry constraints.

Future research should focus on refining and validating the techno-economic model through empirical data collection across varied operational settings. Incorporating dynamic emission patterns and real-world variability in monitoring performance will enhance model accuracy and applicability. Additionally, exploring integration with emerging technologies such as machine learning algorithms for anomaly detection and predictive maintenance could further improve monitoring effectiveness and cost efficiency.

Expanding the model to include broader environmental and social impacts, such as community health benefits and carbon credit valuations, would provide a more comprehensive assessment of methane mitigation programs. Investigating hybrid monitoring approaches that combine continuous and intermittent elements may also offer valuable insights into optimized strategies.

Lastly, future work should consider the evolving regulatory landscape and market incentives to ensure the model remains relevant for guiding methane emission reduction efforts in a rapidly changing context.

REFERENCES

[1] ADEGBOYE, M. A., FUNG, W.-K. & KARNIK, A. 2019. Recent advances in pipeline monitoring and oil leakage detection technologies: Principles and approaches. Sensors, 19, 2548.

[2] AHMED, A., HASSAN, I., IBN-MOHAMMED, T., MOSTAFA, H., REANEY, I. M., KOH, L. S., ZU, J. & WANG, Z. L. 2017. Environmental life cycle assessment and techno-economic analysis of triboelectric nanogenerators. Energy & Environmental Science, 10, 653-671.

[3] AJAYI, T., GOMES, J. S. & BERA, A. 2019. A review of CO2 storage in geological formations emphasizing modeling, monitoring and capacity estimation approaches. Petroleum Science, 16, 1028-1063.

[4] ALKADI, N., CHOW, J., HOWE, K., POTYRAILO, R., ABDILGHANIE, A., JAYARAMAN, B., ALLAMRAJU, R., WESTERHEIDE, J., CORCORAN, J. & DI FILIPPO, V. Ubiquitous sensing network for continuous monitoring and quantification of methane emissions. SPE Offshore Europe Conference and Exhibition, 2019. SPE, D021S004R007.

[5] BALAFOUTIS, A., BECK, B., FOUNTAS, S., VANGEYTE, J., VAN DER WAL, T., SOTO, I., GÓMEZ-BARBERO, M., BARNES, A. & EORY, V. 2017. Precision agriculture technologies positively contributing to GHG emissions mitigation, farm productivity and economics. Sustainability, 9, 1339.

[6] BALCOMBE, P., ANDERSON, K., SPEIRS, J., BRANDON, N. & HAWKES, A. 2017. The natural gas supply chain: the importance of methane and carbon dioxide emissions. ACS Sustainable Chemistry & Engineering, 5, 3-20.

[7] BALCOMBE, P., SPEIRS, J. F., BRANDON, N. P. & HAWKES, A. D. 2018. Methane emissions: choosing the right climate metric and time horizon. Environmental Science: Processes & Impacts, 20, 1323-1339.

[8] BUCHNER, G. A., ZIMMERMANN, A. W., HOHGRÄVE, A. E. & SCHOMÄCKER, R. 2018. Techno-economic assessment framework for the chemical industry—based on technology readiness levels. Industrial & Engineering Chemistry Research, 57, 8502-8517.

[9] DAVIES, A. 2012. Handbook of condition monitoring: techniques and methodology, Springer Science & Business Media.

[10] DEAN, J. F., MIDDELBURG, J. J., RÖCKMANN, T., AERTS, R., BLAUW, L. G., EGGER, M., JETTEN, M. S., DE JONG, A. E., MEISEL, O. H. & RASIGRAF, O. 2018. Methane feedbacks to the global climate system in a warmer world. Reviews of Geophysics, 56, 207-250.

[11] DEAN, M. & TUCKER, O. 2017. A risk-based framework for Measurement, Monitoring and Verification (MMV) of the Goldeneye storage complex for the Peterhead CCS project, UK. International Journal of Greenhouse Gas Control, 61, 1-15.

[12] DUSSEAULT, M. B., JACKSON, R. E. & MACDONALD, D. 2014. Towards a road map for mitigating the rates and occurrences of long-term wellbore leakage.

[13] EL HAGGAR, S. 2010. Sustainable industrial design and waste management: cradle-to-cradle for sustainable development, Academic Press.

[14] FERREIRA, A., MARTINS, L., TEIXEIRA, S. & NUNES, M. Techno-economic assessment of micro-CHP systems. International Conference on Industrial Engineering and Operations Management, July 9-11 2012, 2012.

[15] GALITSKY, C. 2008. Energy efficiency improvement and cost saving opportunities for the vehicle assembly industry: an energy star guide for energy and plant managers.

[16] GANESAN, A. L., SCHWIETZKE, S., POULTER, B., ARNOLD, T., LAN, X., RIGBY, M., VOGEL, F. R., VAN DER WERF, G. R., JANSSENS-MAENHOUT, G. & BOESCH, H. 2019. Advancing scientific understanding of the global methane budget in support of the Paris Agreement. Global Biogeochemical Cycles, 33, 1475-1512.

[17] GATLAND, J. R., SANTOS, I. R., MAHER, D. T., DUNCAN, T. & ERLER, D. V. 2014. Carbon dioxide and methane emissions from an artificially drained coastal wetland during a flood: Implications for wetland global warming potential. Journal of Geophysical Research: Biogeosciences, 119, 1698-1716.

[18] GBABO, E. Y., OKENWA, O. K. & CHIMA, P. E. Constructing AI-Enabled Compliance Automation Models for Real-Time Regulatory Reporting in Energy Systems.

[19] GBABO, E. Y., OKENWA, O. K. & CHIMA, P. E. Integrating CDM Regulations into Role-Based Compliance Models for Energy Infrastructure Projects.

[20] GCR, N. 2004. Cost analysis of inadequate interoperability in the US capital facilities industry. National Institute of Standards and Technology (NIST), 223-253.

[21] GOLSTON, L. M., AUBUT, N. F., FRISH, M. B., YANG, S., TALBOT, R. W., GRETENCORD, C., MCSPIRITT, J. & ZONDLO, M. A. 2018. Natural gas fugitive leak detection using an unmanned aerial vehicle: Localization and quantification of emission rate. Atmosphere, 9, 333.

[22] HEST, T. 2013. Factors that determine and control the Total Cost of Ownership of an ERP solution-A maturity model that increases reliable ERP cost estimation. University of Twente.

[23] HO, C. K., ITAMURA, M. T., KELLEY, M. J. & HUGHES, R. C. 2001. Review of chemical sensors for in-situ monitoring of volatile contaminants. Sandia National Lab.(SNL-NM), Albuquerque, NM (United States); Sandia ….

[24] HOWARTH, R. W. 2015. Methane emissions and climatic warming risk from hydraulic fracturing and shale gas development: implications for policy. Energy and Emission Control Technologies, 45-54.

[25] HOWARTH, R. W., SANTORO, R. & INGRAFFEA, A. 2012. Venting and leaking of methane from shale gas development: response to Cathles et al. Climatic Change, 113, 537-549.

[26] ISA, N. M., DAS, H. S., TAN, C. W., YATIM, A. & LAU, K. Y. 2016. A techno-economic assessment of a combined heat and power photovoltaic/fuel cell/battery energy system in Malaysia hospital. Energy, 112, 75-90.

[27] KALINA CAPDEVILA, A. 2019. Study of a preliminary value-cost model of earth observation (eo) satellites operating in very and low earth orbit (vleo/leo) for the detection of methane emission. Universitat Politècnica de Catalunya.

[28] KHALILI, N. R. & DUECKER, S. 2013. Application of multi-criteria decision analysis in design of sustainable environmental management system framework. Journal of Cleaner Production, 47, 188-198.

[29] KNOBELSPIES, S., BIERER, B., PEREZ, A. O., WÖLLENSTEIN, J., KNEER, J. & PALZER, S. 2016. Low-cost gas sensing system for the reliable and precise measurement of methane, carbon dioxide and hydrogen sulfide in natural gas and biomethane. Sensors and Actuators B: Chemical, 236, 885-892.

[30] LAZARUS, W. F., GOODKIND, A., GALLAGHER, P. W. & CONWAY, R. K. 2011. Carbon prices required to make digesters profitable on US dairy farms of different sizes.

[31] MAJUMDAR, D., PATEL, J., BHATT, N. & DESAI, P. 2006. Emission of methane and carbon dioxide and earthworm survival during composting of pharmaceutical sludge and spent mycelia. Bioresource technology, 97, 648-658.

[32] MCHALE, L. E., MARTINEZ, B., MILLER, T. W. & YALIN, A. P. 2019. Open-path cavity ring-down methane sensor for mobile

monitoring of natural gas emissions. Optics express, 27, 20084-20097.

[33] MCKERCHER, G. R., SALMOND, J. A. & VANOS, J. K. 2017. Characteristics and applications of small, portable gaseous air pollution monitors. Environmental Pollution, 223, 102-110.

[34] MILOUSI, M., SOULIOTIS, M., ARAMPATZIS, G. & PAPAEFTHIMIOU, S. 2019. Evaluating the environmental performance of solar energy systems through a combined life cycle assessment and cost analysis. Sustainability, 11, 2539.

[35] MOLNÁR, A. 2018. Leaking away the future: the role of methane emission and natural gas supply chains in global warming. Energy Policy Studies.

[36] NEUMANN, P. P., KOHLHOFF, H., HÜLLMANN, D., LILIENTHAL, A. J. & KLUGE, M. Bringing Mobile Robot Olfaction to the next dimension—UAV-based remote sensing of gas clouds and source localization. 2017 IEEE International Conference on Robotics and Automation (ICRA), 2017. IEEE, 3910-3916.

[37] OGUNNOWO, E. O. A Conceptual Framework for Digital Twin Deployment in Real-Time Monitoring of Mechanical Systems.

[38] OKUH, C. O., NWULU, E. O., OGU, E., IFECHUKWUDE, P., EGBUMOKEI, I. N. D. & DIGITEMIE, W. N. Creating a Sustainability-Focused Digital Transformation Model for Improved Environmental and Operational Outcomes in Energy Operations.

[39] OKUH, C. O., NWULU, E. O., OGU, E., IFECHUKWUDE, P., EGBUMOKEI, I. N. D. & DIGITEMIE, W. N. An Integrated Lean Six Sigma Model for Cost Optimization in Multinational Energy Operations.

[40] OLIVEIRA, M. D., MATALOTO, I. & KANAVOS, P. 2019. Multi-criteria decision analysis for health technology assessment: addressing methodological challenges to improve the state of the art. The European Journal of Health Economics, 20, 891-918.

[41] PARANHOS, E., KOZAK, T. G., BOYD, W., BRADBURY, J., STEINBERG, D. & ARENT, D. 2015. Controlling Methane Emissions in the Natural Gas Sector. A Review of Federal and State Regulatory Frameworks Governing Production, Gathering, Processing, Transmission, and Distribution.

[42] REAY, D., SMITH, P. & VAN AMSTEL, A. 2010. Methane sources and the global methane budget. Methane and climate change. Routledge.

[43] ROBINSON, J., LEVACK, D., RHODES, R. & CHEN, T. Need for technology maturity of any advanced capability to achieve better life cycle cost. 45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 2009. 5347.

[44] SHAFIEE, M., ANIMAH, I. & SIMMS, N. 2016. Development of a techno-economic framework for life extension decision making of safety critical installations. Journal of loss prevention in the process Industries, 44, 299-310.

[45] SHINDELL, D., FUGLESTVEDT, J. & COLLINS, W. 2017. The social cost of methane: theory and applications. Faraday Discussions, 200, 429-451.

[46] SI, J., MARJANOVIC-HALBURD, L., NASIRI, F. & BELL, S. 2016. Assessment of building-integrated green technologies: A review and case study on applications of Multi-Criteria Decision Making (MCDM) method. Sustainable cities and society, 27, 106-115.

[47] SIEBENALER, S. P., JANKA, A. M., LYON, D., EDLEBECK, J. P. & NOWLAN, A. E. Methane detectors challenge: Low-cost continuous emissions monitoring. International Pipeline Conference, 2016. American Society of Mechanical Engineers, V003T04A013.

[48] SOLTANI, A., HEWAGE, K., REZA, B. & SADIQ, R. 2015. Multiple stakeholders in multi-criteria decision-making in the context of

municipal solid waste management: a review. Waste Management, 35, 318-328.

[49] TIWARI, D. N. 2000. Sustainability criteria and cost–benefit analysis: an analytical framework for environmental–economic decision making at the project level. Environment and Development Economics, 5, 259-288.

[50] TIWARI, D. N., LOOF, R. & PAUDYAL, G. N. 1999. Environmental–economic decision-making in lowland irrigated agriculture using multi-criteria analysis techniques. Agricultural systems, 60, 99-112.

[51] TOMEI, M. C., BERTANZA, G., CANATO, M., HEIMERSSON, S., LAERA, G. & SVANSTRÖM, M. 2016. Techno-economic and environmental assessment of upgrading alternatives for sludge stabilization in municipal wastewater treatment plants. Journal of Cleaner Production, 112, 3106-3115.

[52] VAN DAEL, M., KUPPENS, T., LIZIN, S. & VAN PASSEL, S. 2014. Techno-economic assessment methodology for ultrasonic production of biofuels. Production of biofuels and chemicals with ultrasound. Springer.

[53] VAN NIJEN, K., VAN PASSEL, S. & SQUIRES, D. 2018. A stochastic techno-economic assessment of seabed mining of polymetallic nodules in the Clarion Clipperton Fracture Zone. Marine Policy, 95, 133-141.

[54] VENTRELLA, J. & MACCARTY, N. 2019. Monitoring impacts of clean cookstoves and fuels with the Fuel Use Electronic Logger (FUEL): Results of pilot testing. Energy for Sustainable Development, 52, 82-95.

[55] WEN, Z., HU, S., DE CLERCQ, D., BECK, M. B., ZHANG, H., ZHANG, H., FEI, F. & LIU, J. 2018. Design, implementation, and evaluation of an Internet of Things (IoT) network system for restaurant food waste management. Waste management, 73, 26-38.

[56] WHITE, C. M., SMITH, D. H., JONES, K. L., GOODMAN, A. L., JIKICH, S. A., LACOUNT, R. B., DUBOSE, S. B., OZDEMIR, E., MORSI, B. I. & SCHROEDER, K. T. 2005. Sequestration of carbon dioxide in coal with enhanced coalbed methane recovery a review. Energy & Fuels, 19, 659-724.

[57] WHITING, G. J. & CHANTON, J. P. 2001. Greenhouse carbon balance of wetlands: methane emission versus carbon sequestration. Tellus B, 53, 521-528.

[58] WILSON, A. D. 2012. Review of electronic-nose technologies and algorithms to detect hazardous chemicals in the environment. Procedia Technology, 1, 453-463.