Strengthening the Environmental Benefits of Anaerobic Digestors

Through Robust Measuring, Monitoring, Reporting, and Verification: an Overview of Current Policies and Gaps

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Executive Summary

Methane is a potent greenhouse gas (GHG) which has significantly increased in the atmosphere by more than two-and-a-half times since pre-industrial times. This increase is primarily driven by human activities; emissions from agriculture (42%), fossil fuels (38%), and waste management (20%) sectors[1] dominate anthropogenic emissions. Methane is the second-largest contributor to global warming after carbon dioxide, particularly because of its high short-term warming impact.

Methane is also the main constituent of both fossil gas and biogas. Biogas is a fuel produced from anaerobic digestion (AD) of organic waste and other organic biomass sources. Biogas, as produced, contains roughly 60% methane and 40% carbon dioxide as well as other impurities (e.g., carbon monoxide, hydrogen sulfide) before it is upgraded (i,e,, purified) to reach a methane content of 90-95% (i.e., biomethane). The global AD industry has expanded rapidly over the past 15 years and is often promoted as a climate mitigation solution because it provides renewable alternatives to fossil-derived energy, processes organic wastes that would otherwise emit methane directly into the atmosphere, generates economic value through energy and fuel production, and produces nutrient-rich by-products that can replace synthetic fertilizers. However, the GHG mitigation benefits of AD systems are contingent on minimizing methane emissions across the AD value chain, which occur due to inadequate or poor operational practices, technology limitations, and/or equipment leaks.

About this Paper

In order to propose action to strengthen the environmental benefits of AD systems, this report aims to:

- Identify methane-emitting equipment and processes within AD systems;
- Assess methane measurement, monitoring, reporting, and verification (MMRV) frameworks from regulators and key stakeholders that are applicable to AD systems; and
- Evaluate the effectiveness of MMRV in ensuring that AD systems deliver real climate and environmental benefits.

Key Findings

Methane emissions from AD systems can vary significantly in magnitude. They can occur due to AD equipment and design and varying types of operations, management, safety, and maintenance. On average, scientific literature estimates today's modern AD plants have methane losses of between 0.5% and 6% of the total methane produced, with a mean value of just under 5%,[2] with legacy plants emitting far greater levels.

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[1] UNEP. 2025.Global Methane Status report. https://www.unep.org/resources/report/global-methane-status-report-2025

[2] Joint Research Centre, *Methane emissions in the biogas and biomethane supply chains in the EU – methodologies, default values and mitigation recommendations*, Publications Office of the European Union, 2023.

Overall, these values are far above average levels in the oil and gas industry.[i]

Regulatory priorities for AD systems differ substantially across countries, resulting in uneven coverage of major emission sources. Most regulations reviewed focus on workers' health and risk management of AD plants without also minimizing methane emissions. The United States, a key biogas producing country, significantly lacks federal and state regulations, relying instead on voluntary guidance, local permitting from air quality agencies focused on criteria pollutants, and best-practice recommendations. Furthermore, industry associations differ markedly in their views on methane emissions and MMRV. While European and global associations acknowledge the significance of methane losses and support improved MMRV for AD systems, the U.S. industry supports the use of general emission factors. Intergovernmental organizations recognize the AD sector as a significant source of anthropogenic methane and emphasize the importance of project-level MMRV, although no direct guidance is given.

Rigorous MMRV frameworks are essential to accurately account for methane emissions at both source and facility scales, ensure implementation and regulatory compliance, and improve net carbon intensity estimates of AD systems. Beyond compliance, MMRV supports better operational decision-making, enables the validation of mitigation measures, and strengthens the credibility of climate benefits associated with biogas and biomethane production.

Recommendations

Based on our assessment, our recommendations are:

First, **comprehensive data on emissions from different contexts** is lacking and is required to support the environmental benefits of AD systems. Much of the existing information that characterizes emissions from AD focuses on medium- to large-scale facilities located in Western Europe. There is little information that assesses emissions from smaller facilities in parts of the world where AD systems are rapidly being deployed, including Eastern Europe, Asia, Latin America, and Africa. It is not known if AD systems in these contexts have a similar emissions profile to those in the US and Western Europe, or if economies of scale have a significant impact on methane emissions. Hence, **regulations that support robust, but feasible MMRV frameworks are needed. Beyond regulations, implementation and effective enforcement of these regulations are critical since the effectiveness of MMRV systems depends not only on regulatory design but also on the capacity and rigor of oversight mechanisms.**

Second, there is a need for context-specific, **improved cost-benefit and techno-economic analysis** of methane mitigation measures, covering both unintentional methane leaks ("fugitive emissions") and practices and designs of AD systems that intentionally vent methane. Although not the focus of this report, recent studies that demonstrated that the vast majority of methane emissions in AD projects in the EU can be eliminated as no net cost, particularly in the feedstock ad digestate storage phases.[3] This demonstrates the need to improve data across multiple geographies to characterize baseline emissions across systems, quantify the costs associated with mitigation measures, and evaluate the associated emissions reductions. Such information should be used in the development of future methane policies, including Leak detection and Repair (LDAR) programs and equipment and work practice standards.

Third, **carbon offset, insetting, and crediting methodologies should apply conservatively high default emissions factors in addition to facility-level accurate values for baselines** to incentivize the adoption of facility-level MMRV and guarantee adequate environmental benefits of AD. Measurement-based accounting for baselines and emissions would enhance the credibility of issued carbon credits, improve buyer confidence, and better align claimed climate benefits with actual performance.

Fourth, **industry trade associations** should play a proactive role by **providing technical guidance, promoting best practices, and fostering collaboration with the research community**, following established models in Europe.

Finally, **intergovernmental and environmental organizations should continue to support the development and dissemination of practical MMRV guidance and tools** that enable AD operators to identify, quantify, and mitigate methane emissions.

Together, these actions will help ensure that AD delivers verifiable climate benefits and contributes effectively to near-term methane mitigation and national climate goals.

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[3] Olczak M. et al. 2026. Majority of methane emissions from European biogas plant supply chains could be eliminated at no net cost. Nature communications, Sustainability 1:88. https://www.nature.com/articles/s44458-026-00065-3

Figure 1: Overview of an anaerobic digestion system with main component stages. The width of the red arrows indicate relative methane losses.

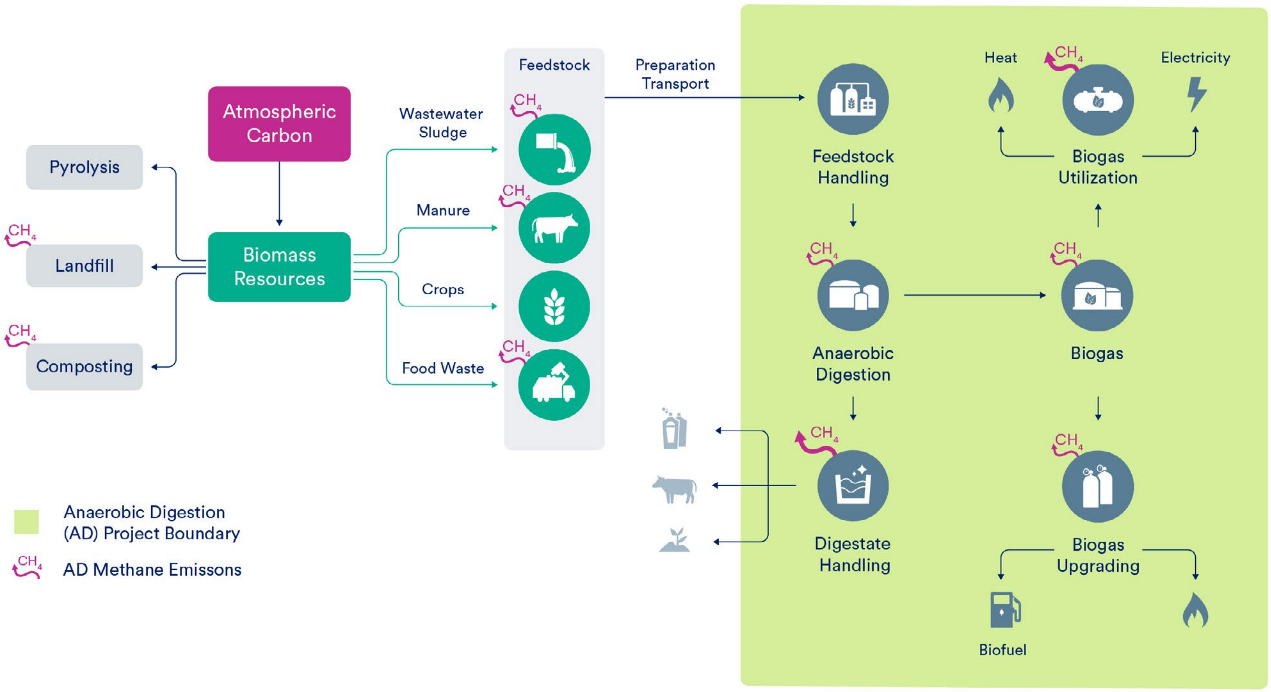

Table 1a: Regulation Scope

Country / Regulation	Feedstock Processing and Storage	Feedstock Storage	AD	Biogas Utilization and Upgrading	Digestate Storage
Denmark **Reg BEK 1535**	Yes	Yes	Yes	Yes	Yes
Germany **Reg TRAS 120**	No. Applies to biogas carrying, consumption and all system componnets exposed to biogas	No. Applies to biogas carrying, consumption and all system componnets exposed to biogas	Yes	Yes	No. Applies to biogas carrying, consumption and all system componnets exposed to biogas
Germany **Reg TRGS 529**	No. Regulation specfically applies to gas-carrying system parts and pipe connections	No. Regulation specfically applies to gas-carrying system parts and pipe connections	Yes	Yes	No. Regulation specfically applies to gas-carrying system parts and pipe connections
United Kingdom **Reg SR2021 No.s 1, 6-10**	Yes. But not specifically pointed to	Yes. But not specifically pointed to	Yes	Yes	Yes
France **Reg ICPE Section 2781**	No	No	Yes	Yes	No

Table 1b: Mitigation Requirements

Country / Regulation	Does the regulation include Leak Detection and Repair (LDAR)? If so, describe.	Does the regulation include any specific equipment or work practice standards? If so which?	Does the regulation include a performance or intensity standard? If so, describe.
Denmark **Reg BEK 1535**	Yes. Following a LDAR plan approved by third party verifier, self inspection and self-repair is permitted. Third party also verifies repairs	No	Yes. Maximum permitted methane loss from biogas upgrading is 1%
Germany **Reg TRAS 120**	Yes. Calls for self-monitoring plan to determine tightness of all components exposed to gas at least every three years unless continuous monitoring is carried out (optional)	No. Test for leaks must be carried out using a suitable, methane-sensitive, optical method; Gas consumption device must have priority over venting through overpressure safety device	No
Germany **Reg TRGS 529**	No. Requires recurring leak tests including those before initial commissioning, after a process change or repair to the facility. It does not mandate repairs	Yes. Foaming agents, inspection with mobile leak detectors, leak detectors, imaging methods with methane sensitive cameras. Suitable portable gas warning devices must at least enable the measurement of the following gas components: methane, carbon dioxide, hydrogen sulfide, and oxygen	No
United Kingdom **Reg SR2021 No.s 1, 6-10**	Yes. Operator to implement a LDAR programme to detect and mitigate release of volatile organic compounds, including methane. Annual inspections minimum	Yes. Sniffing to be done using EN 15446 and optical gas imaging methods. Emissions monitoring to be done using EN122619 method. Auxillary flare usage and pressure relief valve gas pressure to be monitored continuously using SCADA. MCERTS certification and/or accreditation required for monitoring equipment, techniques and personnel	Yes. Emissions limit for biogas utilization (CHP) plant on total volatile organic compounds, including methane, at 1000 mg/m^3 using EN12619 monitoring method
France **Reg ICPE Section 2781**	No	Yes. Biogas venting due to storage capacity in the anaerobic digester tank is forbidden. A regularly checked and calibrated monitoring system for detecting methane, hydrogen sulfide and carbon monoxide t ensure that indoor premises are properly ventilated	Yes. 0.5% by volume of biomethane produced, for facilities with a biomethane production capacity greater than 50 Nm^3/h; 1% for facilities with production capacity of less than 50 Nm^3/h

Table 1c: MMRV

Country / Regulation	Does the regulation include a performance or intensity standard? If so, describe.	Does the regulation require measurement, including direct or indirect quantification of emissions?	Does the regulation require regular monitoring of faciltiies?	Does the regulation require regular reporting of emissions in a standardized format?	Does the regulation require third-party veritification of reported emissions?
Denmark **Reg BEK 1535**	Yes. Maximum permitted methane loss from biogas upgrading is 1%	Yes. Only required to determine methane loss from biogas upgrading	No	No	No. Verification requirement is set for identifying sources of methane loss and to repair/reduce those losses
Germany **Reg TRAS 120**	No	No	No	No	No
Germany **Reg TRGS 529**	No	No	No	No	No
United Kingdom **Reg SR2021 No.s 1, 6-10**	Yes. Emissions limit for biogas utilization (CHP) plant on total volatile organic compounds, including methane, at 1000 mg/m³ using EN12619 monitoring method	Yes. Emissions quantification of monitoring stacks at CHP plants using specified methods	Yes. LDAR monitoring of fugitive emissions at points as specified in a DSEAR risk assessment and LDAR programme and at frequency agreed with the Environment Agency	Yes. Annual Reporting includes emissions from the combustion plant, efficiency of biofilter and abatement systems, auxillary flare burning surplus biogas, digester process and gas production process monitoring, under- and over-pressure relief events detailing mass balance release, and LDAR reports	No
France **Reg ICPE Section 2781**	Yes. 0.5% by volume of biomethane produced, for facilities with a biomethane production capacity greater than 50 Nm³/h; 1% for facilities with production capacity of less than 50 Nm³/h	Yes. Quantification would be required to determine methane loss from biogas upgrading	No	No	No

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SECTION 1

Introduction, Context, and Focus of this Report

Methane is a potent greenhouse gas (GHG), and its global concentrations in the earth's atmosphere have increased by more than two-and-a-half times since pre-industrial era (1750) levels, mainly due to anthropogenic sources.[4] Globally, anthropogenic methane emissions primarily stem from the agriculture (42%), energy (38%), and waste (20%) sectors[1] with agriculture and waste contributing significantly through unmanaged organic residues.

Although methane is emitted globally in much smaller quantities than carbon dioxide, it has a much higher short-term global warming potential, trapping over 80 times more heat than carbon dioxide over a 20-year period.[5]

Two generators using biogas, and digesters

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[4] IEA (International Energy Agency). (2024). *Global Methane Tracker 2024.* Retrieved August 2025, from: https://www.iea.org/reports/global-methane-tracker-2024/understanding-methane-emissions

[5] IPCC (Intergovernmental Panel on Climate Change). (2021). Forster et al., 2021: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 923–1054, doi: 10.1017/9781009157896.009

This makes methane the second most important GHG after carbon dioxide in terms of perpetuating a warming influence on the earth's climate. As a result, methane has become a priority target for near-term climate mitigation, with global efforts aiming to reduce methane emissions by at least 30% by 2030.[6] Reducing methane emissions rapidly in the near term can have a significant and immediate climate change mitigation impact due to its shorter lifetime compared with carbon dioxide (7 to 12 years). Additionally, reducing methane emissions provides multiple co-benefits, including improved air quality and public health,[7] enhanced industrial safety, and economic value through captured energy.

Anaerobic digestion (AD) is a technology that reduces methane emissions from agricultural and organic waste sources by capturing methane for energy use. AD works by breaking down organic materials such as animal manure, food waste, and wastewater biosolids in sealed, oxygen-free tanks, producing a biogas mixture of methane and carbon dioxide.[8,9] The AD industry has taken off in the last fifteen years, and global installed biogas power generation capacity has increased from under 10 gigawatts (GW) in 2010 to almost 25 GW in 2022.[10,11] While anaerobic digesters can provide a source of non-fossil energy for power generation and transportation, methane emissions from these systems can reduce, or potentially negate the climate benefits of AD,[12] particularly when non-waste sources are used. Therefore, strong guardrails to minimize emissions are fundamental to guaranteeing the climate benefits of AD, and policies are needed to ensure that such guardrails are utilized.

Rigorous frameworks and protocols for measurement, monitoring, reporting, and verification (MMRV) are an essential part of methane emissions policy for AD. They ensure that emissions are accurately quantified and tracked. MMRV can support emissions reductions when paired with zero or low methane emitting equipment and policies and standards to reduce or limit emissions from AD plants design and operations. An effective MMRV framework includes systematic measurement of emissions, standardized reporting, and independent verification.

The principal components of an emissions MMRV framework for an AD facility include:[13,14]

- **Measurement:** This involves direct and indirect measurements to quantify emissions.
- **Monitoring:** This activity refers to monitoring facilities to observe equipment, emission sources, and mitigation efforts.
- **Reporting**: This requires compiling, aggregating, and disseminating measured GHG emissions and emissions reduction data using standardized formats.
- **Verification**: This requires independently assessing reported GHG emissions and emissions reductions, through a third-party verification body, to establish completeness and accuracy.

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[5] GMP (Global Methane Pledge). (2024). *Factsheet: 2024 Global Methane Pledge Ministerial.* Retrieved July 2025, from: https://www.globalmethanepledge.org/news/factsheet-2024-global-methane-pledge-ministerial

[6] Mar et al. (2022). Beyond CO_2 equivalence: The impacts of methane on climate, ecosystems, and health. Environmental Science and Poilyc, 134:127-136. https://www.sciencedirect.com/science/article/pii/S1462901122001204

[7] WBA (World Biogas Association). (2022). *Biogas Insight 1, Delivering the Global Methane Pledge.* Retrieved September 2025, from: https://www.worldbiogasassociation.org/wp-content/uploads/2022/11/WBA-biogas-insight1-Deliveing-the-Global-Methane-Pledge-pamphlet.pdf

[8] USEPA (United States Environmental Protection Agency). (2025). *Environmental Benefits of Anaerobic Digestion (AD).* Retrieved September 2025, from: https://www.epa.gov/anaerobic-digestion/environmental-benefits-anaerobic-digestion-ad

[9] IEA (International Energy Agency). (2020). World Energy Outlook Special Report. *Outlook for biogas and biomethane.* Retrieved July 2025, from https://iea.blob.core.windows.net/assets/03aeb10c-c38c-4d10-bcec-de92e9ab815f/Outlook_for_biogas_and_biomethane.pdf

[10] IEA (International Energy Agency). (2025). World Energy Outlook Special Report. *Outlook for biogas and biomethane.* Retrieved July 2025, from https://iea.blob.core.windows.net/assets/5b757571-c8d0-464f-baad-bc30ec5ff46e/OutlookforBiogasandBiomethane.pdf

[11] Liebetrau et al. (2017). IEA Bioenergy. Methane emissions from biogas plants. Methods for measurement, results, and effect on greenhouse gas balance of electricity produced. Available on https://www.ieabioenergy.com/wp-content/uploads/2018/01/Methane-Emission_web_end_small.pdf

[12] GMI (Global Methane Initiative). (2022). *The Role and Importance of Measurement, Reporting, and Verification (MRV) for Biogas Projects.* Retrieved July 2025 from https://globalmethane.org/resources/details.aspx?resourceid=5240

[13] GMI (Global Methane Initiative). (2023). *Measurement, Reporting, and Verification MRV Best Practices for Biogas Projects.* Retrieved July 2025 from https://globalmethane.org/resources/details.aspx?resourceid=5264

Robust MMRV across the full anaerobic digestion system is essential to ensure that emissions estimates and policy assessments accurately reflect real-world performance.[3] Without such frameworks, policies that incentivize AD risk overstating climate benefits and directing climate finance toward projects that may be less effective than alternatives.

The Focus of this Report

This report analyzes MMRV frameworks and protocols, scientific literature, national regulatory approaches, carbon accounting methodologies, and industry stakeholder perspectives to assess whether current frameworks adequately capture methane emissions from AD and support effective mitigation. We identify methane-emitting processes within AD, characterize their magnitude, and assess how well existing methane MMRV frameworks from regulators and other key stakeholders accurately characterize emissions from each of those processes. Additionally, we note best practices for reducing methane leaks and venting from AD and assess the extent to which regulatory programs require those measures. While not a comprehensive review of regulations in key biogas producing countries, this report provides a critical analysis of the effectiveness of MMRV frameworks and regulations in guaranteeing that AD can realize climate and environmental benefits.

MMRV and LDAR

MMRV frameworks serve the important purpose of quantifying and tracking emissions across facilities over time. Robust MMRV frameworks have multiple benefits in that they can: 1) inform policy and standards, from plant design to operation, that can reduce and limit emissions from AD; 2) strengthen biogas and biomethane carbon markets, including voluntary and Article 6 markets, by enabling transparent and credible claims; 3) track the climate and environmental benefits of AD; and 4) enhance operational safety and risk management.

Leak Detection and Repair (LDAR) is the process through which operators use a detection technology (often an optical gas imaging camera) to inspect facilities at a regular frequency (often multiple times per year), and repair components and equipment found to be sources of fugitive emissions. Thus, LDAR is a method of ensuring that an AD facility is working properly and free of leaks. While some companies perform LDAR on a voluntary basis as part of regular facility maintenance, regulatory LDAR mandates can ensure that all operators implement LDAR programs that meet minimum standards. Often, MMRV and LDAR are incorrectly used interchangeably; however, they serve very different purposes, and both are necessary to guarantee the climate and environmental benefits of AD.

SECTION 2

Anaerobic Digester Projects and Emissions

Anaerobic digestion is a technology that can be used to reduce atmospheric emissions of methane originating from decaying organic waste such as food waste, manure, or agricultural residues, capturing it for use as electricity or fuel. It can also be used to generate biogas or biomethane from other non-waste biomass resources like purpose-grown crops. AD involves a series of controlled processes where microorganisms digest organic matter in the absence of oxygen to generate biogas, which is a mixture of methane (50-75%), carbon dioxide and other impurities.[15] Since biogas and biomethane from AD enables energy utilization of biomass carbon, it is considered to be a form of renewable energy.[16]

However, AD can itself be a source of methane emissions due to structural design features, operational practices, and accidental equipment failures. **If these emissions are substantial, they can significantly reduce, or even negate, the climate and environmental benefits of AD.**[12]

Anaerobic Digester Projects

Anaerobic digesters operate within broader systems that include the production and management of feedstock upstream, and product and digestate management downstream. When an AD is installed with the goal of treating organic waste and residues, it is usually referred to as a *discrete project*, or AD project, and clear boundaries

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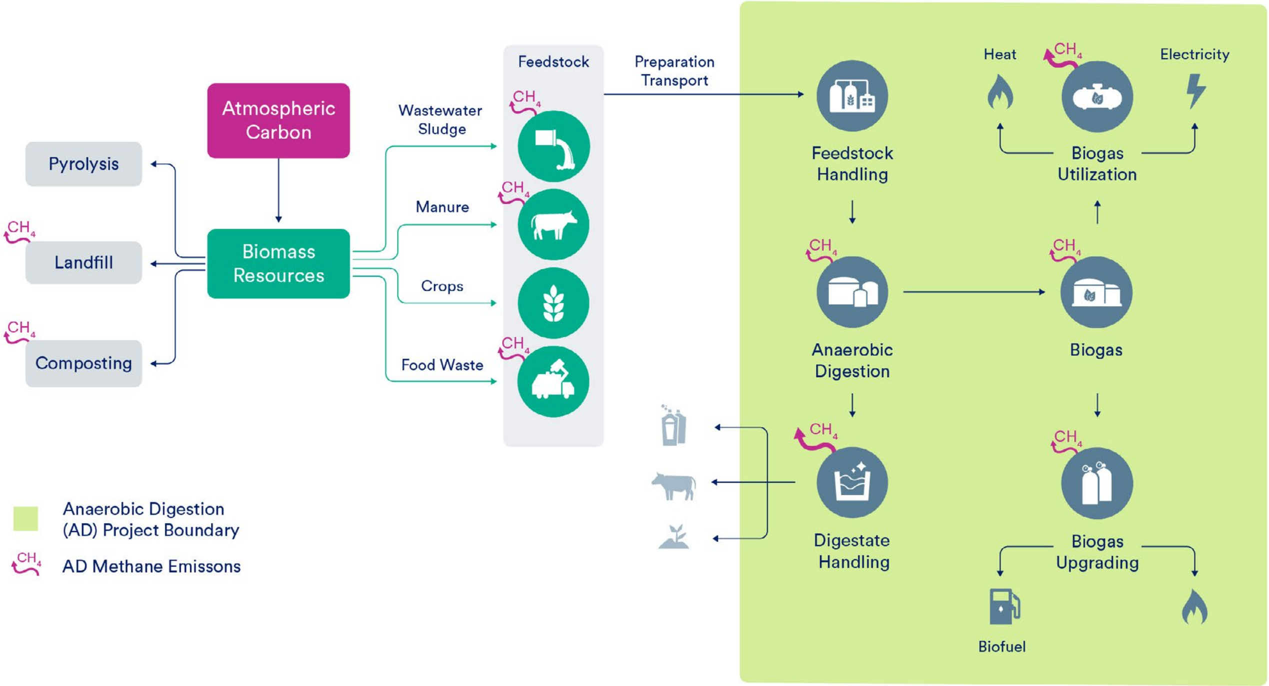
[15] USEPA (United States Environmental Protection Agency). (2019). *AgSTAR Project Development Handbook.* EPA 430-B-20-001. Retrieved July 2025, from https://www.epa.gov/sites/default/files/2014-12/documents/agstar-handbook.pdf

[16] AD systems discussed in this Report do not include a carbon capture and sequestration mechanism, which are considered net removal projects (e.g., digesters to inject processed biomass into geologic storage).

for that project are drawn. In the context of an AD project, some processes of the broader AD system are outside of the project boundaries. These processes are either "upstream" of the project (such as feedstock production and land use change) or "downstream" of it (such as spraying digestate onto farmland). A typical AD system and project with its boundaries are represented in Figure 1.

This report focuses only on emissions from AD projects, as do the MMRV protocols we review. However, it is important to note that in order to assess the greenhouse gas emissions benefits of AD, the emissions implications of broader AD *systems* – including any changes to upstream and downstream emissions – must be considered, and evaluated in comparison to a baseline scenario that represents business-as-usual if the AD project did not exist.[17,18] Land use change emissions and enteric fermentation are excluded from scope. To illustrate: if energy crops serve as AD feedstock, the upstream emissions associated with growing those crops, including land use change, are not covered by the MMRV frameworks and protocols examined here.

Figure 1: Overview of an anaerobic digestion system with main component stages. The width of the red arrows indicate relative methane losses.



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[17] ABC (American Biogas Council). (2025). *Carbon Accounting Tool for Biogas (Biogas CAT). Version 1.1.* Retrieved August 2025, from https://americanbiogascouncil.org/wp-content/uploads/ABC-Biogas-Carbon-Accounting-Tool-Version-1.1-3-JAN-2025.pdf

[18] There are other alternate and non-conventional baseline scenarios to managing biomass and organic waste that may have a higher methane mitigation potential than an AD system like biomass acidification, biomass aeration, and biomass solid-liquid separation, but we do not consider those baseline/alternate scenarios here. See World Resources Institute. (2025). Promising Technologies Need a Bigger Push to Cut Manure Emissions in the US. https://www.wri.org/technical-perspectives/us-manure-methane-mitigation-solutions

The main process stages within the AD project boundary are:

- **Feedstock processing and storage:** Feedstock can range from animal manure, wastewater biosolids, food waste, and other biomass resources. Included within the project boundary are pretreatment and storage for different incoming feedstocks and the mixing of feedstock for co-digestion. Production of feedstock is considered outside of the project boundary (upstream).
- **Anaerobic digestion:** This is the main operational phase of an AD project. Feedstock is conveyed into the digester (typically, an enclosed tank or a covered lagoon) where it undergoes anaerobic decomposition by microorganisms to produce biogas. External heat and mechanical mixing may be applied to maximize biogas production. The commonly observed residence time of substrate in an AD system is variable and can range from 15 to 60 days depending on AD design and feedstock type.[12] Following the AD process, two primary AD products emerge that need to be handled and processed – biogas and digestate.
- **Biogas utilization / upgrading:** Biogas is commonly used to generate heat, electricity, or both by burning it in a combined heat and power (CHP) system. Biogas can also be upgraded through a separation process, where it is first cleaned to remove water and impurities, then passed through membranes that selectively separate CO_2 from methane, to produce biomethane or renewable natural gas, which can be used as transportation fuel or injected into the gas pipeline grid. Occasionally, biogas and biomethane are flared during maintenance, abnormal operations, or during periods of high production when there is not adequate storage availability and/or takeaway capacity for the product.[10]
- **Digestate processing and storage:** Digestate is a combination of liquid and solid residual byproducts of the AD process. The anaerobic decomposition process continues in the substrate (digestate) beyond the digester. Digestate can be a significant source of methane[19] due to residual organic matter content, and it is recommended storage period can range from 50 to 150 days.[16] Liquid digestate can be used for land application as a soil amendment or nitrogen fertilizer. Solid digestate can be used as animal bedding. Separated digestate can be composted for farm and garden use. Utilization of digestate resulting emissions are considered outside the AD project boundary (downstream).

Adjacent Impacts and Scope Limitations

Additional elements associated with AD systems but outside the scope of this report include ammonia and volatile organics emissions from digestate storage, additional methane emissions after land application of digestate, and diversion of feedstock for biofuels towards methane-emitting AD systems. Furthermore, baseline assumptions may disincentivize broader energy system decarbonization because of highly “negative” carbon intensity scores assigned to AD systems without carbon capture and storage.

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[19] JRC (European Commission, Joint Research Centre). 2024. *Methane emissions in the biogas and biomethane supply chains in the EU*, Publications Office of the European Union, Luxembourg. Retrieved July 2025, from https://publications.jrc.ec.europa.eu/repository/handle/JRC139485

Understanding Digester Methane Emissions

Methane emissions occur across all stages of AD projects and vary widely depending on plant design, technology choice, and operational practices.[20,21] Depending on their magnitude, these methane emissions can significantly reduce the net GHG benefits and sustainability criteria of an AD project. Therefore, accurate methane measurement and accounting are crucial to ensure that potential benefits of AD systems are correctly evaluated.

Quantification Approaches

There are two main measurement approaches that are used to quantify methane emission rates:

- **On-site (bottom-up) approach:** Emissions are measured at individual known point sources (sub-component or component scale), allowing quantification and source attribution. Then, the estimates are aggregated to individual AD process stages (e.g., methane emissions from biogas upgrading). Since only known sources of emissions are included in the scope of measurements, emissions from unknown leaks and/or sources may not be captured in the measurements, and the aggregate emission rate determined for the AD system may be an underestimation. Second, for many sectors, research has shown that unusual but very large and episodic emissions events (often referred to as "super-emitters") are a very important source of sector-wide emissions. These large-but-unusual sources are very difficult to account for on equipment-scale, limited-duration, bottom-up measurement campaigns.
- **Site-wide (top-down) approach:** Emissions are measured further away from the site or from an airborne platform, at the facility-scale. Although these methods typically do not allow for apportionment and attribution of emissions at a source level (some airborne approaches do provide emissions estimates at the equipment level), they are more likely to detect and quantify emissions from all known and unknown sources, making these methods more likely to be representative of the entire facility and process.[22] Site-wide measurement studies at AD projects processing various feedstocks report total methane losses of 3.5–6%, with substantial variability across projects;[23,24,25,26,27] and emissions rates as high as 41% have been observed.[20] While whole-plant measurements provide useful estimates of total emissions, they must generally be complemented by on-site measurements or inspections to identify and mitigate specific emission sources.

Insights and Uses of Site-wide Emission Measurements

Whole-site measurement methods provide a robust quantification of methane emission rates from AD projects which can allow for national-level inventory emissions factor determination, provided a sufficient sample of projects are measured.[20,23] Additionally, it is helpful to summarize some of the patterns that have been observed by researchers utilizing site-wide measurement techniques. Low methane losses (<1%) are mainly observed for newly constructed or renewed plants that have gas-tight digestate tanks.[20,22]

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[20] BEIS (Department of Business, Energy and Industrial Strategy). (2017). *Methodology to Assess Methane Leakage from AD Plants*, Part I, Final Report 1230/10/2016(1). Retrieved July 2025, from https://assets.publishing.service.gov.uk/media/5c8fa89940f0b640d944b99f/Methodology_to_Assess_Methane_Leakage_from_AD_Plants_final_report_part1.pdf

[21] IEA (International Energy Agency Bioenergy). (2017). *Methane emissions from biogas plants.* IEA Bioenergy: Task 37: 2017: 12. Retrieved July 2025, from https://www.ieabioenergy.com/wp-content/uploads/2018/01/Methane-Emission_web_end_small.pdf

[22] Guha, A., S. Newman, D. Fairley, T. Dinh, L. Duca, S. Conley, M. Smith, A. Thorpe, R. Duren, D. Cusworth, K. Foster, M. Fischer, S. Jeong, N. Yesiller, J. Hanson, and P. Martien. (2020). *Assessment of Regional Methane Emission Inventories through Airborne Quantification in the San Francisco Bay Area.* Environmental Science & Technology, Volume 54, Issue 15, 0013-936X

[23] Anders Michael Fredenslund, Einar Gudmundsson, Julie Maria Falk, and Charlotte Scheutz. (2022). *The Danish national effort to minimize methane emissions from biogas plants*, Waste Management, Volume 157, 2023, Pages 321-329, ISSN 0956-053X. Retrieved July 2025, from https://doi.org/10.1016/j.wasman.2022.12.035

[24] Fredenslund, A. M., & Scheutz, C. (2017). *Total methane loss from biogas plants, determined by tracer dispersion measurements.* In Proceedings Sardinia 2017 CISA Publisher. Retrieved July 2025, from https://backend.orbit.dtu.dk/ws/portalfiles/portal/137677923/153.pdf

[25] Charlotte Scheutz, Anders M. Fredenslund. (2019). *Total methane emission rates and losses from 23 biogas plants*, Waste Management, Volume 97, 2019, Pages 38-46, Retrieved October 2025, from: https://doi.org/10.1016/j.wasman.2019.07.029

[26] Semra Bakkaloglu, Dave Lowry, Rebecca E. Fisher, James L. France, Dominik Brunner, Huilin Chen, and Euan G. Nisbet. (2021). *Quantification of methane emissions from UK biogas plants*, Waste Management, Volume 124, 2021, Pages 82-93, ISSN 0956-053X. Retrieved in July 2025, from https://doi.org/10.1016/j.wasman.2021.01.011

[27] Semra Bakkaloglu, Jasmin Cooper, and Adam Hawkes. (2022). Methane emissions along biomethane and biogas supply chains are underestimated, One Earth, Volume 5, Issue 6, 2022, Pages 724-736, ISSN 2590-3322. Retrieved in July 2025, from https://doi.org/10.1016/j.oneear.2022.05.012

Methane Emissions Sources

Methane emissions, which are typically expressed as a percentage of total (gross) methane production, occur across the AD project. These emissions can be classified in several ways (which are not mutually exclusive), and the common terminology is described in Table 2.

Table 2: Classification Terminology for Methane Emissions from AD Projects

	Emissions
Plant and Equipment Design and Operation	**Structural Emissions:** Originate from certain equipment (e.g., compressors). They are determined by the design of a plant and equipment type and happen under known circumstances (i.e., venting by design valves, controllers and actuators)
	Maintenance Emissions: Related to operational needs to release gas (e.g., pressure release valves, venting equipment for maintenance); typically happen occasionally
Characteristics of the Methane Emissions	**Point-Source Emissions:** Released through an emission point such as a stack or a chimney
	Diffuse Emissions: Emissions that arise from various scattered sources, or emanating in a diffuse fashion (e.g., emissions from digestate stored in open bunkers)
Intentionality of the Emission	**Fugitive Emissions:** Unintentional, caused by loss of tightness and/or depressurization of equipment that is designed to be tight, or intermittent emissions caused by abnormal operations
	Non-fugitive Emissions: Originating from open surfaces, atmospheric vents, and storage, incomplete combustion, during normal operations

Below, we discuss the major sources of emissions at each of the four major process stages of AD projects. It's important to notice that the vast majority of emissions from AD could be eliminated, with approximately 60% of these at no net cost.[3] Appendix A provides a detailed listing of typical emissions sources that have been observed within AD projects, as well as approximate typical magnitudes of emissions for each source based on a review of literature on AD emissions. Understanding the type and source of emissions is critical to the design of robust frameworks for AD MMRV and mitigation policies.

Feedstock Processing and Storage

Studies have consistently found that handling of feedstock prior to adding it to the digester has the lowest emissions of the AD process stages, typically emitting less than 0.5% of total methane production.[24,28,29] However, when hydrolysis tanks are utilized, emissions as high as ~5% have been observed.[30] Emissions may occur if biomass begins decomposing prior to digestion, particularly in non-gas-tight storage or mixing tanks.[27]

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[28] O. Hurtig, M. Buffi, R. Besseau, N. Scarlat, C. Carbone, and A. Agostini. (2024). Mitigating biomethane losses in European biogas plants: A techno-economic assessment, Renewable and Sustainable Energy Reviews, Volume 210, 2025, 115187, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2024.115187

[29] Hrad, M., M. Huber-Humer, T. Reinelt, B. Spangl, C. Flandorfer, F. Innocenti, J. Yngvesson, A. Fredenslund, and C. Scheutz. (2022). Determination of Methane Emissions from Biogas Plants, Using Different Quantification Methods. Agricultural and Forest Meteorology, Vol. 326, November 2022, p. 109179. https://doi.org/10.1016/j.agrformet.2022.109179

[30] Viktoria Wechselberger, Torsten Reinelt, Johan Yngvesson, Deborah Scharfy, Charlotte Scheutz, Marion Huber-Humer, and Marlies Hrad. (2022). Methane losses from different biogas plant technologies, Waste Management, Volume 157, 2023, Pages 110-120, ISSN 0956-053X. Retrieved July 2025, from https://doi.org/10.1016/j.wasman.2022.12.012

Potential fixes and improvements: Studies note that gas-tight feedstock mixing and storage tanks can eliminate methane emissions from this stage.[25,27] These are usually seem as "no-regret" mitigation options.[3]

Anaerobic Digestion

This stage is a major source of emissions. Methane emissions during the digestion stage arise primarily from leaks in digester tanks, roofs, and gas holders, as well as from pressure relief valves (PRVs).

Reported methane losses from this stage typically range from 1.0–1.6%, though higher values such as 5% have been observed under suboptimal conditions.[3,25] While PRVs are safety devices intended for rare overpressure situations, poor maintenance, faulty settings, or operational practices can result in frequent or continuous venting, with emissions ranging from 0.6-1.8%.[31] Digester roof design and maintenance plays an important role (emissions varying from 0.02% - 0.79%), with membrane diffusion through well-maintained double-membrane roofs generally associated with very low operational emissions compared to older/legacy roof designs (e.g., single membrane, concrete roofs, etc.) or poorly maintained digester structures that have leaks at inspection hatches, soft covers, mixer axles, etc.[20,26,27]

Potential fixes and improvements: The correct choice of equipment and AD design combined with regular leak monitoring and maintenance can reduce emissions during this stage. Implementing automatic flares, correct dimensioning of biogas pipes, conservative target filling of gas in digester tanks, proper roof design, and frequent maintenance (to avoid stuck and leaky valves) can reduce methane emissions, particularly from PRVs. Frequent LDAR surveys can identify leaking components and allow the operator to repair fugitive emissions.

Biogas Utilization and Upgrading

Biogas utilization is often one of the largest sources of methane emissions within the AD project. Methane slip from Combined Heat and Power (CHP) units due to incomplete combustion is a significant emission source, with measured emissions commonly ranging from 1–5%.[3,20,24,25,26,27,32] Biomethane upgrading is another source of emissions, with reported values ranging between 0.9 and over 3.0%.[20,24,25,26,27,33] For comparison, the Intergovernmental Panel on Climate Change (IPCC) assumes almost negligible methane losses from biogas combustion (<0.01 % of utilized methane), while not considering emissions from biogas upgrading.[34]

Potential fixes and improvements: Outdated upgrading technologies, such as physical scrubbers using water or organic solvents (e.g. polyethylene glycol) or pressure swing absorption, can lead to more than 3% methane loss, while newer reactive technologies, such as chemical absorption, carbonates, chemical scrubbers (using amines) and recent membrane technologies generally lead to less than 1% methane loss, with emissions as low as < 0.1% in some cases.[20,24,26,27,30] Frequent LDAR surveys are particularly useful to identify and fix leaking equipment and components during this process stage.

Digestate Processing and Storage

Digestate processing and storage are frequently the largest contributors to methane emissions, particularly when digestate is stored in open or non-gas-tight tanks and in summer months.[3,16,18] Residual methane potential (which is dependent on the amount of organic matter or volatile solids present in the digestate)[33] can be quite significant; storage duration, temperature, and substrate characteristics strongly influence emission rates.

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[31] Reinelt, T., and, Liebetrau, J. (2020). *Monitoring and Mitigation of Methane Emissions from Pressure Relief Valves of a Biogas Plant.* Chem. Eng. Technol. 43, 7–18. https://doi.org/10.1002/ceat.201900180

[32] Liebetrau, J., Reinelt, T., Clemens, J., Hafermann, C., Friehe, J., and, Weiland, P. (2013). *Analysis of greenhouse gas emissions from 10 biogas plants within the agricultural sector.* Water Sci. Technol. 67, 1370–1379. https://doi.org/10.2166/wst.2013.005

[33] Torben Kvist, and Nabin Aryal. (2019). *Methane loss from commercially operating biogas upgrading plants*, Waste Management, Volume 87, 2019, Pages 295-300,ISSN 0956-053X. Retrieved July 2025 from https://doi.org/10.1016/j.wasman.2019.02.023

[34] Intergovernmental Panel for Climate Change. (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan, Volume 5, Chapter 4, Section 4.1. Retrieved October 2025, from: https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_4_Ch4_Bio_Treat.pdf

Measured methane losses from digestate handling commonly vary from 2–4%,[20,24,25,26,27] with higher values (up to 12-15%)[24,35] observed during warmer months and at facilities without gas-tight storage. Although IPCC default emission factors for digestate storage are in the range of 2.6-3.6% to cover methane emissions from not gas-tight digestate storage[31] (calculated based on the methane production potential of the feedstock), this value doesn't account for seasonality or the high values observed in certain regions or during summer months, which can be as high as 15%.

Potential fixes and improvements: Various studies have recommended using closed or gas-tight digestate storage with vapor-recovery systems, that are directed to the biogas upgrading units to address emissions from this stage.[24] Increasing the retention time during the AD phase can also reduce emissions from digestate storage.[16] Research has demonstrated the economic feasibility of covering digestate storage tanks.[3]

Although default emissions factors are recommended when no measurement data are available for inventory estimation (for instance, the IPCC recommends a default emission factor of 5% for leakages and process disturbances within the AD for the waste sector),[31] the large variability in methane emissions between AD projects and numerous potential sources in each plant means that on-site source-by-source measurements are still key for an effective methane MMRV framework. This level of granularity also provides necessary information to inform methane mitigation measures by highlighting differences in emissions between stages, equipment and/or designs of AD systems.

The Importance of Digestate Management for AD Climate Benefits

Digestate has been identified as a significant source of methane emissions in AD projects, affecting the overall environmental performance of these projects.[33] Generally, digesters are designed to maximize methane production. This means that the time waste and other biomass resources spent in the digester (retention time) is enough to degrade soluble and fast-degrading volatile solids, or roughly 50% – 60% of solids. The remaining, slow-degrading solids, which have methane producing potential, are left and end up in the digestate lagoon, contributing to methane emissions in that stage.[36] Particularly in the U.S., where digestate lagoons are not covered, much of the benefit of AD is lost.

Shorter retention times can also be caused by more feedstock intake (for example, more manure produced due to increased farm size), and build-up of solids in the AD.[37] Retaining longer retention times during the AD phase can reduce emissions from digestate. Furthermore, digestate lagoons should be covered, ideally gas-tight, and whenever possible, residual gas should be treated.[12]

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[35] Hambaliou Baldé, Andrew C. VanderZaag, Stephen D. Burtt, Claudia Wagner-Riddle, Anna Crolla, Raymond L. Desjardins, and Douglas J. MacDonald. (2016). *Methane emissions from digestate at an agricultural biogas plant*, Bioresource Technology, Volume 216, 2016, Pages 914-922, ISSN 0960-8524. Retrieved July 2025, from https://doi.org/10.1016/j.biortech.2016.06.031

[36] World Resources Institute (2025). Analysis of US manure management and recommendations to mitigate associated greenhouse gas emissions. https://www.wri.org/research/analysis-and-recommendations-mitigate-greenhouse-gas-emissions-us-manure-management

[37] Aguirre-Villegas et al. (2019). Anaerobic digestion, solid-liquid separation, and drying of dairy manure: Measuring constituents and modeling emission. Sc. Total Environment 696. https://www.sciencedirect.com/science/article/pii/S0048969719340367

SECTION 3

National Regulatory Frameworks for AD Methane Emissions: MMRV and Mitigation Policies

Several countries have regulatory frameworks for AD projects. Ideally, these frameworks should contain a comprehensive MMRV framework. MMRV creates an emissions estimate that is robust and reliable and that can be compared across facilities and over time.
This emissions estimate is essential to:

- Assess the overall GHG implications of AD (individually and across a jurisdiction), for example to inform policies promoting AD.
- Guide and evaluate the impact of mitigation policies and technologies.
- Improve ADs participation in offset programs and other voluntary incentive programs.

While robust MMRV is a critical part of effective regulations, it is also essential that jurisdictions with AD projects apply mandatory emissions standards to AD projects as emissions can significantly reduce AD climate benefits, particularly when non-waste feedstock is used.

We analyzed national AD regulations and other relevant documentation from Denmark, France, Germany, the United Kingdom, Italy, and the United States to evaluate if current frameworks include both robust MMRV and protective standards for each process stage of AD systems. For European Union Member States, the analysis focused on the national regulations following the transposition into national law of the Renewable Energy Directive (RED) and its 2018 (RED II) and 2023 updates (RED III). We anticipate regulations and other documentation may be missing from the current report, but given the comprehensiveness of our review, the most important regulations are covered. Relevant national regulations, at the federal level, are summarized in Table 3. More detailed information about the regulations can be found in Appendix B. It is worth noting that the People's Republic of China is the largest producer of biogas in the world, followed by Germany, however, the PRC's regulations were not covered in this report.

Overall, the regulations evaluated were developed with a focus either on 1) leak detection and repair and methane mitigation (e.g., Denmark and United Kingdom), or 2) workers' health and safety (e.g., Germany and France). Regulations focused on workers' health and safety are essential in protecting workers at AD facilities but, on their own, they generally fall short of what is needed to mitigate methane emissions.[38]

None of the regulations reviewed have a **methane emissions cap** that encompasses all four major AD process stages identified in *Chapter 1*. For example, the French regulation has strict emission cap on biogas upgrading (0.5-1.0%) but no limits on other major processes. This means that an AD plant which does not sell upgraded gas (instead using biogas for onsite heat and power generation, for example) would not be subject to any emission cap under the French rule. As a result, the French regulation, which is safety- and maintenance-centric, is only somewhat effective at reducing methane emissions project-wide. Similarly, the United Kingdom regulation has provisions for reducing methane emissions (by limiting total volatile organic compound emissions) in the CHP plant exhaust stack but contains no limit if the AD facility is upgrading the biogas to biomethane.

Regulations should address emissions from all major AD methane-emitting process stages.

An additional key characteristic is an **independent verifier requirement**. This approach is partially used in some current rules but with a focus on LDAR, not MMRV; for example, Denmark's rules require third-party development of a monitoring plan, allows for self-inspection, but also requires verification of the operator's leak detection reports and accompanying repairs. This approach provides superior accountability and data transparency compared to operator-run self-monitoring programs observed in Germany and United Kingdom, which are not required to have third-party oversight.

Annual inspection requirements, as seen in Denmark and the UK, seem to be the most common frequency standard in the current regulations. In some jurisdictions, inspection requirements are more infrequent; for example, Germany's equipment tightness checks and inspection requirements range from every three to every twelve years for most 'technically tight' components; this is likely a gross underestimate of how often leaks and breakdown typically occur.

Digestate processing and storage is not included across the regulations assessed here, with no methane emissions cap and/or gas-tight design requirements for tanks or covers. This is despite overwhelming evidence that significantly large emissions occur from this process as per most research studies reviewed in *Chapter 2*.

Italy does not have regulations that require MMRV or LDAR for AD projects. Instead, Italy has adopted a biomethane marketplace decree/standard that provides partial government financing (up to 40% of the capital cost) to AD projects and a 15-year guarantee of feed-in tariff rates for projects that achieve >65% GHG emissions reduction for biomethane used as transportation fuel (a stricter 80% for other uses like heating).[39] The decree incentivizes investments in fugitive emissions monitoring equipment and digestate treatment with a similar 40% grant. However, the decree stops short of putting any emissions caps or a MMRV or LDAR mandate, and it is not clear how projects demonstrate that these strict sustainability standards have been achieved or would be maintained in the future.

The United States, despite being a large biogas producing country globally, does not have dedicated, binding regulations at the federal or state levels designed to directly reduce methane emissions from the AD supply chain. The U.S., instead, relies on voluntary compliance with best available technology system development handbooks, local permitting from air

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[38] Europe's strict ammonia regulations for manure and digestate management (NEC Directive, IED BAT) have sometimes reduced methane as a co-benefit. Leveraging existing ammonia and waste management rules for methane monitoring and mitigation could offer a faster adoption path where enforcement capacity already exists.

[39] Ministry of Ecological Transition. (2022). Official Journal General Series No. 251. *Legislative Decree No. 199 of 8 November 2021, to support the production of biomethane fed into the natural gas network, in accordance with Mission 2, Component 2, Investment 1.4, of the PNRR.* (22A06066) Retrieved February 2025, from https://www.gazzettaufficiale.it/atto/serie_generale/caricaDettaglioAtto/originario?atto.dataPubblicazioneGazzetta=2022-10-26&atto.codiceRedazionale=22A06066&elenco30giorni=false

Feedstock storage

quality agencies focused on criteria pollutants, and best practice operation and maintenance guidance to promote efficient AD design and operation principles within the AD industry.[12,40] **Without a regulatory framework in place to identify and address methane emission sources across different process stages of an AD system, operational guidance, by itself, is inadequate in ensuring that AD systems are minimizing methane emissions.**

Additionally, a key challenge in MMRV frameworks for anaerobic digestion plants lies not only in the absence of rules, but in their uneven implementation and enforcement. For example, in Germany, although a comprehensive set of technical standards exists, their legal character varies, and compliance is not consistently achieved in practice. Reports from the German Commission for Plant Safety (KAS) show that since 2007, more than two thirds of inspected biogas plants have exhibited significant deficiencies, pointing to a persistent enforcement gap rather than isolated non-compliance.[ii] These findings suggest that the effectiveness of MMRV systems depends not only on regulatory design but also on the capacity and rigor of oversight mechanisms. In particular, recurring issues such as methane leakages highlight how weak enforcement can undermine both environmental integrity and the credibility of monitoring and reporting frameworks.

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[40] USEPA (United States Environmental Protection Agency). (2020). *AgSTAR Anaerobic Digester/Biogas System Operator Guidebook.* EPA 430-B-20-003. Retrieved August 2025, from https://www.epa.gov/sites/default/files/2020-11/documents/agstar-operator-guidebook.pdf

Table 3: Evaluation of Methane Emission Sources and Emissions Monitoring Requirements for AD Systems Across Select National Regulations

The United States is not represented on this Table as it currently does not have regulations that cover MMRV or LDAR frameworks for Ads.

Denmark | Regulation and Adoption Date: BEK 1535[41] – December 2022

Important Features

- Focus: Methane loss and climate benefits
- Customized LDAR programs by independent verifier
- Requires self-monitoring and reporting with audits by verifier

Coverage of Major AD Methane Emissions Sources

Anaerobic Digestion – PRVs, Tanks and Roofs
- Openings and covers are included in self-monitoring and LDAR programs

Biogas Utilization – CHP Units
- Included in self-monitoring and LDAR programs
- Combined 1% emissions cap (including upgrading)

Biogas Utilization – Biomethane Upgrading
- Included in self-monitoring and LDAR programs
- Combined 1% emissions cap (including CHP units)

Digestate Handling – Storage tanks
- Openings and covers are required to be included in the scope of self-monitoring and LDAR programs

Monitoring and LDAR Requirements and Reporting

- Annual LDAR by an independent verifier
- Verifier to prepare plans for measures to avoid methane loss
- Rule specifies minimum requirements for self-inspection program, facility-changes trigger program update, and program has to be approved by verifier before
- Repair actions are required from the operator following verifier's annual audit results

Strengths and Shortcomings

Strengths
- Third-party LDAR and repair verification is required
- Cessation of state subsidies and fines on failure to comply

Shortcomings
- No emissions cap on digestate tanks
- Does not require continuous monitoring
- Frequency of mandatory LDAR survey may be reduced to every two years on initial compliance
- Specific LDAR methods not identified

United Kingdom | Regulation and Adoption Date: SR2021 No.s 1, 6-10[42] – December 2021

Important Features

- Focus: Best practice-oriented rule for operations of AD facilities for purpose of biogas recovery
- Annual LDAR program required with aim to reduce methane by limiting total volatile organic compound emissions from CHP plant exhaust

Coverage of Major AD Methane Emissions Sources

Anaerobic Digestion – PRVs, Tanks and Roofs

- PRVs to be inspected and properly operating
- Auxiliary standby flare to be installed and used first to combust surplus before use of PRV
- Venting and flaring gas for disposal is not permitted
- All flare operations shall be recorded and reported

Biogas Utilization – CHP Units

- Monitoring required on exhaust stack of CHP units
- Total volatile organic compound emission rates, including methane should be 1000 mg/m^3 or lesser

Biogas Utilization – Biomethane Upgrading

- Not addressed

Digestate Handling – Storage tanks

- Not addressed

Monitoring and LDAR Requirements and Reporting

- Annual self-LDAR by operator with summary report
- Centralized industrial monitoring, control and process analysis using systems like SCADA is required to reduce downtime
- Continuous monitoring required on auxiliary flare usage, pressure relief valves, and gas pressures on vacuum systems
- Annually reported parameters include total emissions from CHP plant, biofilter efficiency

Strengths and Shortcomings

Strengths

- Monitoring and reporting requirements are extensive and specific
- Monitoring methods, accreditation and data acquisition protocols are well-defined

Shortcomings

- Emissions caps and limits are not specified
- Self-inspection requirement
- Penalties for non-compliance are not mentioned

Germany | **Regulations and Adoption Dates:**
TRAS 120[43] – Feb 2019; TRGS 529[44] – May 2025; TA-Luft – 2021 (last rev); 44. BimSchV – 2019; GasNZV – 2019

Important Features

- Focus: safety. TRGS Rule 529 reflects the state of the art for activities involving hazardous substances use in biogas plants
- TA-Luft focuses on air pollutant emissions and partially covers AD methane from storage tanks and digestate handling, with indirect support for safety and flow-rate design via TRAS 120 guidance
- 44. BImSchV sets emission limits and monitoring requirements for biogas CHP units, influencing plant design, but does not address storage or upgrading emissions
- GasNZV regulates biomethane grid access, with no emissions or safety requirements, only indirectly affecting upgrading. Overall, emphasis on plant design to maintain flow rates and capacities

Coverage of Major AD Methane Emissions Sources

Anaerobic Digestion – PRVs, Tanks and Roofs
- Membrane roof systems must be replaced after six years with double-shell monitorable roofs
- Single membrane roof systems to be checked weekly at points using portable gas detection devices and every six months using methane optical methods
- TA-Luft requires gas-tight design of digesters and storage systems, capture of off-gases, and verification that methane losses remain below 3.7%, supported by periodic tightness testing

Biogas Utilization – CHP Units
- 44. BimSchV requires annual emission measurements and a total carbon limit, indirectly covering methane, but without specific leak detection requirements

Biogas Utilization – Biomethane Upgrading
- GasNZV requires proof that methane slip does not exceed 0.2% at the grid connection point, based on certification

Digestate Handling – Storage tanks
- TA-Luft requires technically gas-tight storage, connection to gas utilization systems, and measures to reduce residual emissions, but no continuous monitoring

Monitoring and LDAR Requirements and Reporting

- Continuous monitoring of generated biogas levels but not emissions
- Gas-components to be tight-tested every three years
- Technically-tight components are to be assessed every twelve years with leak tests every three years
- Gas-carrying system parts and pipe connections must be tested for technical leaks after a change requiring testing or repair and at appropriate intervals (TRGS 529)
- Leak tests must be ensured through foaming agents, inspection with mobile leak detectors, imaging methods with methane sensitive cameras, (TRGS 529)

Strengths and Shortcomings

Strengths
- Guidance on plant design, volume flow rates, over or under pressure protocols
- 44. BImSchV provides clear monitoring requirements and emission limits for CHP units
- GasNZV ensures low methane losses (0.2%) at the point of biomethane grid injection

Shortcomings
- Heavily rely on self-inspection and -regulation
- No explicit methane emissions caps across the component stages
- Digestate storage emissions (or design) are not comprehensively addressed
- Leak test intervals are too long, no continuous monitoring
- Methane is generally indirectly regulated via total corbon, no explicit target
- Penalties for non-compliance are not clearly defined
- No binding requirement for installation-wide methane measurement (fragmented framework)

France | Regulation and Adoption Date: ICPE 2781[45] – May 2025

Important Features

- Focus: best available techniques (BAT) for operation applicable to certain waste treatment and biogas production facilities
- No continuous monitoring or LDAR component
- Rule focused on fire, explosion and plant safety considerations and on odor prevention

Coverage of Major AD Methane Emissions Sources

Anaerobic Digestion – PRVs, Tanks and Roofs
- No requirements for LDAR or emissions monitoring except simple requirement for a PRV to be present

Biogas Utilization – CHP Units
- Not addressed

Biogas Utilization – Biomethane Upgrading
- These units have to be designed, operated, maintained and tested to limit methane emissions in effluent gases to 1% or 0.5%. This is the upper emissions by volume of biomethane produced for facilities with a biomethane production capacity of less than or more than 50 Nm3/h, respectively
- Compliance determined annually

Digestate Handling – Storage tanks
- There is no requirement for digestate storage to be under gas-tight conditions, or to be monitored for emissions

Monitoring and LDAR Requirements and Reporting

- The tightness of the digester, their biogas pipes and the over- and under-pressure protection equipment is checked during start-up and each restart, or at least on a monthly basis
- Monitoring of flare and digester operating pressure is required
- The devices ensuring the sealing of equipment whose failure is likely to cause gas release are subject to regular checks

Strengths and Shortcomings

Strengths
- Upper emission thresholds for biogas upgrading to biomethane

Shortcomings
- No monitoring and reporting requirements
- No emissions caps across most stages
- Methane emissions from AD tanks and roofs, biogas combustion in CHP, and digestate storage emissions are not addressed
- Leak test intervals are not well-defined and seem mostly self-enforced. Penalties for non-compliance are not mentioned

Refer to footnotes below for the citations used in the table and listed here:
BEK 1535[41]; SR2021 No.s 1, 6-10[42]; TRAS 120[43]; TRGS 529[44]; ICPE 2781[45]

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[41] Danish Energy Agency. (2022). BEK nr 1535 – *Executive Order on sustainability and reduction of greenhouse gas emissions for biomass fuels and liquid biofuels for energy purposes, etc.* Ministry of Climate, Energy and Utilities, Danish Energy Agency, j.nr. 202217539. Retrieved August 2025, from https://www.retsinformation.dk/eli/lta/2022/1535

[42] Environment Agency. (2021). SR2021, No.s 6, 7, 8, 9 – *Anaerobic digestion and on-farm anaerobic digestion facility, including use of the resultant biogas – installations and waste recovery operations.* Retrieved August 2025, from https://www.gov.uk/government/publications/sr2021-no-6-anaerobic-digestion-facility-including-use-of-the-resultant-biogas-installations

[43] Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. (2019). *Technical Rule for Plant Safety "Safety requirements for biogas plants (TRAS 120)"*. Retrieved August 2025, from https://www.dbds-gmbh.de/Medien/Dokumente/Lesefassung%20TRAS120.pdf

[44] Federal Ministry of Labor and Social Affairs. (2025). *Technical Rules for Hazardous Substances "Activities in the production of biogas (TRAS 529)"*. Retrieved August 2025, from https://www.baua.de/DE/Angebote/Regelwerk/TRGS/TRGS-529

[45] Ministry of Ecological Transition, Energy, Sustainable Development and the Sea. (2021). *ICPE 2781 – Order of 12/08/10 relating to the General Requirements Applicable to Classified Methanization Installations falling under the Registration Regime under Heading "No. 2781" of the Nomenclature of Classified Installations for the Protection of the Environment*. Amended by Order of June 17, 2021. Retrieved October 2025, from: https://www.legifrance.gouv.fr/loda/id/JORFTEXT000022727437/

SECTION 4

Non-Regulatory MMRV for Anaerobic Digesters

AD MMRV in Carbon Offsets and Other Crediting Methodologies

Carbon offsetting is the practice of compensating for GHG emissions via projects that reduce, avoid, or remove GHGs from the atmosphere outside the supply chain. The financial instrument used is a carbon credit and is defined as "a convertible and transferable instrument that allows an organization to benefit financially from an emission reduction of one unit of carbon."[46] A unit of carbon credit is equal to one metric tonne of carbon dioxide equivalent of emissions. Carbon credits can be transferred from the entity that produces the credit to the entity that needs the credit or another buyer, thus creating an economic opportunity for credit producers and a marketplace for carbon credit trading.

The AD industry is a major global carbon credit producer and seller. An important driver for developing a methane MMRV framework is to derive measurement-based data that can be used by reputable carbon crediting and offset accounting methodologies to calculate AD project methane emissions reductions and to generate verifiable carbon credits. Incorrect accounting of carbon emissions avoided or reduced by an AD project due to systemwide methane emissions can undermine a project's claimed positive climate impact and even result in negative impacts (compared to recommended GHG thresholds to meet accepted sustainability standards) in extreme cases due to methane's potency as a GHG.[9,24,47]

A summary of the carbon accounting methodologies developed by prominent carbon offset and crediting standards organizations for the AD project boundary is provided in Table 4.[48] These standards are responsible for certifying the vast majority (>90%) of all carbon credits ever traded and/or retired on voluntary carbon markets.[49]

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[46] IPCC (Intergovernmental Panel for Climate Change). (2005). *IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change* [Metz, B.,O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp. Annex II: Glossary, acronyms and abbreviations. Retrieved October 2025, from: https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_annex2-1.pdf

[47] IEA Bioenergy (International Energy Agency Bioenergy). (2025). *Reduction of methane emissions from biogas systems and landfills.* Retrieved August 2025, from: https://www.ieabioenergy.com/wp-content/uploads/2025/07/IEA-Bioenergy_T37_Reduction-of-methane-emissions-from-biogas-systems-and-landfills-oxidation.pdf

[48] The American Carbon Registry, the world's first independent and private carbon offset registry established in 1996; Gold Standard, a non-profit carbon crediting standard that was formed in 2003 with the intent to issue real, verifiable carbon credits for compliance projects under the United Nations-operated carbon offset scheme known as the Clean Development Mechanism, adopted under the Kyoto protocol; and Verified Carbon Standard, administered by the non-profit Verra to offset emissions for non-Kyoto protocol-related voluntary carbon offsets.

[49] SustainCert. (2025). *Main Carbon Standards.* Retrieved October 2025, from: https://academy.sustain-cert.com/topic/main-carbon-standards/

Table 4: Evaluation of methane emission sources, quantification principles, and emissions monitoring requirements for AD systems in the carbon accounting methodologies of select carbon offset and crediting standards

Carbon Offset and Crediting Standard	Baseline Scenario	Project Scenario for Carbon Credit Accounting	AD Methane Emissions Sources Included / Not Included	AD Process Stage Emissions Quantification	Default Values	Monitoring and Measurement-based Inputs
American Carbon Registry (ACR)[50]	Biomass sent to landfills and undergoes anaerobic decay	• Diversion of biomass to anaerobic digester • Biogas upgraded to biomethane • Digestate stored and cured • Compost land application • Compost displacement of fertilizer	**Included** • Pre-processing • Digester operations and leaks • Post-processing of digestate • Biogas upgrading to biomethane **Not Included** • Flaring	• Methodology only allows for lump sum emissions calculation for entire AD project (no breakdown for individual processes) • Methodology only allows component stage estimation for biogas upgrading with fixed emission factor	• 0.06-0.12 $MTCO_2e$/ short ton feedstock for pre-processing, digester and digestate post-processing combined • 0.0264 $MTCO_2e$/ short ton feedstock for biogas upgrading	• No ambient monitoring-based methane emissions rate or point source measurement survey inputs allowed
Gold Standard (GS)[46] via Clean Development Mechanism methodology: • Tool 14[47]: Project and leakage emissions from anaerobic digesters	Animal manure, agricultural waste and other organic waste in farms is decaying anaerobically	• Diversion of animal and agricultural waste from farms into anaerobic digester • Production of biogas for thermal application • Flaring • Digestate is stored on-site before soil application	**Included** • Pre-processing • Digester operations and leaks • Post-processing of digestate (storage) • Flaring **Not Included** • Biogas upgrading to biomethane • Biogas combined heat and power	• Methodology allows for calculating digestate storage and flaring emissions separately • Methodology does not allow breakdown for emissions from pre-processing, digester stages like pressure-relief valves, etc. into component-specific fractions	• 2.8-10% methane loss during digester stage • Flare methane destruction efficiency of 50% (open flare) to 90% (enclosed flare)[51] • Methane production capacity of liquid digestate can range from 5-20% • Methane generation capacity of solid digestate can range from 15-35% of biogas produced	• No ambient monitoring-based methane emissions rate or point source measurement survey inputs allowed for determining AD-stage emissions • Ambient monitoring based inputs to determine methane destruction efficiency in flares allowed

Carbon Offset and Crediting Standard	Baseline Scenario	Project Scenario for Carbon Credit Accounting	AD Methane Emissions Sources Included / Not Included	AD Process Stage Emissions Quantification	Default Values	Monitoring and Measurement-based Inputs
Verified Carbon Standard (VCS) via Clean Development Mechanism methodologies: • **AMS-III.AO**[48] Methane recovery through controlled AD • **AMS-III.D**[49] Methane recovery in animal manure management systems • **AMS-III.H**[50] Methane recovery in wastewater treatment	Three baseline cases include: • Biomass decomposing anaerobically in a solid waste disposal site (landfill) • Animal manure decomposing anaerobically in an animal waste management system • Wastewater sludge decomposing anaerobically decaying in a wastewater treatment system	• Diversion of organic waste from landfill to anaerobic digester • Diversion of liquid sludge from wastewater treatment system to anaerobic digester • Diversion of animal manure to anaerobic digester • Flaring • Digestate handled aerobically for soil application • Digestate stored under anaerobic conditions and/or delivered to a landfill • Liquid digestate discharged to a subsequent	**Included** • Digester operations and leaks • Post-processing of digestate (treatment, storage and disposal) • Flaring **Not Included** • Pre-processing • Biogas upgrading to biomethane • Biogas combined heat and power	• Methodology allows for calculating digestate storage and flaring emissions separately • Methodology does not allow breakdown for emissions from pre-processing, digester stages like pressure-relief valves, etc. into component-specific fractions • Emissions from biogas utilization considered zero as biogas is combusted for "gainful purposes"	• Physical leakages from the digester and recovery system are estimated using a default factor of 0.05 m^3 biogas leaked/ m^3 biogas or 5% methane loss • Flare methane destruction efficiency of 50% (open flare) to 90% (enclosed flare)[51]	• No ambient monitoring-based methane emissions rate or point source measurement survey inputs allowed for determining AD-stage emissions • Continuous flow measurements of biogas at different stages can be combined with methane fraction measured with a continuous analyzer to determine AD-stage methane loss from physical leakage and flare emissions using material mass balance

Refer to footnotes below for the citations used in the table and listed here: ACR,[50] GS,[51] CDM[52,53,54,55,56]

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[50] ACR (American Carbon Registry), (2021). *Methodology for the Quantification and Registration of Environmental Impacts of Green Finance for Diversion of Organic Waste for Anaerobic Digestion Project.* Version 1.1. Retrieved August 2025, from https://winrock.org/wp-content/uploads/2021/07/AnaerobicDigestion_Methodology_V1.1.pdf

[51] GS (Gold Standard). (2022). *Methodology for Animal Manure Management and Biogas Use for Thermal Energy Generation.* Retrieved August 2025, from https://globalgoals.goldstandard.org/standards/433_V1.0_Methodology-for-Animal-Manure-Management-and-Biogas-Use-for-Thermal-Energy-Generation.pdf

[52] CDM (Clean Development Mechanism Tool 14). (2024). *Methodological tool: Project and leakage emissions from anaerobic digesters.* Retrieved August 2025, from https://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-14-v3.pdf

[53] CDM (Clean Development Mechanism AMS-III.AO). (2010). *Methane recovery through controlled anaerobic digestion.* Retrieved August 2025, from https://cdm.unfccc.int/UserManagement/FileStorage/CDM_AMSU745LJQM81SDJJOJ2S4G7ID9EIKFGD

[54] CDM (Clean Development Mechanism AMS-III.D). (2017). *Methane recovery in animal manure management systems.* Retrieved August 2025, from https://cdm.unfccc.int/UserManagement/FileStorage/1AWXEKHVTYF423LCN56Z9GIMQOS8JR

[55] CDM (Clean Development Mechanism AMS-III.H). (2017). *Methane recovery in wastewater treatment.* Retrieved August 2025, from https://cdm.unfccc.int/UserManagement/FileStorage/I2PQUV5XSB1O3H7EW6DJ0ANTKRYF9G

[56] CDM (Clean Development Mechanism Tool 06). (2022). *Tool to determine project emissions from flaring gases containing methane.* https://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-06-v4.0.pdf

All the reviewed carbon offset and crediting methodologies promote the use of default emissions factors and values, with some limiting the ability to enter measured values. Default values can be useful to estimate emissions in the absence of available measurements. However, methane emissions estimates generated from default values may not be as representative as those obtained using measured values. Of note, there is a wide range of variation in the default values: In the Gold Standard methodology, methane loss can be assumed to vary from 2.8-10% during the digester stage, depending on the choice of digester-type, while methane destruction efficiency can be assumed to be as low as 50% (for open flares) to as high as 90% (for enclosed flares). Furthermore, there is no requirement for the producer and seller of AD carbon credits to quantify its "actual" emissions which can affect the accuracy and quality of credits sold, as well as not deliver the intended climate and environmental benefits.

The three reviewed methodologies (American Carbon Registry, Gold Standard and Verified Carbon Standard) have incomplete coverage of emissions in AD projects, failing to include important sources identified in Chapter 2. Further, there is inadequate provision in the current methodologies for AD projects which may have an in-place MMRV framework to use component-specific, measurement-based emissions factors to substitute the use of whole-system default values. Robust MMRV frameworks can strengthen AD carbon credits methodologies, which can be designed to incorporate project-level emissions values.

Industry Associations

Industry associations represent AD operators and their position on environmental issues. The public positions of selected biogas industry associations are summarized in Table 5. Overall, the **potential for AD systems to be a significant source of methane emissions is usually recognized and frequently treated as an economic loss**. Hence, best practices to avoid methane leaks and "losses" in operations are supported. For instance, the European Biogas Association recommends the use of "actual" measured methane loss values and breaking down default methane leakage values by emissions source to generate representative estimates. The World Biogas Association calls to set maximum GHG emissions thresholds for bioenergy feedstocks, or to set net minimum emissions reductions requirements over the baseline scenario. However, the role of these systems as significant sources of emissions is downplayed.

Robust MMRV is not clearly advocated for, and AD regulations are usually not publicly supported by the reviewed organizations. The main justification provided by European Biogas Association in their public response to legislative efforts to measure and mitigate methane emissions is the relatively small size of AD facilities and limited emissions compared to the fossil fuel sector.[57] **However, IEA notes that today's biogas plants emit between 2% and 5.5% of their methane output, far above average levels in the oil and gas industry (1.2%).**[9]

Biogas pipeline leading to the combined heat and power unit

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[57] EBA (European Biogas Association). (2021). *Consultation on legislation to measure and mitigate methane emissions in the energy sector.* Retrieved August 2025, from: https://www.europeanbiogas.eu/wp-content/uploads/2025/06/EBA-Contribution_Consultation-on-Legislation-to-Measure-and-Mitigate-Methane-Emissions-in-The-Energy-Sector.pdf

Furthermore, in the US, biogas and biomethane facilities are larger scale (average of 500 CH4 m3/hour and 1200 CH_4 m^3/hour in 2025, respectively) compared to the average EU biogas and biomethane plants (121 CH_4 m^3/hour and 483 CH_4 m^3/hour in 2025, respectively).[58] Best-practice safety-oriented regulations are recognized as contributing to the development of state-of-the-art biogas plants with a focus on minimizing methane losses. However, as reviewed in Chapters 2 and 3, methane emissions from AD can be significant, and current regulations are not sufficient to consistently or comprehensively quantify and reduce emissions.

Voluntary monitoring schemes that are focused on preventing methane emissions are usually supported by industry (e.g., the European Biogas Association) and are proposed as a more effective mitigation strategy, with conservative emissions default values in the accounting methodologies. The World Biogas Association recommends development of an LDAR plan with requisite optical imaging and sniffing methods. They recommend surveying AD sites every six months for unknown emissions leaks, and for each identified "leak to be documented, risk-assessed and repaired as soon as possible".[59]

Table 5: Evaluation of public positions of select industry trade association on methane emissions, emission sources, quantification principles and emissions monitoring requirements of AD systems

Trade Organization	American Biogas Council (ABC)[14]
Motivation and Goal	- Provides guidance for AD industry to estimate GHG emissionsintensity (CO_2e/MJ) of AD projects and convert that to equivalent GHG reduction amount for carbon offset purposes
Core Position on AD Methane Emissions	- As per ABC *"limited carbon emissions produced by methane digesters are vastly outweighed by significant emissions reduced"*
Position on Methane Regulations	- No official position found
Position on Methane Emission Sources and Quantification Principle	- Prescribes lifecycle analysis GREET model in their carbon accounting tool[54] - Recognizes emission sources within biogas system project boundary that need to be quantified but does not provide calculations to estimate methane emissions
Position on Emissions Monitoring and MRV Frameworks	- Does not advocate for any LDAR or emissions monitoring requirements - Does not provide any recommendations for a methane MMRV framework

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[58] To estimate the average size of biogas and biomethane facilities in the US and the EU, we used references from the American Biogas Council (2025) and The European Biogas Association (2025). In the US, approximately 2.5 million m^3 of biogas is captured per hour. Approximately 55% and 44% of this volume is used as biogas and biomethane, respectively. There are 1926 biogas and 659 biomethane plants in the US, and therefore the average production is 713 m^3/hour (power and heat) and 1,669 m^3/hour (biomethane) in 2025. For the EU, EBA says the average biomethane plant in the EU produces 483 m^3 of biomethane / hour, and that this is four times the size of biogas plants producing electricity and heat.

[59] WBA (World Biogas Association). (2024). *Global Biogas Regulatory Framework*. Retrieved august 2025, from: https://globalbiogasframework.org/

Trade Organization | European Biogas Association[55]

Motivation and Goal

- Advocates for the recognition of biogas, biomethane and other renewable gases as sustainable, on-demand and flexible energy sources that provide multiple socio-economic and environmental benefits

Core Position on AD Methane Emissions

- Recognizes the potential for significant methane emissions from different operational point and area sources

Position on Methane Regulations

- State that existing best-practice and plant-safety regulations (e.g. Germany TRAS 120 and France ICPE 2781) have led to state of-the art biogas plants with minimal methane losses[52]
- An oil and gas industry-styled EU methane regulation is not necessary due to relatively small size of the AD facilities, limited emissions compared to the fossil fuel sector, young maturity and small scale of the biogas industry, and having mostly small farmers and cooperatives as the main stakeholders[56]

Position on Methane Emission Sources and Quantification Principle

- Stress the need to voluntary quantification emissions from feedstock holding tanks, leakages at digester gas holders and gas holder fixation, emissions from safety valves, from open and not gas-tight covered digestate tanks, and from biogas upgrading and utilization units[56]
- Advocates detailing default methane leakage values and breaking down emissions by sources
- Prefers that the use of measured (actual) methane loss values be allowed in carbon accounting methodologies

Position on Emissions Monitoring and MRV Frameworks

- Advocates that a voluntary monitoring scheme based on LDAR surveys to reduce methane emissions including optional additional quantification to build inventories rather than regulatory MMRV and LDAR
- Believes that existing conservative emissions default values in the RED III directives are already incentivizing the calculation of actual emission values[52,58]
- EBA supports differentiated emission factors based on measurements across member states, feedstock types, and AD system plants[60]
- EBA has developed guidance to establish a voluntary LDAR plan with optional, additional quantification to build inventories for self (operator-conducted) and external (third-party) inspection of methane from biogas plants to enable operators to identify sources and reduce methane emissions from AD plants, and thus improve the environmental performance of the biogas industry, without being subject to any mandatory requirements[48]

Trade Organization | World Biogas Association (WBA)[53]

Motivation and Goal

- Provides tools for their members in terms of market knowledge and biogas infrastructure costs, and also influence policy development in countries in order to support the growth of the biogas industry

Core Position on AD Methane Emissions

- Framework calls for standards to avoid fugitive methane leaks in operations

Position on Methane Regulations

- No mention of or opinion presented on existing or proposed methane regulations in their flagship policy, regulations and standards framework – the Global Biogas Regulatory Framework[53]

Position on Methane Emission Sources and Quantification Principle

- Framework has policy resources for feedstock, digestate, biogas utilization and gas quality but does not address or recognize these components as emission sources of concern
- Framework calls to set maximum GHG intensity depending on bioenergy feedstocks, or minimum net emissions reductions required over the baseline scenario

Position on Emissions Monitoring and MRV Frameworks

- Framework recommends *"to set up and implement a risk-based LDAR programme"* similar to EU's Waste Treatment Best Available Technique Reference Document[59] which lays out the program fundamentals with applicable optical imaging and sniffing methods, and quantification of emissions using complementary methods. Both the LDAR plan and quantification for inventories are on a voluntary basis rather than a regulatory LDAR and MMRV.
- Framework calls to "*a method of surveying the site every six months for unknown emissions sources must be developed", and "any leaks identified during these surveys must be documented, risk assessed and repaired as soon as possible*"
- Framework recommends use of a documented environmental management system, which involves a fugitive emissions management plan with ongoing LDAR schedules and must be aimed at preventing leaks or emissions from gas, digestate, etc., Fugitive emissions should be recorded and reported to the local enforcing authority

Refer to footnotes below for the citations used in the table and listed here: ABC,[14,61] GREET,[62] EBA,[52,60,63,64,65] WBA[53,66]

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[60] EBA (European Biogas Association). (2023). *Design, build, and monitor biogas and biomethane plants to slash methane emissions.* Retrieved March 2026, from: https://www.europeanbiogas.eu/wp-content/uploads/2025/06/Design-build-and-monitor-biogas-and-biomethane-plants-to-slash-methane-emissions.pdf

[61] ABC (American Biogas Council). (2025). *Resources – Frequently Asked Questions (FAQs).* https://americanbiogascouncil.org/resources/biogas-faqs-american-biogas-council/#methane

[62] GREET (United States Department of Energy). (2025). *Greenhouse gases, Regulated Emissions, and Energy use in Technologies.* Retrieved August 2025, from: https://www.energy.gov/eere/greet

[63] EBA (European Biogas Association). (2020). *Minimum requirements for European voluntary systems for self and external inspection of possible methane emissions on biogas and biomethane plants.* Retrieved August 2025, from: https://www.europeanbiogas.eu/wp-content/uploads/2020/10/Minimum-requirements-for-European-voluntary-systems.pdf

[64] EBA (European Biogas Association). (2030). *Design, build, and monitor biogas and biomethane plants to slash methane emissions. Pursuing an efficient and sustainable scale-up of the sector.* Retrieved May 2026, from: https://www.europeanbiogas.eu/wp-content/uploads/2025/06/Design-build-and-monitor-biogas-and-biomethane-plants-to-slash-methane-emissions.pdf

[65] EBA (European Biogas Association). (2026). Improving GHG emissions calculation for the biogas and biomethane sector. Retrieved February 2026, from: https://www.europeanbiogas.eu/wp-content/uploads/2026/01/EBA_Position-Paper_-Annex-VI_20260123.pdf

[66] EU (European Commission). (2018). (EU) 2018/1147: *Establishing Best Available Techniques (BAT) Conclusions for Waste Treatment, European Union.* Retrieved August 2025 from: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32018D1147

Intergovernmental Organizations

Projects that utilize AD to reduce methane emissions are recognized under the Clean Development Mechanism (CDM) and Article 6 to meet the goals of national climate action plans submitted by countries in their Nationally Determined Contributions as part of the Paris Agreement.[67,68] A number of intergovernmental organizations and interagency partnerships have shown an increased recognition of the impact of unmitigated methane emissions on the carbon intensity calculations of AD systems. Many of these organizations actively advocate for development and deployment of methane MMRV frameworks to quantify and reduce methane emissions from the AD industry.[18,62,63] A summary of their positions is presented in Table 6.

Overall, the **potential for AD systems to be a significant source of methane emissions** is recognized. The IEA notes that today's biogas plants emit between 2% and 5.5% of their methane output,8 far above average levels in the oil and gas industry (1.2%), and advocates for routine monitoring of potential large sources whose emissions are dependent on operation and are time-variant.

AD regulations are supported by IEA Bioenergy, which also provides guidance on national regulations on flare combustion, biogas CHP utilization, and country-specific regulatory limits on methane emissions from upgrading.[42] They promote off-gas post-treatment technologies to meet local and national regulations on clean air and eligibility for renewable gas support mechanisms. Although the Global Methane Initiative (GMI) and IPCC do not offer a position on the need and efficacy of national AD methane emissions reduction regulations, GMI notes that adopting a methane MMRV at facility-level does support policies and regulations that require quantification of methane emissions and those which incentivize methane emission reductions, such as emissions trading schemes, cap and trade, among others.[62]

Overall, **project-level emissions monitoring is recognized as important for meeting reporting requirements, assessing climate risks and opportunities, and assessing mitigation impacts**. Documentation and reporting of monitoring results need to be harmonized to obtain comparable and representative results. However, no comprehensive and detailed MMRV framework or mitigation measures, including LDAR recommendations, are provided by these organizations.

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[67] UNFCCC (United Nations Framework Convention on Climate Change). (2025). *Paris Agreement Crediting Mechanism*. Retrieved August 2025, from: https://unfccc.int/process-and-meetings/the-paris-agreement/article-64-mechanism

[68] UNFCCC (United Nations Framework Convention on Climate Change). (2025). *The Paris Agreement and Nationally Determined Contributions* (NDCs). Retrieved August 2025, from: https://unfccc.int/process-and-meetings/the-paris-agreement/nationally-determined-contributions-ndcs

Table 6: Evaluation of public positions of select intergovernmental organizations on methane emissions, emission sources, quantification principles and emissions monitoring requirements of AD systems

Organization	Global Methane Initiative (GMI)
Motivation and Goal	• Advance cost-effective recovery and use of methane as a valuable energy source • Provides support for project development, training and capacity building, technology demonstration and market development
Core Position on AD Methane Emissions	• Holds the position that since biogas production is a significant source of methane emissions, robust accounting of emissions and reductions is needed to generate and sell carbon reduction credits in voluntary and compliance markets
Position on Methane Regulations	• No specific position taken • States in its Measurement Reporting Verification (MRV) guidance that purpose of MRV at facility-level is to support policies and regulations, such as emissions trading schemes which require source-level data.[62]
Position on Methane Emission Sources and Quantification Principle	• Project-level MMRV is important for methane emissions inventory accounting. • Does not provide any list of specific emissions sources and quantification methods/estimates • Proponent of MRV to develop nation-specific methane recovery rates and country-specific emission factors, compared to using generic default values which can be more conservative
Position on Emissions Monitoring and MRV Frameworks	• GMI considers project-level emissions MRV as vital for meeting reporting requirements, assessing climate risks and opportunities, and assessing mitigation impacts • Project MRV can be leveraged by governments and industry alike to develop better estimate of activities that cause emissions, and practices that can prevent such emissions from occurring • GMI has developed a biogas project MRV handbook,[63] intended primarily for national governments focused on best practices for project-level MRV but no emissions sources detailing • No specific emissions monitoring methodology, LDAR best practices and recommendations for other mitigation policies

Organization | International Energy Agency Bioenergy (IEA Bioenergy)

Motivation and Goal

- Mission to increase knowledge and understanding of bioenergy systems in order to enable market deployment and commercialization of environmentally sound, socially acceptable and cost-competitive low-carbon renewable energy technologies

Core Position on AD Methane Emissions

- Concerted application of best practices for methane management is essential to underpin the environmental case for biogases
- Today's biogas plants emit methane emissions in a range between 2% and 5.5% of their output, far above average levels in the oil and gas industry
- Practices such as closed digestate storage, combustion of off-gases during biogas upgrading processes, and LDAR programs are key

Position on Methane Regulations

- States that national regulations (time of residence, flare temperature, methane slip) need to be considered when selecting a technology for AD project
- Clarify in its post-treatment guidance that off-gas needs to be treated depending on local and national regulations on clean air and eligibility for renewable gas support mechanism[42]
- States the regulatory limits of different countries on methane emissions from upgrading

Position on Methane Emission Sources and Quantification Principle

- Compiles a lot of academic research to indicate that methane emission sources are both structural (deployed technologies) and operational (e.g. gas management) and that open storage of digestate, the CHP engine, leaks and the PRV are the most important sources, including long lasting pressure relief events[18]
- Observes that methane loss rates can range from 0.02-23.8% across European biogas plants with the highest emissions observed at older plants digesting sewage sludge
- Provides elaborate discussion on how to measure methane emission rates from sources, results of measurement studies and proposed mitigation measures

Position on Emissions Monitoring and MRV Frameworks

- Provides detailed content on different measurement and quantification devices and methods (further described in *Appendix A*) including both quantification in the scope of LDAR and side-wide measurements[18]
- The agency does not propose a formal methane MRV framework but rather describes all measurement technologies, their suitability for different applications, strengths and shortcomings, costs, etc.
- In support of a common MRV framework, their position is that, currently, several methods are in use and data sets have been provided by different international teams. The documentation and reporting of the results needs to be harmonized in order to obtain comparable and representative results
- A crucial part of any operation should be leak detection and repair plans and in particular frequent monitoring of any potential emission source on site. Potential large sources are the Combined Heat and Power units, Pressure Release Valves and large leaks. They need to be routinely monitored.

Organization | Intergovernmental Panel for Climate Change (IPCC)

Motivation and Goal

- Assess science to provide policymakers with most up-to-date knowledge on climate change

Core Position on AD Methane Emissions

- Fugitive emissions of methane may reduce the potential mitigation benefits of biogas production[64]

Position on Methane Regulations

- No position taken or found

Position on Methane Emission Sources and Quantification Principle

- States that 0–10% of the methane production is lost by leakages and other processes recommends a default value for national emissions inventories for biogas plants in the waste sector of 5% of the methane produced in absence of detailed information

Position on Emissions Monitoring and MRV Frameworks

- IPCC provides monitoring, calculation, and reporting guidelines for methane emissions from feedstock in baseline processes that ultimately AD systems are aiming to replace. IPCC does not provide a recommendation on the need for MMRV frameworks to quantify methane emissions from AD systems

Refer to footnotes below for the citations used in the table and listed here: GMI,[69,70] IEA Bioenergy,[18,42] IPCC[71]

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[69] GMI (Global Methane Initiative). (2022). *The Role and Importance of Measurement, Reporting, and Verification (MRV) for Biogas Projects.* Retrieved August 2025, from: https://globalmethane.org/documents/MRV%20for%20Biogas%20Projects%20Webinar%20Presentation.pdf

[70] GMI (Global Methane Initiative). (2022). *Policy Maker's Handbook for Measurement, Reporting, and Verification in the Biogas Sector.* Retrieved August 2025, from: https://globalmethane.org/documents/GMI_MRV%20Handbook%20for%20Biogas.pdf

[71] Nabuurs, G-J., R. Mrabet, A. Abu Hatab, M. Bustamante, H. Clark, P. Havlík, J. House, C. Mbow, K.N. Ninan, A. Popp, S. Roe, B. Sohngen, S. Towprayoon, 2022: Agriculture, Forestry and Other Land Uses (AFOLU). In IPCC, 2022: *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.009 https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter07.pdf

SECTION 5

Conclusions and Recommendations

Measurement-based research over the past decade has consistently demonstrated that methane emissions occur throughout AD systems. If left unmitigated, these emissions can substantially reduce the climate and environmental benefits that AD systems are intended to deliver.

Although countries have introduced regulations focusing on AD systems, these have primarily focused on improving the health and safety outcomes of plant operations. Economically feasible and operation-adjusted regulations that focus on **methane MMRV frameworks** and informed mitigation strategies are needed to guarantee the climate and environmental benefits of these plants. Methane MMRV frameworks serve multiple, interrelated purposes. They enable the quantification of methane emissions at both the source and facility levels, support compliance with regulatory requirements, allow for more accurate estimation of an AD facility's net carbon intensity, and help to prioritize methane mitigation efforts. More broadly, the implementation of methane MMRV within AD systems contributes to improved understanding and management of emissions across the sector.

Specifically, methane MMRV frameworks help to:

- Develop a clearer conceptual and quantitative understanding of methane emission sources, leak mechanisms, and effective mitigation strategies across AD component stages;
- Verify whether technological upgrades, operational improvements, and LDAR programs designed to reduce methane emissions are delivering the intended outcomes;
- Generate equipment-, industry- and country-specific methane leaks emission factors that can replace generic default values used in carbon accounting methodologies;
- Provide robust, measurement-based data to support emissions trading schemes, carbon crediting programs, and climate finance mechanisms; and
- Track progress toward national and sectoral climate mitigation goals.

This report synthesizes the current state of knowledge on methane emissions within the AD project boundary, reviews national regulatory approaches to curbing these emissions, and examines publicly available positions from key stakeholders. **Based on this assessment, we make the following policy and practice-oriented recommendations:**

First, **comprehensive data on emissions from different contexts needed to support the environmental benefits of AD systems is lacking**. Much of the existing information that characterizes emissions from AD focuses on medium- to large-scale facilities located in Western Europe, namely the UK, Germany, and Denmark. European digesters are generally more strictly regulated, so their methane mitigation is likely higher and digestate leakage lower compared to the U.S. There is little information that assesses emissions from smaller facilities in parts of the world where AD systems are rapidly being deployed, including Eastern Europe, Asia, Latin America, and Africa. It is not known if AD systems in these contexts have a similar emissions profile to those in the US and Western Europe, or if economies of scale have a significant impact on methane emissions. Hence, **regulations that support robust, but feasible MMRV frameworks are needed. Beyond regulations, implementation and effective enforcement of these regulations are critical since the effectiveness of MMRV systems depends not only on regulatory design but also on the capacity and rigor of oversight mechanisms**.

Second, **MMRV regulations must be paired with comprehensive LDAR programs that account for context-specific cost-benefit and techno-economic analysis of methane mitigation measures, covering both fugitive emissions and AD system designs or practices that intentionally vent methane.** Although not the focus of this report, recent studies that demonstrated that the vast majority of methane emissions in AD projects in the EU can be eliminated as no net cost, particularly in the feedstock ad digestate storage phases.[3] This demonstrates the need to improve data across multiple geographies to characterize baseline emissions across systems, quantify the costs associated with mitigation measures, and evaluate the associated emissions reductions. Such information should be used in the development of future methane policies, including LDAR programs and equipment and work practice standards.

Third, **carbon offset and crediting methodologies should apply conservatively high default emissions factors in addition to facility-level accurate values for baselines** to incentivize the adoption of facility-level MMRV and guarantee adequate environmental benefits of AD. Stronger, facility-level MMRV could also support an insetting market by issuing methane attribute certificates, linking verified emissions reductions directly to corporate climate commitments. Measurement-based accounting for baselines and emissions would enhance the credibility of issued carbon credits, improve buyer confidence, and better align claimed climate benefits with actual performance.

Fourth, **industry trade associations** should play a proactive role by **providing technical guidance, promoting best practices, and fostering collaboration with the research community**, following established models in Europe.

Finally, **intergovernmental and environmental organizations should continue to support the development and dissemination of practical MMRV guidance and tools** that enable AD operators to identify, quantify, and mitigate methane emissions.

Together, these actions will help ensure that AD delivers verifiable climate benefits and contributes effectively to near-term methane mitigation and national climate goals.

APPENDIX A

Process Breakdown within the Anaerobic Digestion Project Boundary and Commonly Observed Methane Emission Points

Table 7: Process breakdown within the Anaerobic Digestion project boundary and commonly observed methane emission points.

Process	Classification	Description of Source	Methane Emissions Location	Typical Emissions*	Leak risk
Process Stage: Feedstock Processing and Storage					
Loading and Unloading	Process, Diffuse, Structural	Emissions can occur if biomass decomposition happens before being fed into the digester	• Open storage tanks • Receiving areas • Not-gastight tanks • Biofilter surfaces following exhaust air treatment • Ventilation exhaust without biofilter • Not-gastight mixing tanks, and gas outlets	< 0.5%	Medium risk, up to 5% observed in literature
Substrate Storage				< 0.5%	
Mixing and Feeding		Mixing can hydrolyze a substrate and trigger decomposition emissions	Not-gastight mixing tanks, and gas outlets	< 0.5%	

Process	Classification	Description of Source	Methane Emissions Location	Typical Emissions*	Leak risk
Process Stage: Anaerobic Digestion (biogas production)					
Anaerobic Digester	Fugitive, Diffuse, Operational	Methane emissions can leak from different components of the digester tanks and lagoons as gas pressure builds up	**Emission points include:** • Inspection hatches • Pipe connections • Leaks near mixer axles	0.5% - 1%	Medium risk, up to 5% observed in literature
Digesters and Gas Storage	Process, Point-Source, Structural	Pressure relief valves are safety devices that allow stored biogas to be quickly vented into the air when abnormal conditions are encountered in the digester.	Pressure release valves are typically located along the top of the digester tank body and/or rooftop.	< 0.5%	
	Fugitive, Point-Source, Operational	Pressure release valves can suffer from breakdown due to a lack of maintenance, which can lead to unnecessary venting of methane emissions. **These conditions include:** • Stuck or a faulty pressure relief valve • Leaking flange connection • Open ball valve • Missing water seal • Pressure release valves can actuate if the gas holders operate at too high-filling levels	Pressure release valves are typically located along the top of the digester tank body and/or rooftop.	0.5% - 1%	
	Fugitive, Diffuse, Structural Operational	**This emissions category is one of the most prevalent observed leaks within the AD system boundary.** • Cracks in concrete walls and roofs • Leaks and tears in soft foil roof covers • Membrane fixation leaks at the transition between digester wall and membrane dome • At wires to adjust agitators (due to lack of sufficient lubrication) • Leaking gasket in pipe leadthroughs • Diffusion can take place through aging digester membrane roofs	**Emission points include:** • Digester walls, roofs • Transition of digester wall and membrane dome • Agitators inside tanks and lagoons • Pipe gaskets • Membrane roofs	1% - 2%	

Process	Classification	Description of Source	Methane Emissions Location	Typical Emissions*	Leak risk
Process Stage: Biogas Utilization (includes upgrading)					
Gas Equipment and Pipework	Fugitive, Diffuse, Operational	Undetected CH_4 leaks	**Emission points include:** • Flange joints and pipe connections, • Gas engines, • Gas upgrade units and filters • Compressors, etc.	< 0.5%	High risk, 8%-10% observed in literature
Combined Heat and Power / Boiler	Process, Point-Source, Structural	Methane slip can occur due to incomplete combustion inside the internal combustion engine. This sub-stage is a major source for methane loss at biogas plants.	Gas engine exhaust	1% - 2%	
Biogas to Biomethane Upgrading	Process, Point-Source, Structural, Operational	Vented off-gas from water or amine physical scrubbers, and some pressure swing adsorption contains a higher percentage of methane, while membrane technology and chemical adsorption lead to lower emissions. There are many moving parts and machinery in biogas upgrading units including compressors, and gas leaks are common in this system.	**Emission points include:** • Off-gas from bio-upgrading units • Compressors	Variable; from < 0.5% to > 2%	
Flaring	Process, Point-Source, Structural, Operational	Flares ought to start automatically under abnormal conditions when the biogas fill level in the digester is too high or when an emergency/safety protocol is activated. Methane leakage will also occur if the biogas in the flare is not fully combusted because of no ignition in the torch, or as a result of using dated flare technology with low combustion efficiency.	Flare stack	0.5% - 1%	

Process	Classification	Description of Source	Methane Emissions Location	Typical Emissions*	Leak risk
Process Stage: Digestate Processing and Storage					
Separation / Dewatering	Process, Diffuse, Structural, Operational	Emissions occur from open and not-gas-tight digestate storage tanks and are influenced strongly by the presence or lack of solid-liquid separation	Screw press in digestate tank or lagoon	< 0.5%	High risk, emissions up to 15% observed in literature
Pasteurization	Process, Point-Source, Structural	An optional closed stainless steel system to remove pathogens before digestate is utilized for other applications	Pasteurization tank	< 0.5%	
Storage	Process, Diffuse, Structural	Significant methane emissions occur from open and not gastight digestate storage tanks. If the retention time of the substrate in the digester tank is not sufficient, the resulting digestate has a high residual methane potential. The digestate temperature, substrate amount and characteristics (e.g. percent of volatile solids), level of filling, and meteorological conditions all have a major influence on the methane emission rate from AD digestate. This stage is potentially the largest source of methane within the AD project boundary.	Digestate tank, roof, membrane cover, or digestate storage area and lagoon	> 2% with high risk of significant emissions	

*Relative magnitude of methane emissions from each AD component sub-stage.

APPENDIX B

Description of National Regulations Affecting AD Industry

National regulations affecting the AD industry are described below and summarized in Table B-1.

Denmark

Denmark has an annual biogas production of 7 TWh[72] with about 80% of the biogas upgraded to biomethane and injected into the gas grid. Denmark was one of the first EU countries to introduce voluntary programs for fugitive methane detection and mitigation from the AD industry. On the basis of outcomes of an industry-wide study commissioned by the Danish Energy Agency (DEA) between 2019-21 that generated a 2.5% national methane emission factor for the Danish biogas industry,[20] the DEA adopted national regulation BEK # 1535[36] in December 2022 (effective January 2023).

The regulation:

- Aims to reduce methane loss, which might reduce the climate benefit of the systems,
- Requires all biogas plants to have a self-monitoring program and an annual leak detection performed by an independent verifier.

The salient features of this regulation are:

- A review of the undertaking's biogas production, upgrading, and purification processes is to be carried out by an independent and competent third party at least once a year to identify methane losses, and a plan for the measures that should be implemented to avoid methane losses,
- Implementation of a customized LDAR or self-inspection program by the regulated undertaking, with audits by the third party, that would include experimental measurements to detect methane leaks, and repair actions performed by the operators aimed to reduce the leakage,

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[72] Gustafsson, M., Meneghetti, R., Souza Marques, F., Trim, H., Dong, R., Al Saedi, T., Rasi, S., Thual, J., Kornatz, P., Wall, D., Berntsen, C., Saxegaard, S., Lyng, K.A., Nägele, H.J., Heaven, S., Bywater, A. (2024). A perspective on the state of the biogas industry in 12 member countries of IEA Bioenergy Task 37. Retrieved August 2025, from https://www.ieabioenergy.com/wp-content/uploads/2024/10/IEA_Bioenergy_T37_CountryReportSummary_2024.pdf

- On demonstration of compliance by a facility, the frequency of the mandatory DEA review to identify methane losses may be reduced to every two years,
- A 1% emissions cap on methane loss from biogas upgrading equipment, and,
- A cessation of state subsidies and fines on failure to comply with rectification deadlines issued by the DEA.

United Kingdom

The total biogas production in United Kingdom (UK) is about 32 TWh.[21] In contrast to Denmark's biogas regulation, the Environment Agency (EA) of the United Kingdom adopted a guidance-styled series of regulations – SR2021 in December 2021,[37] which were further updated in 2022 and 2023. **The SR2021 series consists of six regulations pertaining to manufacture and use of biogas, namely:**

- **SR2021 No 6:** Anaerobic digestion facility, including use of the resultant biogas – installations
- **SR2021 No 7:** anaerobic digestion facility, including use of the resultant biogas – waste recovery operation
- **SR2021 No 8:** On-farm anaerobic digestion facility using farm wastes only, including use of the resultant biogas – installations
- **SR2021 No 9:** on-farm anaerobic digestion facility, including use of the resultant biogas – waste recovery operation
- **SR2021 No 10:** anaerobic digestion of non-hazardous sludge at a wastewater treatment works, including the use of the resultant biogas
- **SR2021 No 1:** capture, treatment and storage of biogas from lagoons and tanks

The main purpose of these regulations is to provide guidance for management, operations, emissions and monitoring of anaerobic digestion facilities for purpose of biogas recovery. **The salient highlights of these regulations aimed at reducing methane leaks and preventing methane losses are:**

- Best Practices
  - The pressure relief and vacuum systems should be inspected to ensure they are correctly seated.
  - Methane leak detection and programmed routine maintenance inspections and repair shall be carried out and a record maintained.
  - An auxiliary standby flare shall be available to combust unburnt surplus biogas or bio methane.
  - The operator shall only use the auxiliary standby flare in the event of an emergency and during maintenance to protect the integrity of the plant.
  - All flare operations shall be recorded and reported.
  - Operators shall have procedures and contingency measures in place for when biogas demand is reduced. Venting and flaring gas for disposal purposes is not permitted.
- **Emissions and Monitoring**
  - Monitoring stacks on CHP biogas utilization units – Total volatile organic compounds (VOCs) emission rates, including methane, should be 1000 mg/m³ or lesser.
  - Monitoring personnel must have MCERTS accreditation (EA's Monitoring Certification Scheme).
  - The operator will implement an LDAR program to detect and mitigate release of VOCs, including methane. The operator shall undertake a minimum of annual inspections and provide a summary report. Emissions limit will be as agreed with the EA as a percentage of the overall gas production.
  - An LDAR program means a structured approach to reduce fugitive emissions of organic compounds by detection and subsequent repair or replacement of leaking components. Currently, sniffing (described by EN 15446) and optical gas imaging methods are available for the identification of leaks.
  - Other parameters that need to be continuously monitored would include auxiliary flare usage, pressure relief valves, and gas pressures on vacuum systems, using the SCADA (Supervisory Control and Data Acquisition) industrial monitoring method.
- **Reporting**
  - Emissions from the combustion plant are to be reported on an annual basis by January 31st each year.
  - Emissions removal efficiency of biofilter and other abatement systems to be reported on an annual basis by January 31st each year.
  - Digester process and gas production process monitoring summary reports – quarterly during the first year then yearly thereafter or as agreed with the EA.
  - Yearly summary report of over-pressure and under-pressure events detailing mass balance based methane-release is required.
  - Leak detection and repair reports to be submitted annually by January 31st.
  - Use of auxiliary flare burning surplus biogas to be reported by January 31st each year.

Germany

Germany is the dominant producer of biogas in Europe with an annual production of 87 TWh.[32] The regulation of methane emissions from the biogas and AD industry is achieved through a series of federal regulations that focus on plant safety considerations, hazardous substances, and plants with combustion engines. **Few key regulations are discussed below:**

TRAS 120

This is formally known as the Technical Rule for Plant Safety – Safety Requirements for Biogas Plants.[38] The purpose of this Rule is to provide state of the art guidance on safety technology in AD plants.

Some of the highlights of this rule include:

- **Emissions Self-Monitoring**
  - The operator must specify in a self-monitoring concept (plan) which conditions and processes must be monitored to ensure proper operation.
  - The biogas level in gas storage tanks, including those in fermentation tanks, must be continuously monitored, and must also be equipped with automatic devices for detecting and reporting impermissible gas levels.
  - An equivalent measure must ensure that the (additional) gas consumption devices (like an enclosed flare) are automatically switched on when the gas utilization device (CHP unit) is shut down or switched off, before any biogas is released from an overpressure safety device.
  - The space between the gas membranes and their outer casing must be monitored to detect leaks in the gas membrane.
- **Inspection and Maintenance**
  - The tightness of all system components exposed to gas, including the functionality of shut-off valves, must be tested and assessed at least every three years unless continuous monitoring is carried out.
  - In the case of system components that are designed to be technically tight in the long term, the recurring leak test can be carried out after twelve years.
  - A test for leaks using a suitable, methane-sensitive, optical method must be carried out after three years between leak tests.
- **Digester Roof Membranes**
  - The components of the membrane systems must be replaced at the end of the service life or after six years of operation at the latest.
  - Membrane systems must be operated with an additional outer covering of the gas diaphragm that enables constant monitoring of the interstitial space. Membrane systems that do not meet the requirement must be replaced with a monitorable double-shell system at the latest by the end of their service life.
  - Existing single-shell membrane systems must be checked daily for mechanical damage, at least weekly at relevant points such as the container connection and inspection openings of the membrane using portable gas detection devices and at least every six months using methane-sensitive optical methods (gas camera) to check for leaks.
- **Plant Design**
  - The gas utilization facilities must be able to utilize the entire minimum and maximum biogas produced.
  - The additional gas consumption device must have priority over the response of an overpressure safety device.
  - System components exposed to gas, including all pipe connections, must be installed, operated, inspected and maintained in such a way that they are ‘technically leakproof’ in the long term. If this cannot be achieved due to design or construction, the corresponding gas-carrying parts of the biogas plant must be at least ‘technically tight’.
  - Gas systems must be dimensioned for expected volume flows and flow resistances so that impermissible negative pressure is not to be expected during normal operation.

TRGS529

This regulation is known as the Technical Rule for Hazardous Substances- Activities in the Production of Biogas.[39] The purpose of this Rule is to reflect the state of the art and proven scientific findings for activities involving hazardous substances, including their classification and labeling for activities involving hazardous substances in the operation and maintenance of biogas plants.
Some of the highlights of this rule include:

- **Tightness of the Gas-Carrying System Components**
  - Gas-carrying system parts and pipe connections must be tested for technical leaks before initial commissioning, after a change requiring testing or repair and at appropriate intervals.
  - A test plan for recurring leak tests must be maintained. Inspection plans must be reviewed or checked by the employer at least every 6 years and adapted as necessary.
  - The leak tests must be ensured through either testing for leaks with foaming agents, and/or Inspection with mobile leak detectors, leak detectors, imaging methods with methane sensitive cameras, etc.
  - The leak test must include detachable connections that are not ‘technically tight’ by design in the long term, e.g. gas storage tank fastenings, flat-sealing flange connections, dynamically stressed system parts, such as diaphragm covers, shaft bushings and expansion joints.
  - If the measurement and monitoring of the gas concentration during the performance of activities are part of the protective measure concept, the suitable portable gas warning devices must at least enable the measurement of the following gas components: methane, carbon dioxide, hydrogen sulfide, and oxygen.

France

The biogas production of France as per latest estimates is about 25 TWh.[32] The main regulation governing methane emissions from the French AD industry is brought forth by the Ministry of Ecological Transition and codified as ICPE (Classified Installations for Environmental Protection) authorization under Section 2781 (General Requirements and Technical Rules for methanization facilities), and was adopted in 2021. These rules are meant to be best available techniques (BAT) applicable to certain waste treatment and biogas production facilities covered by the permit regime and the IED Directive. **Some of the key points in the regulation pertaining to methane emissions reduction are as follows:**

- **Space ventilation:** A regularly checked and calibrated monitoring system for detecting methane, hydrogen sulfide and carbon monoxide is needed that ensures that the premises are properly ventilated.

- **Biogas treatment**
  - Biogas-to-biomethane systems are designed, operated, maintained and tested to limit methane emissions in effluent gases to 2% by volume of biomethane produced, for facilities with a biomethane production capacity of less than 50 Nm^3/h. From Jan 1st, 2025, the value is reduced to 1% by volumed of biomethane produced.
  - 1% by volume of biomethane produced, for facilities with a biomethane production capacity greater than 50 Nm^3/h. From January 1st, 2025, this value is reduced to 0.5% by volume of biomethane produced.
  - Compliance with these values is assessed annually.
  - Biogas venting due to storage capacity in the AD tank is forbidden.
- **Periodic verification**
  - In the case of solid or waste-based anaerobic digestion plants requiring repeated loading and unloading of materials, the tightness of equipment is checked every time it is handled, or at least once a month.
  - The operator also checks the reliability of the installed gas analyzers (methane, O_2) every six months.
- **Inspection and layout of biogas and biomethane pipeline:** Biogas pipe fittings are welded if located in the immediate vicinity of a room where people are present, other than the combustion, purification or compression room. If they are not welded, a fixed gas detection system is installed in the room. An audible and visual alarm is set up to be triggered when detection is greater than or equal to 10% of the lower explosive limit for methane.

United States

The U.S. Environmental Protection Agency and the U.S. Department of Agriculture operate a collaborative program, AgSTAR, that promotes the use of biogas recovery systems to reduce methane emissions from livestock waste. The AgSTAR program has published a biogas toolkit that serves as a centralized knowledge hub for biogas project stakeholders. **Some of the prominent resources published by AgSTAR that serve as the primary design and operational handbook for biogas and AD facilities include:**

- **Project Development Handbook[12]:** This is a comprehensive compilation of latest knowledge and a framework for project development for the AD/biogas systems industry.
- **Anaerobic Digester/Biogas System Operator Guidebook[35]:** This is a comprehensive technical resource that provides best practice guidance on operation and maintenance of AD/biogas systems. Topics like emissions and leak detection are covered across the Biogas Handling and Conveyance, System Inspection and Maintenance, and Safety chapters.

In the absence of federal regulations curtailing methane emissions and leaks from biogas plants, the AD industry in the U.S. is by and large self-regulated. The AD industry is still subject to state, regional and local permitting from air quality agencies focused on criteria pollutant, reactive organics and air toxics emissions control, and this can indirectly lead to some degree of methane emissions control from regulated biogas plan.

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[i] IEA Outlook for Biogas and Biomethane, https://www.iea.org/reports/outlook-for-biogas-and-biomethane/key-findings

[ii] KAS, KAS-3.K Committee report. 2022