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Methane emissions in the biogas and biomethane supply chains in the EU

An analysis to update the greenhouse gas emissions accounting methodology of Renewable Energy Directive Annex VI

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Contents

Abstract

The report summarizes the current knowledge on the state of methane emissions from biogas plants. It delves into modern methods to detect and quantify biomethane emissions as well as best practices to mitigate them. Based on recent initiatives and good examples, the report defines a methodology to consider biomethane emissions within the greenhouse gas emissions assessment of biogas for CHP and biomethane pathways, consistent with the EU Renewable Energy Directive. The methodology relies on a set of best practices that allow to avoid and mitigate as much the methane emissions as possible while remaining feasible. Following the best practices allows operators to claim reduced default values for the greenhouse gas emissions.

Authors

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Executive summary

Full accounting of methane emissions from biogas and biomethane plants is challenging, since they come partly from leaks, accidental losses and incorrect management operations and partly from emissions sensitive to operating procedures and climate conditions. The main goal of this report is to carry out a review of all methane emissions from biogas and biomethane production in order to provide an updated, comprehensive methodology for emissions accounting for biogas and biomethane production, including methane losses.

Policy context

Considering the greenhouse gas (GHG) emissions calculation for gaseous fuels in the Renewable Energy Directive (EU) 2018/2001 (RED II), the typical and default values for biogas and biomethane in Annex VI already consider some specific sources of methane emissions, such as the ones associated with digestate management, biomethane upgrading section and CHP engine. All other emission sources, especially fugitive and operational emissions, are not included. However, RED II includes a list of default values for the GHG emissions saving for biofuels and biomass fuels (including biogas and biomethane), conservative values compared to normal production processes, that are obtained by increasing the emissions from processing (including upgrading) by 40%. When included in RED II, it was considered that this increase contained the fugitive and operational methane emissions. This increase in GHG emissions related to processing accounts for a variability of biogas plant configurations, technologies and efficiencies in operation.

In the current methodology, RED II neither explicitly includes a term in the formula for accounting for methane losses, nor a specific methodology to calculate such losses from biogas and biomethane production. Besides improving the accuracy of the calculation of environmental benefits of biogas pathways, such methodology could also encourage operators to minimize their methane emissions and thus their overall GHG emissions by incentivizing leak detection and repairs as well as the deployment of less emitting technologies.

To define and include actual (bio)methane emissions from biogas plants in the current EU legislative framework, this report: (1) reviews recent existing experimental evidence from measuring campaigns of methane losses from biogas plants (retaining 11 studies measuring over 100 plants); (2) proposes updated methane emission factors; (3) proposes a methodology to account for methane emissions in the current RED II GHG emissions calculations.

Key conclusions

The report provides insights on the experimental detection of (bio)methane emissions, best practice measurement methods and quantification of methane emissions from scientific literature, EU funded projects and measurement campaigns. Specific emissions factors were then derived for the major components of biogas plants from direct measurements. Voluntary systems proved to be able to successfully reduce methane emissions, based on guidelines to monitor and quantify the methane emissions, integrating regular self-inspection and measuring campaign activities by third parties, and by repairing or replacing components with methane emissions.

The methodology proposed in this report also allows using a mix of actual (measured) and pre-calculated default values for methane emission factors for the different parts (sections) of the biogas/biomethane plant. Plant operators can follow a programme to claim a lower default value for methane emission factors, conditional on the compliance (verified by a Voluntary Certification Scheme) with the minimum requirements, such as the use of best available technologies and the

implementation of methane detection, monitoring and repair programme. Proposed default values are summarized in **Table 1**. For the biogas upgrade section and the Combined Heat and Power (CHP) unit, actual values could also be provided by the equipment manufacturer, based on documented measurements, subject to subsequent regular measurements.

Table 1: Summary of proposed emission factors in [% of produced methane] and additional emission factors if not using best practices for all processing steps (methane global warming potential of 27)

<table>
<tr><th>Plant part</th><th>Type</th><th>Best practice [%]</th><th>Standard practice [%]</th><th>Emissions for standard practice [g CO_2eq/MJ]</th></tr>
<tr><td>biogas processing</td><td>piping, maintenance, overpressure events, leaks</td><td>0.5</td><td>5.0 (0.0)</td><td>24.3</td></tr>
<tr><td rowspan="2">digestate management</td><td>digestate composting or storage [silage]
[biowastes]
[manure]</td><td>0.1 (0.0)</td><td>2.2
2.5
10.0</td><td>11.3
13.0
53.5</td></tr>
<tr><td>storage with RMP measurement below the proposed default emission factor for (open) digestate storage</td><td>X = RMP * 0.25</td><td>X= RMP * 0.75</td><td>(X - 0.1) * 5.4</td></tr>
<tr><td rowspan="3">Biogas upgrading to biomethane</td><td>Any technology</td><td>0.0</td><td>3.0</td><td>16.2</td></tr>
<tr><td>Technologies certified or measured to have < 0.2% of produced methane in the off-gas</td><td colspan="2">0.2</td><td>15.1</td></tr>
<tr><td>Technologies certified or measured to have < 1% of produced methane in the off-gas</td><td colspan="2">1.0</td><td>10.8</td></tr>
<tr><td>Biogas use in CHP</td><td>Slippage of methane in the exhaust gas</td><td colspan="2">1.7</td><td></td></tr>
</table>

Colours: **Same as in current RED II**

Newly proposed value in this study

(Current RED II value)

Source: JRC analysis

Main findings

Emissions due to the design of the technology deployed (named “structural emissions”) can be strongly reduced through regular maintenance interventions and the use of best available technologies. Operational emissions can be limited with correct management operations, regular leak detection and the use of best available technologies and practices.

The proposed action to mitigate biomethane emissions claiming default values in compliance with minimum requirements of monitoring programmes, regular maintenance and repairing actions, already showed positive results in some member states.

The inclusion of all biomethane emissions in the GHG emissions calculations, proposed in this report could significantly affect biogas and biomethane sustainability. The impact of the proposed changes is summarized in chapter 6.

1 Introduction

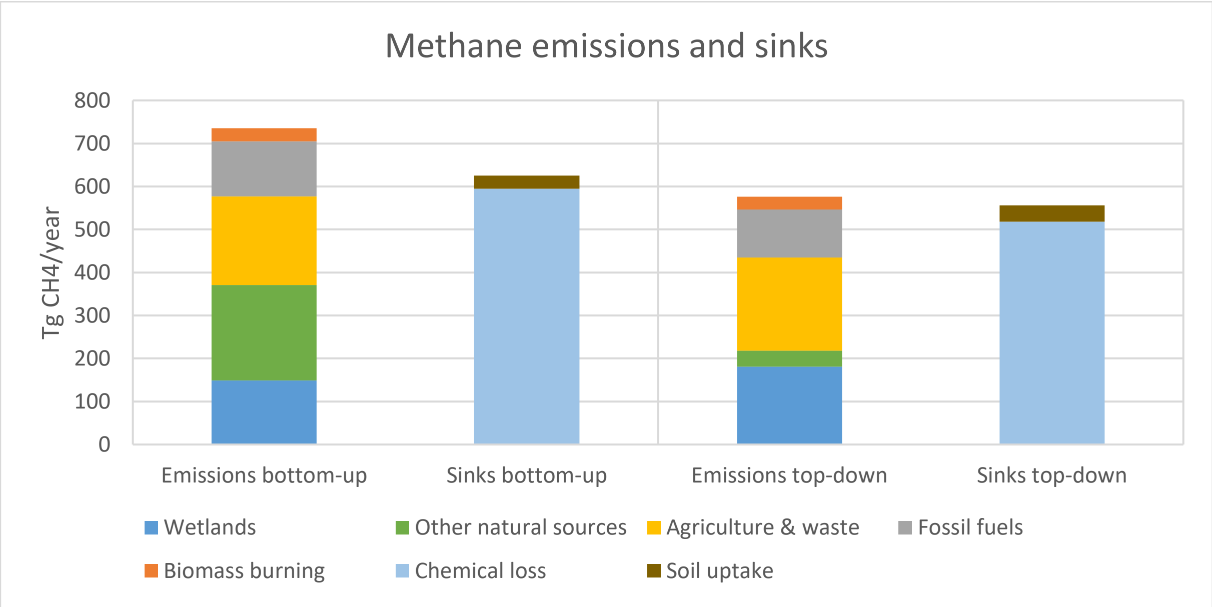
1.1 Methane as a GHG and its main anthropogenic emission sources

Methane is a major greenhouse gas (GHG), having a global warming potential of about 30 times higher than carbon dioxide over a 100 years period, according to IPCC AR6 (IPCC, 2021). However, methane is a short-lived gas compared to carbon dioxide and a significant mitigation in short times would have a rapid and significant effect on climate change.

The main anthropogenic sources of methane are the fossil fuels, agriculture and waste management sectors. Anthropogenic methane emission sources include landfills, fossil fuels extraction and processing, agricultural activities, stationary (energy production) and mobile combustion (transport sector) systems, wastewater treatment and certain industrial processes. Over the last two hundred years, the atmospheric methane concentration has almost doubled, largely due to human-related activities, and probably all methane emissions attributed to the energy sector have been underestimated so far according to the latest findings (IEA, 2022). Over the last 30 years, with the reduction of coal production in Europe, methane emissions from coal mining have declined considerably (77%), while those from the natural gas sector increased (by 16%), despite high uncertainties in the estimation (Van Dingenen et al., 2018).

Statistics show that in the EU, 54% of man-made methane comes from the agriculture sector - of this: enteric fermentation is responsible for about 81%, manure for 17%, while contributions from rice cultivation are about 1% (EEA, 2019; European Energy Agency, 2022). Thus, the largest CH_4 emitting source is the farming sector and in particular livestock. Depending on the way to estimate the emissions (bottom-up by summing emissions from process models or top-down through atmospheric observations), the absolute value of natural emissions and sinks can vary, but the scale of emissions from agriculture is relatively certain (**Figure 1**).

Figure 1: Global methane emissions and sinks for 2017. About half of the agriculture and waste emissions come from enteric fermentation and manure. Emissions associated to sinks are negative, hence considered absorbed/mitigated by plants, oceans, atmosphere and soil.



Source: Saunois et al. (2020), JRC analysis

1.2 Biomethane production and its potential

In 2021, Europe was the largest producer of biogas in the world (IEA, 2024). Biogas production in EU27 reached 223 TWh (about 21 billion cubic meters of biomethane equivalent) in 2022, with 68 TWh electricity production in 2022 in EU27 from biogas and about 5 Mtoe biogas heat production (Eurostat, 2020; Statista, 2022; Motola et al., 2022; European Biogas Association, 2023). The number of biogas plants exceeded 20,000 units, where Germany is by far the largest market with 99 TWh, accounting for two-thirds of Europe's biogas plant capacity (IEA Bioenergy, 2021; European Biogas Association, 2023; European Biogas Association, 2021). In 2021, the „Energy Balances" (Eurostat) recorded 2.37 bcm injected to the natural gas grid, which represents 13% from the total biogases (14,928.90 ktoe or 17.17 bcm) produced in 2021. If added 0.14 bcm from biogas used in road transport, total biomethane production in the EU27 was at least 2.51 bcm as there is no track if the „Industry" (507 ktoe) and „Other sectors" (1,816 ktoe) has consumed biogases for heat, electricity or combined or as biomethane. In 2021, biomethane was injected to the grid in 14 Member States (BE, CZ, DK, DE, IE, ES, FR, IT, LU, HU, NL, AT, FI, SE). Upgrading biogas to biomethane increased significantly in the EU since 2011 to reach about 4.2 billion cubic meters in 2022 and the number of biomethane plants reached 1,323 (European Biogas Association, 2023). Today, the situation is still growing but there are still no available official data to refine such numbers.

Moreover, in the coming years a rapid market uptake of biomethane production is expected as proposed by the REPowerEU (European Biogas Association, 2022), aimed to deliver 35 bcm biomethane by 2030. According to a recent IFEU report published in 2022 (Abdalla et al., 2022) in EU there is sufficient sustainable feedstock to achieve this goal. The expected ramp-up in biomethane production would also increase the impact of biomethane emissions, therefore monitoring and mitigating actions are of high importance to achieve methane emission targets.

1.3 Biogas plants and possible methane emissions

A biogas plant uses biogenic feedstock from different sources in an anaerobic digestion (AD) process to produce biogas, as well as a digestate that can be used as fertilizer. The biogas can be combusted (mostly in Combined Heat and Power - CHP plants), upgraded to biomethane to be injected into the gas grid, or used directly in natural gas vehicles. Either as combusted or upgraded, biogas produces biogenic carbon dioxide (CO_2) as biogas is composed, roughly, 60:40 of methane and CO_2 (Marconi and Rosa, 2023). All biogas and biomethane production pathways may generate unexpected methane losses from leaks, accidental releases and incorrect management operations, which if accounted within the GHG emissions calculation, may strongly affect the biomethane sustainability. Methane, regardless its origin (from fossil sources or biogenic processes), contributes to global warming. Therefore, in this report, the terms of biomethane and methane will be used interchangeably. Apart from avoiding the impact on global warming, there is an economic incentive to avoid such losses, since methane releases represent lost energy production and less revenues for the operators.

For the expected rapid market uptake of biogas, the sector shall comply with the sustainability criteria described by the Renewable Energy Directive 2018/2001 (RED II) (European Parliament, 2018) and the revised Directive (EU) 2023/2413 (RED III) (European Commission (EC), 2023) and should guarantee lower GHG emissions compared to the threshold along its full supply chain. Therefore, all emission sources from feedstock/digestate storage, biogas production, upgrading and distribution should be well monitored and mitigated to reduce methane losses (see **Figure 2**).

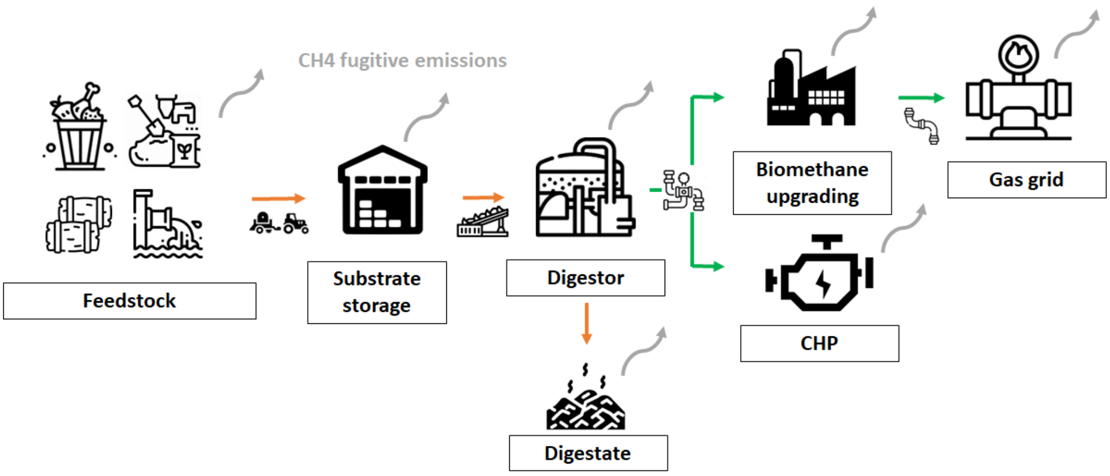
A recent IEA report entitled "Methane emissions from biogas plants: methods for measurement, results and effect on greenhouse gas balance of electricity produced" (Liebetrau et al., 2017) categorizes methane emissions from biogas plants as:

- structural (that happen constantly, thus related to the technology deployed); and
- operational (that happen occasionally, thus due to plant management operations) ones.

The most important sources of methane emissions from biogas plants are from:

- feedstock (substrate) storage through the direct emissions of methane generated through natural decomposition of feedstock in open air;
- open storage of the digestate through the direct emissions of methane generated through the continuation of the digestion process after removal from the digestor;
- the exhaust of the CHP engine as non-combusted gas (methane) due to the incomplete combustion inside the internal combustion engine;
- leaks (from piping, valves, tanks, digesters);
- accidental gas release (through Pressure Release Valve (PRV) safety device, incorrect management operations or maintenance);
- the off-gas of biogas upgrading to biomethane as methane slip.

Figure 2: Short overview of the emissions for a traditional biogas value chain.



Source: JRC analysis

In addition to structural and operational emissions, this report uses the following terms for emissions:

- Channelled emissions: incomplete combustion emissions, incomplete separation during upgrading and venting.
- Fugitive emissions: unintentional non-channelled emissions to air caused by loss of tightness of equipment, wear and cracks. Fugitive emissions can arise from: moving equipment, such as agitators, compressors, pumps, valves (manual and automatic); or static equipment, such as flanges and other connections, open-ended lines, sampling points.

Some emissions can be of a continuous nature, such as from pipeline, pump and compressor seals, valve, handling equipment or storage tanks etc. Other emissions are accidental, of a one-off nature, and occur from sources such as equipment failure, venting, etc.

Factors driving these releases of emissions are equipment design, quality of the sealing system, of monitoring and of the maintenance and repair programmes. Accidental events can cause large quantities of uncontrolled methane emissions due to equipment failure or pressure relief events. From a recent Danish survey, 473 individual leaks and point sources were identified in 50 plants, varying between 0 and 38 leaks and point sources at each plant (Fredenslund et al., 2023).

1.4 Legislative context

The impact of methane emissions on climate change is increasingly recognized. At global level, the UN Climate Change Conference of the Parties (COP26) launched in 2021 “The Global Methane Pledge” initiative, setting a collective goal of reducing global methane emissions, both from fossil and biogenic origin, by at least 30% compared to 2020 level by 2030.

The European Commission launched the EU Methane Strategy in October 2020 (European Commission, 2020) that aims to reduce methane emissions from the oil, fossil gas and coal sectors and includes liquefied natural gas (LNG), gas storage and biomethane injected in the gas network. The main focus to reduce methane emissions in the energy sector is to improve detection and repair of leaks in gas infrastructure and prevent flaring and venting. The European Commission adopted in December 2021 a proposal for a regulation (COM(2021) 805 final) aimed at reducing methane emission in the energy sector (European Commission, 2021), which has been adopted as Regulation (EU) 2024/1787 (European Parliament and the Council of the European Union, 2024). This regulation includes provisions for improved measurement, reporting and verification of methane emissions from energy sector and for the reduction of emissions through mandatory leak detection and repair and a ban on venting and flaring.

This report covers only the methane losses in the biogas and biomethane plants up to the output of the CHP plant or injection into the gas grid, respectively. All related GHG emissions from biogas value chain are not included in the scope of this regulation, while the RED II already regulates the accounting for such emissions. Typical and default values for GHG emission savings for biomass fuels, if produced with no net-carbon emissions from land-use change, representing pre-calculated carbon intensities for gaseous biofuels and bioenergy, are included in the Annex VI of the RED II. These default values can be used by biogas and biomethane producers in their reporting of GHG savings of their production to demonstrate that they meet RED II sustainability requirements detailed in the Article 29 and supporting Annexes. More details are presented in the Chapter 2.

Typical GHG emission savings values in the RED II already include some methane losses along the supply chain up to the point of injection into the distribution network, e.g. emissions from digestate management and methane losses at the exhaust of the CHP engine. Estimates of methane losses that are already included in the calculations were derived from the JRC report describing the input values for solid and gaseous bioenergy pathways (Giuntoli et al., 2017). Since then, the experience and data with regards to methane losses from biogas plants has significantly improved, which warrants an update of those estimations with the use of new emission factors derived from recent measuring campaigns and best practices.

In addition, the Taxonomy Regulation (European Commission, 2021), establishing the economic activities that qualify as contributing substantially to climate change mitigation or climate change adaptation, states that biogas plants (see section 4.7 on “Electricity generation from renewable non-fossil gaseous and liquid fuels" - and section 4.19 on "Cogeneration of heat/cool and power from renewable non-fossil gaseous and liquid fuels") shall install equipment to detect methane emissions, mitigate them and repair the leaks. Section 4.13 "Manufacture of biogas and biofuels for use in transport and of bioliquids", refers to 5.6 and 5.7 (Anaerobic digestion of sewage sludge, Anaerobic digestion of bio-waste) that requires "A monitoring and contingency plan is in place in order to minimise methane leakage at the facility".

Finally, the Net Zero Industrial Act (NZIA) adopted through the Regulation (EU) 2024/1735 (European Parliament and the Council of the European Union, 2024) serves as a comprehensive framework to enhance Europe's manufacturing ecosystem for net-zero technologies , including biogas and biomethane. The NZIA recognizes the strategic importance of biogas and biomethane in the transition towards a climate neutral, resource-efficient and net-zero economy and aims to support the REPowerEU plan. The NZIA is designed to facilitate the roll-out of the industrial capacity necessary to achieve this target, thereby incentivizing the expansion of manufacturing capabilities across the EU and ensuring that the biogas and biomethane sector can effectively be produced with innovative technologies ensuring the lowest GHG emissions.

1.5 Scope of the work

In the GHG emissions calculation methodology for biofuels and bioenergy, the RED II specifies that GHG emissions related to biogas production, referred to as leakages, should be included, without explicitly including a term in the formula (see Equation 1 in section 2.1) for emission accounting and without including a specific methodology to calculate such losses. Such methodology to account for methane emissions into the atmosphere needs to be developed and added into the RED II Annex VI. Besides improving the accuracy of the calculation of environmental benefits of biogas pathways, such a methodology should also encourage operators to minimize their methane emissions and thus their overall GHG emissions, by incentivizing leak detection and repairing actions, as well as deployment of less emitting technologies.

With this in mind, the rest of this report contains:

- A review and update of the methane losses included in the typical and default emission factor values for biogas and biomethane with the most recent data;
- A review and update of the methodology that the JRC employed to calculate those losses against other existing methodologies;
- Insights on best practice measuring methods and quantification of emissions; results of consultations of stakeholders including experts, companies, NGOs, industry associations and MSs;
- Estimates of representative and more granular typical and default values for methane losses;
- A methodology for operators to calculate and deliver actual values of emission losses, in cases when such values are lower than the default methane losses;
- Recommendations on mitigation measures.

2 RED II greenhouse gas emissions reduction targets

The Renewable Energy Directive 2018/2001 (RED II) (European Parliament, 2018) set targets for the use of renewable energy in the transport sector (including biofuels and biomass fuels). The revised Directive (EU)2023/2413 entered into force on 20 November 2023 but it doesn't contain modifications concerning the methane emissions of biogas and biomethane plants that are discussed in this document. Therefore, RED II is used as a reference throughout this document.

2.1 Greenhouse gas emissions accounting for biofuels and biomass fuels in RED II

Biofuels and biomass fuels (which include biogas and biomethane) consumed in the EU are eligible for counting towards the RED II transport target, as long as they meet the required levels of GHG savings and adhere to other sustainability criteria required by the Directive. RED II also provides a methodology for the calculation of the GHG emission factors from the production and use of biofuels and biomass fuels that must comply with the same sustainability and GHG emission saving requirements.

RED II Annex VI contains default values of GHG emission factors and GHG savings for several biofuels and biomass fuels pathways. GHG emission factors and savings can also be derived by using a combination of actual values calculated by operators themselves, in accordance with the RED II GHG emission factor calculation methodology, and disaggregated default values, also included in the annexes of the RED. Economic operators can also calculate and report only actual values.

- RED II includes several production pathways for electricity and heat generation from biogas, or biomethane for the transport sector. Biogas pathways have been modelled based on the initial feedstock as:
- an energy crop: maize silage;
- an agricultural waste: manure;
- municipal organic and agro-industrial waste: biowaste.

Those were combined with two means of digestate management:

- open tank storage;
- closed tank storage (gas tight).

They were also combined with two end-use processes for the biogas produced:

- biogas for combined power and heat production (CHP);
- biogas upgrading to biomethane.

The biogas-to-electricity pathways are sub-divided depending on the origin of the power and heat consumed to run the plant (e.g. digester and engine auxiliaries).

- Case 1: Electricity and heat required in the process are taken directly from the output of the CHP engine (lower net power output but imposed by the legislation in some MS);

— Case 2: Electricity required in the process is taken from the grid and the process heat is supplied from the biogas plant CHP engine;

— Case 3: Electricity required in the process is taken from the grid and heat is produced on site with a biogas boiler (CHP engine is not on-site and biogas is transported to a central location for energy generation or upgrading to biomethane).

The various biogas upgrading technologies available in the market are grouped into two main categories:

— Upgrading without combustion of the off-gas (Off-gas Vented – OGV);

— Upgrading with combustion of the off-gas with the purpose of oxidising the methane molecule and turning it into a less potent GHG (Off-gas Combusted – OGC).

According to the methodology contained in Annex VI, part B, point 1, the GHG emission factors from the production and use of transport fuels, biofuels and bioliquids, and biomass fuels[1] should be calculated as follows:

$$\mathbf{E} = \mathbf{e_{ec}} + \mathbf{e_l} + \mathbf{e_p} + \mathbf{e_{td}} + \mathbf{e_u} - \mathbf{e_{sca}} - \mathbf{e_{ccs}} - \mathbf{e_{ccr}} \qquad \text{Equation 1}$$

where:

E Total emissions from the use of the fuel in Annex V or total emissions from the production of the fuel before energy conversion in Annex VI;

e_{ec} Emissions from the extraction or cultivation of raw materials;

e_l Annualised emissions from carbon stock changes caused by land use change;

e_p Emissions from processing;

e_{td} Emissions from transport and distribution;

e_u Emissions from the fuel in use;

e_{sca} Emission savings from soil carbon accumulation via improved agricultural management;

e_{ccs} Emission savings from carbon capture and geological storage;

e_{ccr} Emission savings from carbon capture and replacement.

In this formula, methane emissions are included in two places: emission factor from processing e_p (digestate storage) and emission factor from the fuel in use e_u (CHP and biogas upgrading). The used values are summarized in **Table 2**.

[1] 'biomass fuels' are defined in RED II as gaseous and solid fuels produced from biomass, while 'biogas' means gaseous fuels produced from biomass. Annex V, part C, point 1 and Annex VI, part B, point 1.

Table 2: Methane emission factors currently considered in the typical values available in the REDII Annex VI (based on IPCC AR4)

Emission source	*Term of accounting [emissions for processing or use]*	*Emission factors expressed as energy loss [MJ/MJ$_{biogas}$]*	*GHG emissions [gCO$_2$eq/MJ$_{biogas}$]*
Open digestate storage – feedstock maize	e_p	0.022	11
Open digestate storage – feedstock biowaste	e_p	0.025	12.5
Open digestate storage – feedstock manure	e_p	0.1	50
Closed digestate storage	e_p	0	0
CHP for heat and electricity production - slip	e_u	0.017	8.5
Upgrading with venting of the off-gas [OVG – off-gas vented]	e_u	0.03	15
Upgrading with oxidation of the off-gas [OGO – off-gas oxidized]	e_u	0	0

The Global Warming Potential (GWP) of methane is 25 kg CO_2eq/kg CH_4 as prescribed by RED II and the lower heating value is assumed to be 50 MJ/kg CH_4.

Source: JRC analysis based on Giuntoli et al. (2017)

2.2 GHG emission savings requirements in RED II and revision of RED II

Directive 2003/30/EC (the Biofuel Directive), the first legislative act to promote the use of biofuels in transport, included an indicative target of 2% of biofuels by 2005 and 5.75% by 2010.

Directive 2009/28/EC (RED I) set GHG savings requirements for biofuels of 35% by 2017 increasing to 50% from 2017 and 60% from 2018 for installations where production started after 2016. As mentioned above, GHG emission requirements also applied to biomass fuels - gaseous and solid fuels produced from biomass (which include biogas and biomethane).

Directive (EU) 2018/2001 (RED II) defines GHG savings requirements for biofuels of 50% for installations in operation from 2015, 60% from 2015 to 2020 and 65% from 2021.

Directive (EU) 2023/2413 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652 (RED III) keeps those GHG emission savings requirements. However, it introduced a new 14.5% GHG intensity reduction target in transport or a target of at least 29 % share of RES in final consumption of energy in the transport sector by 2030 (Article 25), replacing the 14% target of renewable energy in transport by 2030, originally set by the RED II.

3 Initiatives to reduce methane emissions

The biogas sector became aware of the prevailing importance of reducing methane emissions over the last few years only, due to the lack of adequate information about their real extent. Recent initiatives and projects detailed in the sections 3.1.1 and 3.1.2 below, demonstrated how reducing such emissions makes the biogas plants more economic, safe and environmentally friendly; therefore new infrastructures/technologies are planned, built and operated with the aim to minimize methane losses. The state-of-the-art biogas plants and their components (gas tight covers, permeation of gas holder membranes, gas flare etc.) has developed significantly and the manufacturers are continuously working on further improvements (Bakkaloglu et al., 2021).

Many plant operators have discovered the benefit of voluntary inspections of biogas plants for methane emissions with the aid of Optical Gas Imaging (OGI) cameras and started to carry out these inspections voluntarily at annual intervals. Together with regular maintenance measures by qualified specialist companies, avoidable emissions can be controlled very well (Fredenslund et al., 2023). The avoided biogas emissions may cover the resulting costs for the OGI camera inspection and maintenance and therefore may ensure a high acceptance in the sector (Bartoli et al., 2019). The most advanced initiatives, programmes, projects and legislations in force are evaluated in the next paragraphs.

3.1 The European Union Member States

3.1.1 EU-funded projects and other initiatives

- EvEmBi (Evaluation and reduction of methane emissions from different European biogas plant concepts – Ref. Nr. BEN11-17-13 (ERA-LEARN, 2018)) is an EU research project funded within 11th ERA-NET Bioenergy Joint Call/ 1st add., call of BESTF3 that aimed to evaluate methane emissions from European biogas plants and to develop a voluntary system for GHG emission mitigation. The project ran from 01/04/2018 to 31/03/2021. The project partners involved in the EvEmBi project included private and public bodies mainly from Germany, Austria, Sweden, Denmark and Switzerland. The EvEmBi project targeted the evaluation of methane emission factors for different biogas plants (e.g., agricultural biogas, bio-waste or wastewater treatment plants) used in Europe. Based on collected emission data, a quantification system for representative emissions for the biogas sector has been developed for the first time (Clauß et al., 2019) enabling the definition of representative emission factors of biogas plants (Hrad et al., 2022) (including the activities of MetHarmo' project, described below). After the identification of the major sources and the quantification of emissions, emission reduction strategies were developed, implemented, and reviewed for specific biogas plants. This resulted in the elaboration of a general European position paper produced by EBA on GHG emissions and mitigation strategies (European Biogas Association, 2020). Additionally, a European voluntary system as well as specific national voluntary systems for emission mitigation in the biogas sectors were developed in cooperation with the respective national biogas associations (in DK and SE) (European Biogas Association, 2020).
- The EvEmBi project was the successor of the MetHarmo project (European Harmonisation of methods to quantify methane emissions from biogas plants). The MetHarmo project published a report which compared different methods for methane emission quantification, which also highlights their strengths and limitations (Clauß et al., 2019).

- IEA Bioenergy Task 37 released a report in January 2018 (Liebetrau et al., 2017), which addressed methane emissions from biogas applications. The report contains methods used for emission quantification and the specific results of measurements done by Deutsches Biomasseforschungszentrum (DBFZ) and other research bodies. The report provided an assessment of the methane emissions on the GHG balance of the biomethane pathways and proposed mitigation measures.
- UNECE (Glöser-Chahoud, Zimmer, and Heck, 2020) prepared a report with an overview of relevant methane emissions in Europe and related mitigation and abatement techniques; this report provides an outlook on methane emissions from biogas plants which is also considered as an important source of methane emissions from technical applications.

3.1.2 National initiatives

EU member states have no additional obligations to mitigate methane emissions in their national transposition of the RED II. However, only several member states have taken action to measure and reduce methane emissions from the biogas sector.

- In Germany, measures to reduce methane emissions have been included in technical regulations, most importantly in TRAS-120 (Bundesministerium and für Umwelt, 2019). Amongst others, TRAS-120 contains a provision that would enable the reduction of methane fugitive emissions through the digestor' membrane by reducing the permeation limit for the membranes of the gas holders from 1,000 ml/(m^2 d bar) to 500 ml/(m^2 d bar) due to technological progress (DWA, Biogas, and DVGW, 2018). There are also further detailed requirements for the design of the gas storage facilities and their connection to the digesters and storage tanks, as well as for monitoring methane emissions.
- In Italy, additional requirements exist at regional level, e.g. for the Abruzzo' region that introduced guidelines for monitoring biomethane emissions from landfill (Teramo, 2003). On 8th August 2022, the new support scheme for the promotion of biomethane in Italy, according to the RePowerEU targets, has been released (European Commission, 2021), making available €1.7 billion for the sector, including also equipment to mitigate emissions such as flaring systems, monitoring instruments and special cells to composting digestate for agriculture (Consorzio Biogas, 2022). This initiative will also introduce a revision of the sustainability requirements, introducing guidelines for new technologies and managing operations for biogas, e.g. it regulates composting of digestate, it sets a minimum of 30 days for digestate retention time in closed pond storage, etc. (Dipartimento energia, 2023).
- In France, ADEME and GRDF have both been active on measuring methane emissions on selected biogas plants. One report from (ADEME et al., 2020) includes the list of plants they examined.

- In Denmark, the Danish voluntary methane monitoring programme for biogas producing facilities was launched by the Danish Biogas Association in 2016 (Kvist, 2016). Methane emissions are monitored and reported to the Biogas Association in yearly reports. The Danish Biogas Association has set a target of a 90% participation of biogas plants in the programme and an overall goal of reducing the total methane loss from Danish biogas and upgrading plants on a national level to less than 1% of biomethane production by 2020 (Fredenslund and Scheutz, 2021). The biogas plants carry out regular and systematic self-monitoring, where critical parts and components are examined for methane leaks. In addition, the plant is periodically inspected by an external company that quantifies the methane loss from identified leaks and sources at the plant. If quantification indicates that the plant's methane loss is higher than 2% of the annual production or more than 50 tonnes per year, the external consultant must suggest mitigation actions to be implemented by the plant operator for each leakage or emission source. A new emissions quantification must be performed within one year (Nielsen, 2019; Scheutz, 2020). Following emissions measurements on 69 biogas plants, representing 59% of Danish biogas production) (Fredenslund et al., 2023), six plants performed measurements before and after the implementation of mitigating actions, showing a reduction of methane emissions by 46 % by applying relatively minor technical fixes and adjustments. Moreover, economic evaluation showed that mitigating actions could be economically beneficial for the biogas plant (positive net present value over a 10 years' time frame), due to an increase in revenue.
- In Sweden, the Swedish Waste Management Association (Avfall Sverige) introduced a voluntary scheme for biogas plants in 2007 (European Biogas Association, 2020), where the plants committed to work systemically to identify and reduce their emissions. One part of the voluntary scheme is to regularly measure emissions at the plant to determine methane losses. Another part of the voluntary scheme is to carry out regular and systematic leak detection work at the plant. The implementation of the system led to lower methane losses by creating awareness of plant operators and provided useful data. The report (Avfall Sverige, 2016) reveals the positive impact of introducing the voluntary programme of self-inspection of methane emissions on methane leaks on biomethane plants in Sweden from 2007 to 2015.
- Other MSs are still at early stages of developments for biogas production. Various studies (Gustafsson and Anderberg, 2022) showed a clear connection between the development of biogas sector and a stable and predictable framework, long-term policies and support through investment support, tax exemption feed-in-premiums or feed-in-tariffs.

3.2 The United States and Canada

Methane emissions are taken into account in the calculation of carbon credits for bio-digestion offset protocols, such as the Organic Waste Digestion Project Protocol (OWDPP, (Syd, 2014; Climate Action Reserve, 2007)) in the United States and the Quantification protocol for the anaerobic decomposition of agricultural materials (Alberta, 2020) in Alberta, Canada. The OWDPP implements methane emission calculations based on emissions during manure management, shutdown, venting and digestate management to determine emission savings. It also prescribes to calculate the methane emissions savings as the difference of baseline emissions (without anaerobic digestion) and saved ("destroyed") emissions and to use the lower of the two calculated emission savings values. In the U.S., there is also the Livestock Project Reporting Protocol (Climate Action Reserve, 2007) that takes into account leaks, without specifying how these should be measured.

The U.S. EPA (Environmental Protection Agency) promotes the Landfill Methane Outreach Program. It is a voluntary program that works cooperatively with industry stakeholders and waste officials to reduce or avoid methane emissions from landfills. The programme provides also informational materials about the benefits of renewable energy from biogas generated from MSW and includes guidelines to reduce emissions (U.S. Environmental Protection Agency, 2022). The U.S. EPA also publishes online the guidelines for best practices to reduce methane emissions from livestock manure management, covering the Biogas supply chain (U.S. Environmental Protection Agency, 2022).

3.3 Switzerland

In Switzerland, the agricultural biogas association, Ökostrom Schweiz, launched climate protection projects in 2010, starting with two biogas plants having their emissions measured by an external company. In 2019, there were 35 agricultural biogas plants participating in the yearly emission measurements carried out with an on-site method. Biogas plant owners receive a report with all the measurement results of the whole biogas plant. The owners can use the report to decide on mitigation measures (European Biogas Association, 2020).

3.4 The United Kingdom

There are no specific regulations or thresholds on methane emissions from biogas plants in the UK. There is no maximum allowable methane slip and no requirement for mandatory testing and reporting of methane emissions. Having said that, all the plants that treat biodegradable wastes will have a permit (a licence to operate) and, within this, the operator will have to implement a leak detection programme that identifies and controls methane slippage through gas combustion units and biogas upgrading plants. This do not apply to plants that are not treating wastes.

However, RICARDO reported that, given the difficulty to accurately measure methane loss – and there is no clear guidance from regulators in the UK on this issue – operators are required to use an emission factor set at 1% (0.2 g methane/MJ) when reporting their GHG emissions. This may lead to operators with low methane leakage being penalized, but operators with lower standards benefiting. Thus, RICARDO developed a specific methodology that considers emissions from experimental measurements on the existing and operating biogas plants (Leonard, Odeh, and Stewart, 2017; Odeh, 2016). The NAE (National Atmospheric Emissions Inventory, 2022) estimated CH_4 emissions of 7.7 kilotonnes from anaerobic digestion processes.

4 Methane emissions in biogas and biomethane plants

4.1 Inventory of methane emissions sources and quantification

Several measurement campaigns have been carried out to quantify real methane emissions from biogas plants, either for single components or the whole plant (Bakkaloglu, Cooper, and Hawkes, 2022; Lansche and Müller, 2017; Adam et al., 2021; Clauß et al., 2019; Wechselberger, 2021; Wechselberger et al., 2023; Vu et al., 2015; Schick et al., 2013; Clemens et al., 2006; Mathieu Dumont et al., 2013; Fredenslund and Scheutz, 2017). Most of the studies concentrated on direct measurements of methane losses for each plant component, using infrared and laser detection instruments. Specific emissions factors were then derived for the major components of traditional biogas plants from these direct measurements.

Even if measurement methods and grouping methodology vary between the studies, Table 3 provides an overview of the importance of emissions from different parts of the supply chain. As an example, some studies included methane emissions from feedstock reception operations and methane leaks from piping in the "biogas processing" value, while most studies had a leakage dedicated category.

Manure storage can have very high methane emissions if not done in a closed environment, as manure emits methane through natural decomposition of organic material. The avoidance of methane emissions from decomposition is the reason why manure receives a credit in the GHG intensity calculation of RED II for the large emissions saved from natural manure decomposition in the field. Adequate manure storage is thus important to reduce high quantities of methane emissions. Nonetheless, manure storage has been excluded from this study as it is outside of the system boundaries of the pathways for biogas or biomethane considered within the RED II. Being a waste related to agricultural activities, its emissions should be accounted for in the waste producing process, which is not regulated in RED II. The same reasoning is valid for sewage sludge.

The second most important source of methane emissions is digestate storage in open air. The Residual Methane Potential (RMP) of digestate is a measure of how much of the remaining organic material can still undergo anaerobic decomposition and how much methane can be produced from digestate. The RMP depends mainly on the feedstock type and process conditions in the digester, including the Hydraulic Retention Time (HRT). A second, less important, parameter is ambient temperature if the operating temperature of the AD is outside the traditional range of 35 – 50 °C (Gaby, Zamanzadeh, and Horn, 2017). While digested energy crops reach a RMP of less than 5% of total initial potential in approximately 70 days (Ruile et al., 2015), manure might need up to 100 days, with mixtures of energy crops and manure in between (Timmerman et al., 2015). As an example, Germany implements an obligation to contain the feedstock and digestate in an airtight system for 150 days (combined time in digester and airtight digestate storage, effectively making closed digestate storage mandatory), with exceptions only for pure manure or some biowastes. If manure is used in the substrate mix, a minimum retention time of 50 days, plus 2 days for each mass percent of other substrates (max 150 days) is prescribed (VDI, 2007; Bundesregierung Deutschland, 2021). A German study (Ruile et al., 2015) suggests that the methane emission potential at 20 °C is roughly a quarter of the RMP, so storing the digestate at lower temperatures can significantly decrease methane emissions.

Table 3: Measured methane emission factors from different parts of a biogas plant reported by the scientific literature, expressed as a percentage of methane loss on the overall methane produced

Plant part	***Studies***	***Mean [%]***	***Median [%]***	***Max [%]***	***Plants***	***Countries***
Feedstock reception[2]	(Wechselberger et al., 2023)	0.3	0.1	2.4	36	AT,DE,CH
	(Fredenslund and Scheutz, 2017)	1.9	1.9	1.9	1	DK
Biogas processing	(Bakkaloglu, Cooper, and Hawkes, 2022)	1.2	0.5	23.7	195	EU
	(Adam et al., 2021)	1.6	1.6	3	2	FR
	(Clauß et al., 2019)	1.6	1.6	2	2	DE
	(Wechselberger, 2021; Wechselberger et al., 2023)	1.1	0	12	117	AT,DE,CH
	(Vu et al., 2015)	5			1	VN
Biogas upgrading	(Bakkaloglu, Cooper, and Hawkes, 2022)	0.9	0.2	16.1	119	EU
	(Wechselberger, 2021; Wechselberger et al., 2023)	2.5	2.4	9.3	117	AT,DE,CH
CHP	(Adam et al., 2021)	2.8	2.8	4.6	2	FR
	(Schick et al., 2013)	0.7	0.7	1.1	2	CH
	(Clauß et al., 2019)	1.9			1	DE
	(Wechselberger, 2021; Wechselberger et al., 2023)	3.2	3.3	6.2	9	AT,DE,CH
Digestate storage	(Bakkaloglu, Cooper, and Hawkes, 2022)	3	0.8	53.7	239	EU
	(Clemens et al., 2006)	7	7	12.8	2	DE
	(Mathieu Dumont et al., 2013)	8.9	11	13.8	3	DE
*Whole plant**	(Fredenslund and Scheutz, 2017)	4.6	2.6	14.9	23	DK

Source: Hurtig et al. (2024)

*Note: "Whole plant" means that the measurement has been done at plant level (with the help of a tracer gas) and thus includes all emissions, even feedstock storage.

For all feedstock mixes, if retention times cannot be met, the operator can perform measurements of the RMP to prove that the potential emissions from digestate storage remain below 1% of the produced methane (measured over 60 days at 20 °C) (Landesamt für Natur, 2018; Landesverwaltungsamt Sachsen-Anhalt, 2017; Bundesregierung Deutschland, 2023; VDI, 2007). However, it is in the interest of the biogas operators to maximise the biogas production and minimise the retention time, thus some MSs have imposed additional requirements regarding the

[2] All types of receiving and storage types were combined into one category

minimum number of days to store the digestate in closed ponds with biomethane recovery (e.g. in Italy, it is 30 days, see details in 4.1.2). Depending on the digestate post-processing, there are many options to reduce methane emissions and transform the digestate into an excellent fertiliser (Kovačić et al., 2022).

Recently, some waste treatment plants (mainly those processing the organic fraction of municipal solid wastes) are composting digestate without storing large digestate quantities in open ponds (Havukainen et al., 2022). Composting can be considered a low methane emissions downstream treatment to stabilise digestate. However, there is considerable variability in terms of waste compositions, organic contents, degradation levels, moisture contents, liquid addition amounts and methods, temperature, and other operational conditions (Ma et al., 2021). Digestate composting is not considered as a downstream digestate treatment option for the RED II since there was insufficient literature and measurements on emissions from digestate composting to determine a range of emission factors resulting from composting. However, recent studies (Patil, Agnes Anto, and Singh, 2017; Pecorini et al., 2020; Vrabie, 2021) have demonstrated that, if composting is performed according to best practices (closed system, direct aeration, cooling and mixing of the digestate with substrate, controlled and aerated composting), methane emissions should be negligible compared to open digestate storage and similar to the case of closed digestate storage. When those conditions are not met, high emissions can occur (Sánchez et al., 2015). For a clear view of methane emissions, operators performing digestate composting should deliver proof of methane emissions by means of closed system operation, RMP measurement on the compost and the measurement of the methane emissions in off-gases.

As an important side note, all digestate treatment options entail biogenic CO_2 emissions in addition to methane emissions, but those are considered to be similar to the CO_2 emissions of the counterfactual treatment of the substrate (spreading on the field or direct composting), so they should not be counted in the GHG emissions assessment.

Thirdly, CHP engines combusting the biogas are a relatively relevant and continuous source of methane emissions, since engines cannot ensure the complete combustion of the fuel. Careful optimization of the engine and regular maintenance can lower those emissions to some extent.

Table 4: Methane loss in the off-gas (expressed in %) for different upgrading technologies according to recent studies.

Upgrading Technologies	(Petersson and Wellinger, 2009)	(Sun et al., 2015)	(Ardolino et al., 2021)
Water scrubbing	<2%	>2% (>1% with regeneration)	1-2%
Physical scrubbing	2-4%	2-13%	
Cryogenic separation		0.5-1%	
Chemical absorption	<0.1%	<0.1-10%	0.04-0.1%
Pressure swing adsorption	<3-10%	2-12%	1.8-2%
Membrane technology		0.5-15%	0.5-1%
In-situ methane enrichment	<2%, <8%	2-8%	
Hydrate formation		"high"	
Biological methods		0% (no off-gas is produced)	

Source: Petersson and Wellinger (2009); Sun et al. (2015); Ardolino et al. (2021)

A fourth source of methane emissions is biogas upgrading, which depends strongly on the installed technology. Outdated technologies, water or organic physical scrubbers and some pressure swing absorption technologies can lead to more than 3% of the biomethane produced being lost. On the other hand, chemical absorption, chemical scrubbers and recent membrane technologies generally lead to less than 1% of losses of the biomethane produced (Bakkaloglu, Cooper, and Hawkes, 2022; Liebetrau et al., 2017; Petersson and Wellinger, 2009). **Table 4** contains the methane emission values reported in three studies for methane emissions from upgrading (Sun et al., 2015; Petersson and Wellinger, 2009; Ardolino et al., 2021).

Finally, as regards methane losses from digesters, piping systems and valves ("Biogas processing"), emissions come mainly from plant management operations and leaks, and could therefore be minimised with regular maintenance, detection and repair.

In conclusion, the range of emissions for the whole plant is quite large, with most plants having methane emission losses of between 0.5% and 6% of the total methane produced. The mean value of just under 5% justifies the suggestion of IPCC (Intergovernmental Panel on Climate Change (IPCC), 2019) to use an emission factor of 5% of methane emission losses of the total methane produced in case no better data is available. These values are aligned with other studies available in peer-reviewed papers (Adams, Mezzullo, and McManus, 2015, p.99; Adams and McManus, 2019) and technical reports (Liebetrau et al., 2017, p.34; Prussi et al., 2020).

4.2 Comparison between current RED II values and recent scientific literature

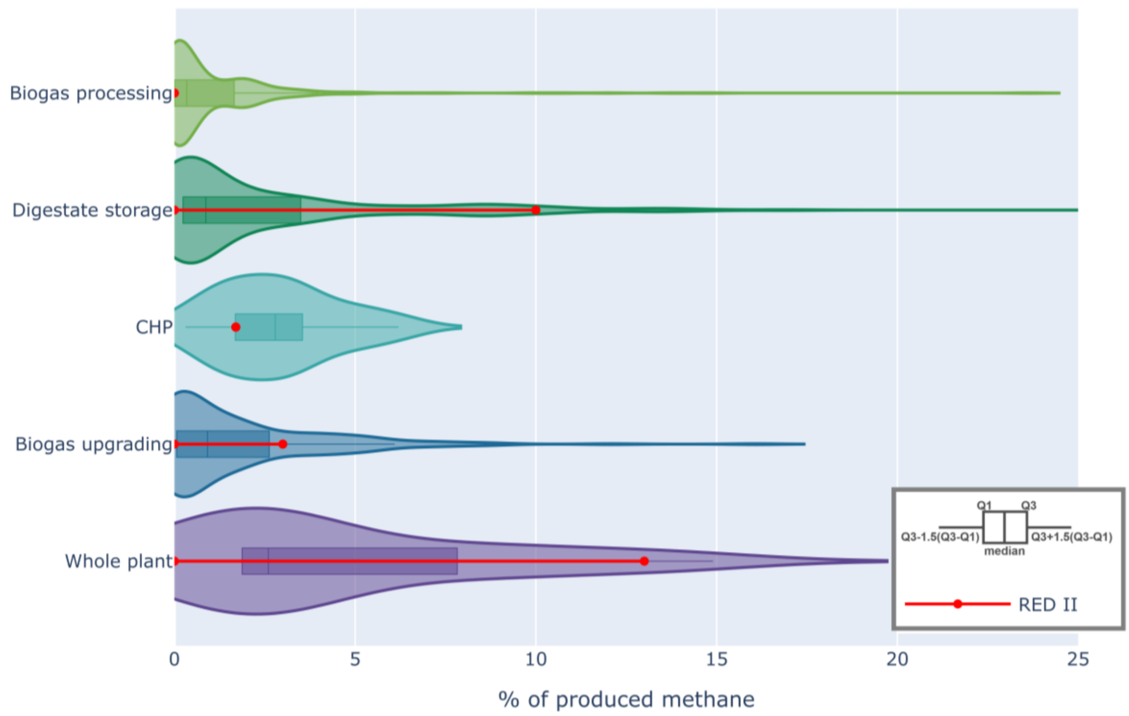
Figure 3 shows an approximated probability distribution of the methane emissions for single components of biogas plants from recent scientific studies as a share of the produced methane (in blue, with the median value in green and the mean value in yellow). It also shows measurements for the whole plant. The range of methane emission factors for different pathways included in the RED II default values for biogas/biomethane pathways is shown as a red line.

This figure shows that the RED II values fit the range of probable methane emissions quite well for all categories except for the processing emissions. Digestate storage emissions are counted in the “processing emissions” in RED II, but are shown in a separate category here. RED II doesn’t account for any other processing emissions. Mean measured digestate emissions are a bit higher than the values assumed in RED II, as some extremely high emission measurement values of up to 53.7% distort the mean. Those high values are not representative and are likely due to unconventional storage practices or incorrect plant operation (such as extraction of digestate in open air at lower HRT). Measured biogas upgrading emissions are generally lower than the maximum value in RED II (when off-gas is vented), which can be attributed to recent improvements in the separation technologies.

Processing emissions consist nearly exclusively of leaks or improper operating conditions. The methane emission values for the current version of the default values (Giuntoli et al., 2017) assumed “structural” biomethane emissions, meaning that operational emissions and unpredictable losses were excluded from the calculations.

The calculations for current RED II default values also did not include the emissions related to feedstock (substrate) storage, because the only feedstock that emits relevant quantities of methane during storage is manure, and being considered a waste, the emissions upstream of the waste processing were not taken into account. The calculations didn’t consider leaks and potential overpressure vents (that open a Pressure Release Valve - PRV) either, as those were considered too uncertain and depending on each plant.

Figure 3: Methane emissions in % of produced methane for single components of a biogas plant as well as the whole plant, based on sources in Table 3.



Source: Hurtig et al. (2024)

Measurements for “whole plants” are not the sum of measurements of single plant parts, as they are measured for the whole different plants. The x axis scale has been truncated at 25%. Literature values are presented as violin plot and box plot with the box representing the first, second and third quartile, the whiskers representing all values without suspected outliers.

Summarizing, when the RED II options related to the lowest disaggregated values for biomethane emissions (i.e. digestate storage and biomethane) are considered, the overall plant methane emissions are underestimated due to the absence of “operational” emissions. In order to quantify such losses to derive new emission factors, next section shows the available measuring techniques that may be used to quantify methane fugitive emissions.

The model widely used in the U.S., “Greenhouse gases, Regulated Emissions, and Energy use in Transportation” (GREET 2022) estimates a 1% leakage at the biogas production stage and a 1% leakage at the CHP stage (Han, Mintz, and Wang, 2011). One of the most widely used LCA databases, EcoInvent 3 (Wernet et al., 2016) assumes a methane emission rate of approximately 5% of the produced methane (for biogas from manure and biowaste), but this also includes emissions from substrate storage. Several other recent studies assumed overall emission rates of 1 to 6% (Vo, Rajendran, and Murphy, 2018; Valli et al., 2017; Agostini et al., 2015).

A study performed by the IEA Bioenergy (Liebetrau et al., 2017) investigated the effect of different levels of methane losses in a calculation model based on the RED II methodology for GHG emissions calculation. It showed that biogas plants operated with maize and with leakage rates above 1% cannot achieve the GHG reduction target imposed by RED II. Manure, on the other hand, complies with the savings threshold even with a 7% leakage rate because of its credit for avoiding emissions compared to the conventional use of manure.

4.3 Tools for detection and measurement of methane emissions

4.3.1 Remote sensing (off-site)

Remote sensing aims to measure the overall plant emissions, without distinguishing the precise sources of the losses. Depending on the sensing technology, the distance between the biogas plant and the sensors can vary a lot. The use of remote sensing originates from the natural gas sector where such technologies can be used to monitor long pipelines or big installations. However, biogas plants cover small areas compared to large natural gas extraction, processing and distribution systems, so such techniques have to be adapted to the scope.

4.3.1.1 Satellites

Satellites are used to detect methane emissions over wide areas at global scale (Copernicus, 2018). They are generally used to detect large methane emissions, especially from the oil and gas extraction industry. Copernicus, the European Union's Earth observation programme, monitors atmospheric methane concentrations with their C3S-CAMS system (Copernicus Atmosphere Monitoring Service, 2022). They can very roughly estimate the quantity of big emitters, even if the uncertainty is quite high due to dispersion being dependent on several meteorological factors. However, the current spatial resolution of the images is still not good enough to attribute increased concentrations to generally small biogas plants (especially as they are often close to other emitters like cattle farms) or to detect small increases in emissions due to fugitive emissions (Ayasse et al., 2019).

4.3.1.2 Tracer gas downwind measurements

This method implies the installation of a tracer gas release system on site. A mobile measuring device is then driven alongside the biogas plant downwind, and the concentration of tracer gas and methane is measured simultaneously. As the quantity of released tracer gas is known, the release of methane can be quantified (Fredenslund and Scheutz, 2017), see an example in **Figure 4**.

The measurements can be quite precise. Uncertainties arise from atmospheric instabilities the unknown exact location and height of the methane emission source, as well as changes in the wind speed and direction (Bakkaloglu et al., 2021). The uncertainty can be limited to less than 0.5% (methane emitted over methane produced) in most cases (Scheutz and Fredenslund, 2019).

Ricardo Energy & Environment developed a specific methodology to measure and estimate methane emissions from different categories of AD plants across the UK as part of a contract with the Department of Business, Energy and Industrial Strategy (UK) (Leonard, Odeh, and Stewart, 2017). This methodology relies on two measurement systems: open-path and multiple-point measurement, utilising sensors located around the site of the plant.

Figure 4: Visualization of the plume measurements of tracer gas and methane

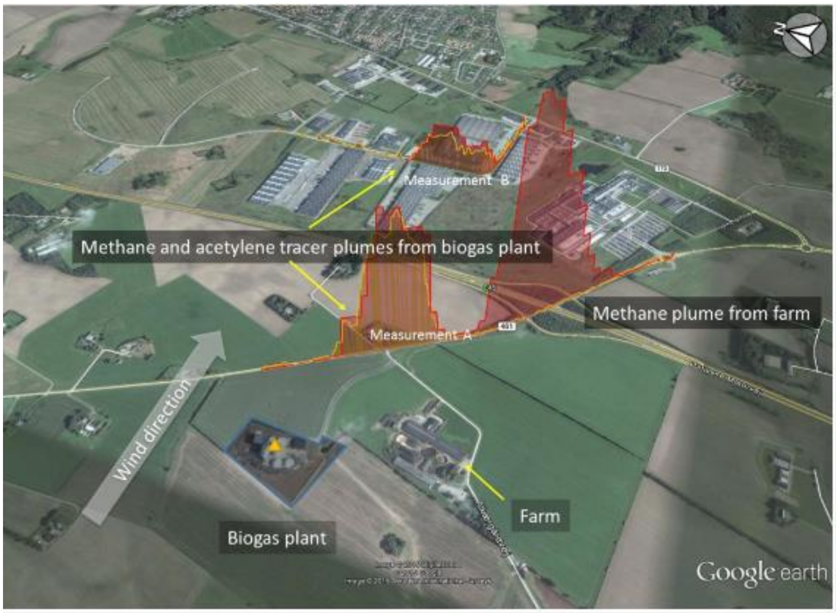


Image reproduced from Fredenslund and Scheutz (2017)

4.3.1.3 Drones or helicopters

Drones can be used with most of the measuring methods described below for on-site measurements, including active and passive thermal cameras, laser scattering and methane concentration measurements, and can thus be used for qualitative or quantitative measurements (Hollenbeck, Zulevic and Chen, 2021). Several solutions are already commercially available such as SeekOps (SeekOps, 2022), and some companies offer services e.g., for natural gas network leak detection (Flynex, 2021), landfills and other similar applications like biogas plants (Percepto, 2022). However, data in literature are not sufficient since such solutions are mostly used to monitor long gas piping networks.

4.3.2 On-site measurements

On-site measurements are advanced systems to quantify single emission sources within the plant site. Depending on the technology employed, it can either directly estimate the real methane losses for a specific component (i.e., quantitative detection), or give the location and a rough estimation of the leak (i.e., qualitative detection). Both approaches are essential within a monitoring program since the former aims to quantify the loss, while the latter helps the operators to quickly single out a leak and repair it. An exhaustive description of the available technologies for on-site measurements are thoroughly presented in other technical reports (Leonard, Odeh, and Stewart, 2017; Liebetrau et al., 2017; Clauß et al., 2019).

4.3.2.1 Detection

There are several methods to rapidly identify methane leaks. The most common solution is the use of a fixed methane gas leak detector that operates especially in closed environments by monitoring the level and concentration of methane gas. Once the detectors identify an increase of the methane concentration in the air, it can give off an alarm or send the methane concentration to a monitoring system. Methane detectors are available in many different versions and start from €20 for home applications, while industrial detectors with interfaces to communicate with plant management systems start from approximately €1000 (Amazon, 2023; Renke, 2023).

Another common solution is the use of a thermographic camera, i.e. a device that creates an image using infrared (IR) radiation, that easily detects warm gas leaks, which in a biogas plant are methane fugitive emissions (i.e. AD is performed at about 35 – 55 °C). Infrared cameras (Flir, 2022) are available starting from around €1000 for trained operators, and companies offer professional surveys starting at around €600 (Carbon Limits, 2014). The same study found that repairing most detected leaks has a payback time lower than one year. Other mobile cameras or sensors like ultrasound cameras exist only for special cases. Such detection of methane is fast and relatively cheap, so it can be easily implemented for each biogas plant size.

4.3.2.2 Emissions measurement

Thermal cameras can also be used for approximate quantification. For this purpose, the use of active Optical Gas Imaging (OGI) cameras with a laser may be easy and rapid to detect methane losses, but in some cases (depending on the number and intensity of the leaks) may need also instrument calibration and images processing (Strahl et al., 2021). As quantitative cameras and software tend to be more expensive and more expertise is needed, this solution is best adapted to industry associations or hired professionals.

For measurements of overall emissions, Tuneable Diode Laser Absorption Spectrometry (TDLAS) can be used to determine the average methane concentration between two points or along multiple connected lines. TDLAS is a technique for measuring the concentration of certain molecule such as methane, water vapour and other gases using tuneable diode lasers and laser absorption spectrometry. From the device, an IR laser beam with a certain wavelength (e.g. 1,653 nm, according to (Liebetrau et al., 2017)) is emitted and reflected back from a surface to the detector with a wavelength sensitive to methane. By placing the lines up and downwind of the biogas plant, it is possible to quantify the natural methane concentration in the atmosphere and the (additional) methane concentration due to the biogas plant. If the geometry and meteorological data are known, a leakage rate can be calculated from that path-averaged methane concentration (Flesch, Desjardins, and Worth, 2011; Liebetrau et al., 2017).

4.3.3 Comparison of measurement methodologies

Measurements of methane emissions need expert operators to obtain reproducible and reliable results. Measuring instruments can be used together and need accurate calibration and harmonization to provide reliable data on the overall plant emissions (Clauß, Reinelt, and Rensberg, 2020). Hrad et al compared on- vs. off-site measurement methods on two biogas plants over several days (Hrad et al., 2022). Their main conclusion was that on-site methods are suitable if most emissions emanate from a few sources, while off-site methods seemed reliable to determine whole-plant emissions. If different methodologies are used in a complementary way depending on plant size, climate conditions, economy resources and time availability, they can lead to a very accurate description of the emissions of the biogas plants (e.g. as done by (Reinelt et al., 2022)).

4.4 Existing guidelines to detect and measure methane emissions

Well-developed international standards and procedures that provide guidelines on how to properly use different detection and measurement devices already exist for different applications. For the oil and gas sector, the United Nations Environment Programme launched the Oil & Gas Methane Partnership (OGMP) at the UN Secretary General's Climate Summit in 2014 (United Nations Environment Programme, 2023). Specifically, OGMP provides a protocol to manage methane emissions from oil and gas operations and it offers a platform to help member companies demonstrate actual reductions to stakeholders. Within this initiative, Technical Guidance Documents (TGDs) on the main emission sources have been developed (United Nations Environment Programme, 2023). The guidance documents present suggested methodologies for quantifying methane emissions from each source and describe established mitigation options that Partners should execute.

Specifically, the Technical Guidance Document Number 2 "Fugitive Component and Equipment Leaks" refers to fugitive emissions that arise from unintentional leaks from components or sources of leaks as flanges, screw and compression fittings, stem packing in valves, pump seals, compressor components, through-valve leaks in pressure relief valves, open-ended lines, hatches, meters, open-ended lines and improperly operated storage tanks. Since some of these components are also used in biogas plants, those guidelines may be adapted to the different conditions of biogas production and upgrading to biomethane (e.g. operating pressure, different contamination levels, components size).

For the purposes of this work, the authors suggest Voluntary Certification Schemes, when designing their verification procedures for biogas and biomethane production, to follow the guidelines to detect and measure methane emissions already designed by the biogas sector in some member states (e.g. Germany, Denmark, and Sweden). Such guidelines recommend the use of detecting devices presented in section 3.1, without mentioning the standards used for the natural gas sector.

The developed long-term initiatives to monitor, track and mitigate biomethane fugitive emissions from biogas and biomethane plants proved important reductions in methane emissions. Moreover, international initiatives as IEA Bioenergy Task 37 on Biogas Production and Utilization (IEA Bioenergy Task 37, 2023) and associations as the European Biogas Association (EBA) through specific projects (e.g. EvEmBI (European Biogas Association, 2023)) provided detailed technical documents aiming at promoting voluntary actions for GHG emissions control in the biogas sector.

4.5 Approaches to reduce methane emissions

Depending on the type of emissions, there are three possibilities to reduce methane emissions:

- For leaks: mechanical repairs or sealing of the leakages need to be executed (more description of current guidelines are available in technical reports and peer-reviewed papers (Adnan et al. 2019; Brinkmann et al. 2016; European Commission Joint Research Center 2015; IEA 2021; Martín-Hernández, Guerras, and Martín 2020; Methane Guiding Principles, 2021; Miltner, Makaruk, and Harasek, 2017)). Specifically, leakages must be mitigated with immediate actions and limited resources, since biogas sector do not deal with high pressurized, long pipelines as the natural gas sector. According to the results from Figure 3, the mean value 1.5% of emitted CH_4 on the overall CH_4 production, shall be reduced to 0.5%, and this could be done with relatively simple interventions (as described in the previous section). It would be beneficial to handle such remediation in the plant maintenance programme. Remediation methods consist first in temporarily sealing gas losses with tape (for an immediate action) and during the maintenance operations, components are replaced or repaired onsite.

- Technologies-related emissions: installing low emission technologies (closed digestate storage, more efficient, recent upgrading technologies) or an exhaust gas treatment. Guidelines for best available technologies are thoroughly described in specific technical reports (Barthe et al. 2015; European Commission, 2004). Section 4.1 also reports the main findings to mitigate such emissions in the modern biogas plants.

- Emissions related to operating practices: holding the gas holder (i.e. the digester) filling level below 50%, performing regular maintenance of moving parts and adjusting substrate feeding before planned maintenance (Strauch, Krassowski, and Singhal 2013; U.S. Environmental Protection Agency, 2022b). The organization of regular best practice training for biogas operators is considered the most effective way to ensure correct plant operation. Training can be organized by associations or by voluntary schemes performing GHG emissions verification checks and may include information on voluntary detective programmes (e.g. as in Denmark and Sweden).

More details and mitigation measures can be found in the report of EBA (European Biogas Association, 2020a), described in chapter 7.

4.6 Existing methodologies to account for methane losses from biogas and biomethane plants

Fully accounting for fugitive methane emissions from biogas plants is challenging. As seen in section 2.5, RED II default values for biogas and biomethane include estimations of structural methane emissions, but operational emissions were not considered. Scientific literature demonstrates that it is possible to measure biomethane emissions in specific plants for certain time spans, but the nature of accidental emissions makes it impossible to predict them and to generalize to other plants, as indicated in section 4.1. The implementation of some best practice guidelines for maintenance and repairs can reduce the incidence of unforeseen events and certain leakages. Therefore, there is a need to develop a specific methodology to account for the operational biomethane emissions in line with the existing experimental evidence.

The first voluntary monitoring systems to reduce methane emissions have been established successfully in Sweden, Denmark and Switzerland (described in Chapter 4). These voluntary initiatives include guidelines to monitor and quantify the methane losses in a biogas plant, integrating regular self-inspection and measuring activities from third-party bodies. Such voluntary programmes led to the adoption of regulations and demonstrated significant improvements in the performances of the biogas production in terms of methane losses. The overarching goals of such programmes have been to further improve the environmental performance of the biogas system; give support to plant owners for performing a structured inventory of their plant to detect leaks; give plant owners better knowledge about the amount of the emissions from their plant and reduce any emissions to improve the economy; give the biogas industry better information and thereby greater credibility in relation to emissions; and establish a better data basis with regard to actual losses.

5 Recommendations to account for methane emissions from biogas and biomethane in the RED II framework

RED II provides the methodology and typical and default GHG emission factors for the use of biofuels and biomass fuels to make sure they achieve minimum GHG emission savings against the fossil alternative. It is thus important to consider all GHG emissions along the biomass to bioenergy supply chain. As shown above, methane emissions have a significant impact on the GHG emissions balance of biogas, but are extremely dependent on a multitude of technological choices and operating conditions.

5.1 Proposals for modifications to RED II typical and default values

Details on how methane leakages have been included so far in the calculation of GHG emissions of digestate storage, CHP and biogas upgrading have been described in section 2.1, including references. Considering the present analysis and further inputs from stakeholders, the following modifications to RED II are proposed:

1. **For operational emissions**, including leaks and over pressure relief venting, as well as emissions due to incorrect plant operation, we propose to the use of default emission factors depending on the application of a Leak Detection and Repair Programme (LDAR) for voluntary emissions monitoring and maintenance and repair. Thus, we propose a value of 0.5% of the produced biomethane to be used as default emission factor if the plant is participating in a voluntary emissions monitoring, maintenance and repair programme (supervised by a Voluntary Certification Scheme). Such programme (proposed by the Voluntary Certification Scheme) could benefit from the experience gained from existing programmes in Member States like Sweden or Denmark, which already demonstrated positive results in mitigating biomethane emissions from biogas plants (Fredenslund et al., 2023). If the biogas plant does not follow such a programme, a default methane emission factor value of 5% of the produced methane should be used.

2. **For digestate management**, we propose four cases with a default methane leakage rate associated to the practice used as follows:

    - **A standard, suboptimal practice containing all cases** (including open digestate storage and composting performed in an open environment) not respecting the best-practice cases (closed digestate storage, actively aerated composting or RMP measurement with temperatures below 20 °C, all described next). For these cases, default methane emission factors should be as follows: 2.2% for energy grasses (maize silage), 2.5% for biowastes (including sewage sludge) and 10% for manure. Those values are the ones currently assumed in the RED II calculations (Giuntoli et al., 2017).

    - **Closed digestate storage or sufficiently high retention times**, similar to the German legislation requiring 150 days in an airtight environment, with some exceptions for manure-based feedstock as explained below. The 150 days can be split between retention time in the digester and in the closed digestate storage. For these cases, we propose a default emission factor for methane emissions of 0.1%.

- **Actively aerated composting in airtight environment** (i.e. closed environment) in line with best practice and the measurement of methane emissions in the off-gas of the composting plant that prove that methane emissions are lower than 0.1% of methane production. We propose a default emission factor for methane emissions of 0.1%. In case the digestate composting is not done in a complete gas-tight environment, the emission factor shall be taken from the standard, suboptimal practice for digestate management (as indicated in the table below).

- **In the case digestate is not stored in airtight environment** (i.e. closed environment), the Remaining Methane Potential (RMP) of digestate can be measured, similar to the German practice (Landesamt für Natur, 2018). If the measured RMP is below the proposed default emission factor for the standard practice (open digestate storage or composting in closed environment), then 75% of the measured RMP can be used as an emission factor[3]. If a temperature inside the digestate storage below 20 °C can be proven over the whole storage period, the value can be reduced to 25% of the RMP.

3. **For biomethane upgrading**, the proposed default emission factors add two categories of emissions, similar to the Italian legislation. The new categories are under 0.2% methane in the off-gas and between 0.2 and 1%. The technology providers can provide certified emission rates for their biogas upgrading technology. The category of 0% (previously called "off-gas oxidation) can be used if off-gas combustion is performed or the CO_2 separated from the biogas is captured and no off-gases are released. As before, actual values can be claimed by measuring the methane in the off-gas.

5.1.1 Proposed default values for methane losses from biogas production

Table 5: Proposed default values for methane losses from biogas production

Plant part	***Type***	***best practice*** ***[%]***	***default (standard practice)*** ***[%]***
biogas processing L_p	piping, maintenance, overpressure events, leaks	0.5	5
digestate management L_d	Storage or digestate composting	0.1	2.2 [maize silage] 2.5 [biowastes] 10 [manure]
	storage with RMP measurement below the proposed default emission factor for (open) digestate storage	RMP * 0.25	RMP * 0.75

Source: JRC analysis

[3] Literature and experts suggest that the real emissions from open digestate storage are between 50% and 100% of the RMP, but can be lower at lower temperatures.

Minimum requirements for practices that qualify as best practice, otherwise the default value should be claimed:

— Biogas processing:

  - follow a certified voluntary leakage detection maintenance and repair programme, and
  - automatically activated flare connected to all pressure release valves and venting systems, and
  - installation of leak detection alarms or other detecting devices in closed environments.

— Digestate storage:

  - Keeping the feedstock or digestate in an airtight environment (combined time in digester and closed digestate storage) for at least *50 + x* days, where "50" represents the minimum retention time of 50 days and "x" is the number calculated as additional 2 days for each mass percent of non-manure-based feedstock (max 150 days)[4].
  - Digestate storage with RMP measurement below the proposed default emission factor for (open) digestate storage:
  - Temperature inside the digestate storage below 20 °C during the whole storage period.

— Composting:

  - The whole process done in complete closed environment, actively aerated cells in a closed environment, direct mixing and cooling of digestate with substrate at the exit of the air-tight section, monitoring and measurement of methane content in the off-gas.

5.1.2 Proposed default values for methane losses from biogas use in CHP and upgrading to biomethane

For the CHP section, the methane loss due to incomplete combustion of biomethane in the internal combustion engines is an emission that is hard to abate. For this reason, the current calculations maintain the same emission factor as reported in section 2.1 and in the current RED (i.e. 1.7% methane loss).

[4] This measure is implemented in the German legislation (Bundesregierung Deutschland, 2021, 5.4.1.15)

Table 6: Proposed default values for methane losses from biogas use in CHP and upgrading to biomethane

Plant part	***Type***	***default [%]***
biogas use in CHP L_c	Slippage of methane in the exhaust gas	1.7
biogas upgrading L_u	Off-gas oxidation or no off-gas emitted	0
	Technologies with less than 0.2% of methane produced in the off-gas	0.2
	Technologies with 0.2% to 1% of methane produced in the off-gas	1
	All other technologies	3

Source: JRC analysis

The values of methane content in the off-gas can be provided by the technology manufacturer with a test, according to industry standards or other significant documentation certified by Voluntary Schemes approved by the European Commission. If manufacturer values are provided, they shall be checked yearly (during general emissions verifications). Actual values (according to the methodology described in 5.2) can be provided by the operator, based on documented measurements of methane in the off-gas.

All proposed values are summarized in the following **Table 7**.

Table 7: Summary of proposed emission factors in [% of produced methane] and additional emissions if not using best practices for all processing steps

Plant part	Type	Best practice [%]	Standard practice [%]	Emissions for standard practice (IPCC AR6*) [g CO_2eq/MJ]
biogas processing	piping, maintenance, overpressure events, leaks	0.5	5.0 (0.0)	24.3
digestate management	digestate composting or storage [silage] [biowastes] [manure]	0.1 (0.0)	2.2 2.5 10.0	11.3 13.0 53.5
	storage with RMP measurement below the proposed default emission factor for (open) digestate storage	X = RMP * 0.25	X= RMP * 0.75	(X-0.1) * 5.4
Biogas upgrading to biomethane	Any technology	0.0	3.0	16.2
	Technologies certified or measured to have < 0.2% of produced methane in the off-gas	0.2		15.1
	Technologies certified or measured to have < 1% of produced methane in the off-gas	1.0		10.8
Biogas use in CHP	Slippage of methane in the exhaust gas	1.7		Not available

Colours: Same as in current RED II

Newly proposed value in this study

(Current RED II value)

*** AR6 refers to the IPCC Assessment reports and the respective GWP values for biogenic methane of 27 g CO_2eq/g CH_4**

Source: JRC analysis

5.2 Proposals for a methodology for methane emissions accounting

The findings from previous chapters demonstrated that the impact of biomethane emissions in biogas plants cannot be overlooked. Since biogas operators must comply with the RED II sustainability criteria for biogas for electricity and biomethane production (as reported in the Chapter 2), updated GHG emission factors including methane emission losses should be considered within:

— the use of default values for the biogas/biomethane plant components;

— the use of "best practice" values for the biogas/biomethane plant operation and use of components, depending on a certain management and monitoring programme aiming to reduce methane losses;

— the use of actual values for the biogas/biomethane plant components, resulting from measurements and quantification of emissions made by an independent third-party.

While the use of typical and default values of GHG emission factors (Annex VI of the RED II) is based on pre-calculated carbon intensities including different options for different pathways (depending or not on the implementation of low-carbon technologies and best available practices), the operators can also deliver their own GHG emissions calculations (actual values) following the same methodology as for the calculation of the typical values.

Instead of including the methane emissions in the terms e_p and e_u, we propose to add an additional term to Equation 1:

$$\mathbf{E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr}} + \boldsymbol{e_{me}} \quad \text{Equation 2}$$

where:

$\boldsymbol{E}$ Total emissions from the use of the fuel in Annex V or total emissions from the production of the fuel before energy conversion in Annex VI;

$\boldsymbol{e_{me}}$ Total methane emissions from biogas and biomethane;

All other terms as described in RED II. The terms $\boldsymbol{e_p}$ and $\boldsymbol{e_u}$ do not include methane emissions anymore.

The methane emissions can be split into emissions sources:

$$\boldsymbol{e_{me} = e_p^{me} + e_d^{me} + e_c^{me} + e_u^{me}} \quad \text{Equation 3}$$

where:

e_p^{me} methane emissions from biogas processing;

e_d^{me} methane emissions from digestate management;

e_c^{me} methane emissions from the use of biogas in CHP;

e_u^{me} methane emissions from biogas upgrading to biomethane.

The overall methane emissions e_{me} can also be measured by state-of-the-art remote sensing (off-site) methods as described in chapter 4.3.1.

All emissions can be calculated from emission rates with the following conversion for each generic emission source “i”:

$$e_i^f = \frac{L_i \cdot GWP_{CH4}}{LHV_{CH4}} = 560 \cdot L_i$$

where:

L_i emission rate for each emission type “i” in the terms [p,d,c,u], as share of produced biomethane

GWP_{CH4} global warming potential of methane, according to IPPC AR5, which is 28 g CO_2eq/g CH_4

LHV_{CH4} lower heating value of methane in MJ/g, a value of 0.05 MJ/g can be used.

As done in RED II, to compare the calculated emissions of biogas for electricity with the fossil fuel comparator, the total emissions "E" have to be divided by the net electric efficiency of the overall plant, including internal electricity consumption. The allocation of emissions to co-produced heat can also be done as before. The calculation of methane emission factors can be undertaken using a mix of actual and default values for the different parts (sections) of the biogas/biomethane plant, conditional on the compliance with the minimum requirements and application of a voluntary programme for inspection, maintenance and repairs, subject to certification by a third party.

5.3 Proposals for requirements for voluntary leakage detection and repair programmes

To be able to use the lower values of methane emission factors for biogas production, described as "best practices", economic operators need to adhere to a voluntary leakage detection monitoring and repair programme. Such programme can be developed by a Voluntary Certification Scheme and be used for validation and verification. To qualify, such a programme needs to include at least the following aspects:

— Define and implement a plan for inspection and screening of plant components to identify leaking components, with the following minimum requirements:

    - at least one monthly visual inspection (with no detecting instruments) of high-risk components (pressure relief valve, moving components);
    - at least once a year regular leak detection (and quantification) by an external professional. It should follow the guidelines developed by the Voluntary Certification Scheme following the existing schemes like EvEmBi, Denmark or Sweden. If the leaks exceed 2% of the annual production or 50 tonnes per year, a mandatory repair should be scheduled, and an additional test, within 6 months of the leak detection should confirm the effectiveness of the repair;
    - a maintenance and repair plan defining the intervals when components need maintenance and how to repair components that show leaks;
    - a documentation system to report each inspection, leak detection, maintenance and repair.

— Install detection systems for increased indoor methane concentrations and for pressure relief valve openings.

— At least one training for each person operating the plant or a written best management practice document available, to avoid overpressure events and other suboptimal management.

— Any other requirements already set by existing voluntary programmes at a member state level.

Most of these measures have been applied very successfully in the Danish and Swedish voluntary programme and are deemed to be replicable across Europe. Good information on those schemes and best practices is available from the EvEmBi project (European Biogas Association, 2020; European Biogas Association, 2020) and should be followed.

The voluntary schemes of industry association could propose a validated detection and repairing programme as well as courses on best operating practices.

5.4 Recommended approach, including mitigation measures

The authors of this report propose the integration of the findings of the report in the RED II' Annex VI through a delegated act updating the GHG emission factors of biofuels and bioenergy pathways.

The monitoring and repairing recommended programme may be included in the EU legislation according to the following options:

(1) either a specific Implementing Act (IA) on certification (integrating the findings proposed in 0 and 5.3);

(2) or a guidance document for voluntary schemes , which is harmonized with the current existing guidelines and measures proposed in this report.

Other options may be evaluated by DG ENERGY depending on the available possibilities.

6 Impact assessment of the proposed measures

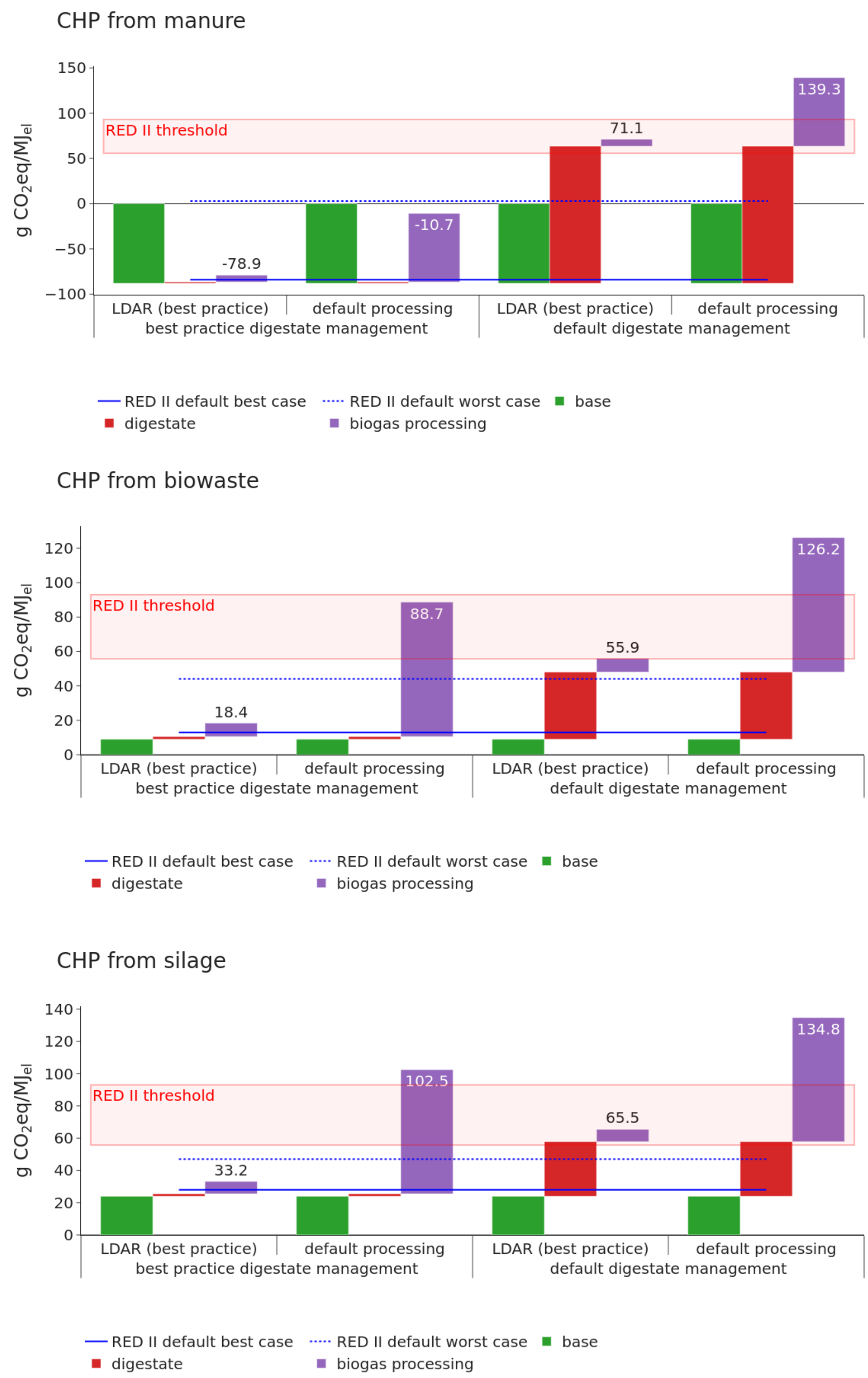
As a final step, this report includes an assessment of the impact on the GHG emission intensity of biogas for electricity and biomethane production to show how the current RED II default values and the newly updated default values (including all proposed updates from chapter 5.1, but using IPCC AR4 GWP as in RED II) for biogas pathways compare. The pathways included in the RED II Annex VI have been displayed in the charts below for all four combinations of best practice (application of Leak Detection And Repair - LDAR programme) and standard practice for biogas processing as well as digestate management best practice (closed digestate storage or aerated composting) and standard practice. The emission thresholds to meet the sustainability requirements set by the EU directive are shown as red area. Blue lines represent the minimum and maximum emission factors in current RED II for all equivalent pathways. The bars show the contributions of different emission sources to the overall emission factors, with the green bars representing the base emission factors (all GHG emissions according to RED II pathways excluding methane emissions). The value shows the updated overall emissions. So, if the overall value is above both blue lines, the updated (default) emission factors are higher than the current emission factors, if they are below, they are always lower. If they are in between, it depends on the exact pathway in the current RED II.

Figure 5 shows the emission factors for all biogas to electricity pathways. In order to evaluate the impact of this proposal, the RED II threshold determining the bio-electricity sustainability has been included (50-70% reduction, compared to the fossil fuel comparator for electricity).

In a full "life-cycle" calculation, emissions would increase the need for more feedstock to produce the same (1 MJ) product, as was done in the current version of the default values. The proposal to add an emission factor after the calculation doesn't consider the increase in feedstock use. The addition of the emission factor instead of modelling the whole system can increase the overall emission factors, especially for manure, where the 10% digestate emissions don't create an additional manure bonus. For high emission factors as e.g. the 10% for open digestate storage in case of manure, this has a significant influence on the resulting carbon intensity. We still believe that this simplification is acceptable and incentivizes operators either to reduce the biggest emissions from open digestate storage through the use of closed digestate system, or to provide actual values.

By avoiding "default" digestate storage, most existing plants can reach the sustainability thresholds. In most cases, participating in the Leak Detection And Repair (LDAR) programme also allows to reach the threshold, and only in very few cases and newer plants, best practice for digestate management and the LDAR programme are necessary to reach the threshold.

Figure 5: Impact assessment of the proposed emission factors on biogas CHP plants for (a) manure, (b) biowastes and (c) silage.



Source: JRC analysis

Figure 6 on biomethane production pathways only includes two of the GHG emission categories for biogas upgrading (in order to limit the number of charts shown): the option with off-gas combustion to avoid methane emissions (0%), and the default case (described as "other" in the charts) with methane emissions of 3% at the upgrading section, as explained before. For the case of biomethane, two thresholds are shown: the option of "grid injection" with minimum GHG emission savings of 50 % to 80 %, considering the FFC for heat (replacing natural gas); and the option of biomethane for transport, with a minimum reduction of 50 % to 65% compared to the FFC for the fuels used in transport.

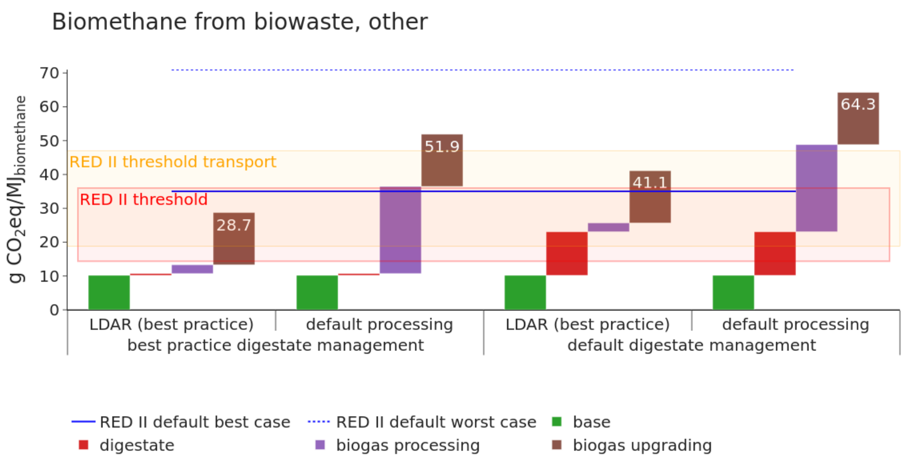
Negative “base” values arise from the manure credit for the emissions savings for improved agricultural management.

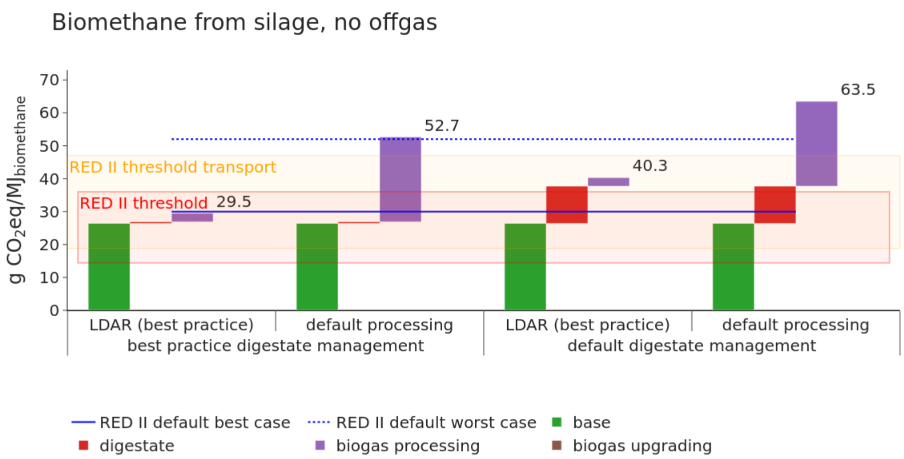
For biomethane production, all manure-based pathways would still be below the thresholds. Biowaste pathways need, in order to reach the thresholds, the application of best practice at least in one of the following stages in the biomethane production: “biogas processing”, “digestate management” and “upgrading”, while silage maize pathways need best practice for all options, and cannot meet the most stringent thresholds for new plants.

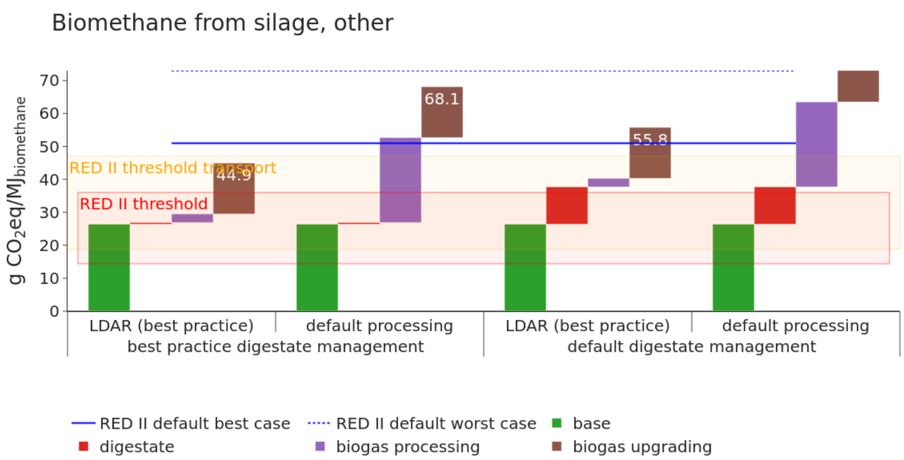
Already operating plants could reach the thresholds by following the LDAR programme and either using closed digestate storage (or best available practices for digestate composting) or have no off-gas emissions from the upgrading section.

Summarising, while for manure-based pathways it is relatively easy to remain within the RED II thresholds, operators using biowastes need to follow some best practices to do so. The use of silage-based feedstock leads to higher GHG emission factors which don’t always reach the sustainability requirements of the RED II even using best practices to avoid methane emissions (as in the case of biomethane production, which wouldn't be sustainable for grid injection). In order to further reduce the GHG emissions of such pathways, it is recommended to use less soil inputs and reduce the transport emissions. These results reflect how the mitigation of biomethane emissions is of primary importance to abate the GHG emissions for biogas pathways. At the same time, the proposed emission factors still enable operators to use a large array of feedstocks and technologies to respect the sustainability thresholds.

Figure 6: Impact assessment of the proposed emission factors on biomethane plants for (a) manure, (b) biowastes and (c) silage.







Source: JRC analysis

7 Feedback from industry and associations

The JRC consulted a number of relevant industry associations, companies and experts. Their responses are summarised below.

7.1 European Biogas Association

The European Biogas Association (EBA) is the European association representing the biogas industry. EBA participated in the EvEmBi project (see 3.1.1) and decided to update the work done for biomethane emissions into their R&D plan for 2022, delivering their white paper in April 2023 (European Biogas Association, 2023). The scope of this document is to support and advise the industry, EU policymakers and biogas operators, on the methane emissions originated from the biogas sector and the most cost-effective manner to reduce methane emissions at AD plants. Summarizing, EBA recommendations to minimise methane emissions consist in a combination of regular self-inspections, periodic reporting of methane emissions as part of monitoring programmes and training courses for plant operators.

The EBA and the JRC prepared a questionnaire in September 2022 on the “EU Member States legislation on fugitive methane emissions”, to gather information as regards the current actions at national level The insights and feedback from this cooperation have been included in the relevant parts of this report.

7.2 World Biogas Association

The World Biogas Association (WBA) recently published their “2022 Vision Document” (World Bioenergy Association, 2021) containing, as one of the key recommendations, comprehensive actions to reduce methane leakage, comprising measurement, reporting and verification practices and the use of best available technology. Minimising methane leakage from biomethane plants is seen as critical to ensure optimal GHG emissions performance. WBA suggested that integrating monitoring programmes, technological solutions to detect emissions and rigorous maintenance regimes will ensure a strong reduction of the overall methane emissions, therefore reducing the carbon intensity of biomethane and enhancing plant revenues. This is in line with the proposal of this report.

7.3 International Council of Clean Transportation

The International Council of Clean Transportation (ICCT) released its position paper as feedback on the public consultation launched by the European Commission on the proposed Regulation on Methane Emissions Reduction (Searle, 2022). ICCT recommended site-level measurements of methane emissions for the biogas sector. In its white paper of 2021 ICCT recommended to provide detailed and consistent guidelines on the methodology for measuring methane leakage and related guidance on how to verify these measurements (Zhou, Swidler, et al., 2021). These suggestions were considered when opting for the leak detection and repair programme proposed in this report.

7.4 Feedback from biogas experts

During the workshop organised during the EBA Conference 2022 by the JRC and EBA, biogas experts provided feedback to the questionnaire prepared to gather specific information, knowledge and experience on monitoring and mitigating fugitive methane emissions. The experts also provided suggestions on the way forward to enable the quantification and the reduction of the methane leakages from biogas and biomethane production. The main suggestions and conclusions are presented in the next:

- *While manure gets a methane credit, biowastes do not. As these can cause emissions, especially when landfilled, the proposal was to provide a credit.*

According to RED II, the methodology for the calculation of GHG emissions from biogas and biomethane production includes a credit of 45 g CO_2eq/MJ of manure used in anaerobic digestion for the emissions savings for improved agricultural management. Specifically, the bonus is given for the avoided methane emissions through the natural decomposition of manure when spread on land. For the use of biowaste for biogas production, the opinion is that the counterfactual scenario (i.e. the current scenario, which considers the traditional practices to dispose this waste) should not be landfilling as this will be forbidden soon in the EU, and separate biowaste collection will be mandatory in 2023; landfilling or burning of separately collected biowaste is already forbidden (European Environmental Bureau, 2022). Currently, around 50% of biowastes (from households) are collected separately and used either in composting or anaerobic digestion facilities, while the rest is collected with other residential wastes and either landfilled or incinerated (EEA, 2020). To conclude, as soon as biowaste is collected separately, landfilling is not an alternative, and thus no bonus should be given. If not collected separately, biowaste cannot be used for biogas production.

- *Create "weighted averages" for the share of leakage rates to take into account that larger plants tend to leak less than smaller plants (including wastewater treatment plants).*

The mean values in **Figure 3** were calculated as a normal average. A weighted average, weighting each emission share value by the plant size, could lead to a different value if indeed larger plants systematically leak less (as share of their methane production) than smaller plants.

There is some experimental data that shows that larger plants tend to leak less than smaller plants. On the other hand, this is not a clear trend, and several studies (including EvEmBi) did not find a clear relation between plant size and share of methane emissions. In addition, most of the available data (Bakkaloglu, Cooper, and Hawkes, 2022; Lansche and Müller, 2017; Adam et al., 2021; Clauß et al., 2019; Wechselberger, 2021; Wechselberger et al., 2023; Vu et al., 2015; Schick et al., 2013; Clemens et al., 2006; Mathieu Dumont et al., 2013; Fredenslund and Scheutz, 2017) do not contain information on plant size. Therefore, based on the available data, considering a mean leakage rate is justified. This mean value, together with the median, distribution and currently assumed leakage rates in the RED II was therefore used to derive plausible leakage rates for best and standard practice. Plants able to prove lower methane emissions can claim actual values.

- *Ensure consistency with the German legislation on clean air for digestate storage which imposes 150 days as minimum digestate retention time in the anaerobic digestion to avoid closed digestate storage* (Zhou, Hülsemann, et al., 2021; Bundesregierung Deutschland, 2023)*. The new German legislation also imposes digestate covered for shorter times, or a measurement of its Remaining Methane Potential (RMP) that is the amount of methane that can still be produced by the digestate, to demonstrate its low emissions.*

Setting some time limits on the digestate retention time and a measurement of the RMP can have a positive impact on reducing methane emissions from digestate storage while giving the operators more flexibility. Therefore, the proposed method in chapter 6.1 includes both practices (a retention time of 150 days and measurement of the RMP on digestate) as best practices for digestate management.

- *The Italian legislation* (Dipartimento energia, 2023) *has established default values for digestate usage in composting plants, producing both compost from digestate and biomethane following best available technologies set at EU level in the Best Available Techniques Reference Document* (Brinkmann et al., 2016).

Including the rules for compliance with Best Available Techniques (BATs) for composting, requiring depressurized cells, oxygenated from the bottom of the compost piles, could guarantee a high efficiency of the composting process which produces only CO_2 emissions and negligible quantities of methane. This is included in our proposal as a best practice option for digestate management.

- *Including additional and more granular default values for biomethane production, as proposed in the new Italian legislation* (Dipartimento energia, 2023) *according to the Italian standards* (UNI, 2020) *(additional feedstocks; different levels of biomethane leaks at the upgrading section; minimum time for digestate storage in closed tanks with biomethane recovery, set at 30 days).*

Our proposal contains different levels of methane emissions for upgrading technologies, which have the benefit of incentivizing technologies with lower emissions and simplifying calculations for operators.

- *Consider additional disaggregated values also for feedstock storage since it consists in a potential source of methane and nitrous oxides emissions.*

Among the various feedstocks used for biogas production, manure is the one that releases large amounts of methane emissions when left in contact with open air. For this reason, RED II provides a credit for its use for biogas production. However, improper manure storage before the anaerobic digestion should be avoided. The Best Available Techniques Reference Document for waste streams (including manure) (Brinkmann et al., 2016) partially regulates such issues. However, a disaggregated value for feedstock storage is not possible as feedstock storage is outside of the system boundaries of RED II (as explained in section 4.1), so no emissions are taken into account for feedstock storage in the proposed methodology.

8 Conclusions

Given the high impact of methane on global warming, accounting methane emissions is crucial to evaluate the sustainability of methane based energy carriers like natural gas, biogas and biomethane. While the EU Methane Strategy already incentivizes natural gas operators to reduce fugitive emissions, the biogas and biomethane sector needs to address these issues within the Renewable Energy Directive (EU) 2018/2001 (RED II). In the RED II default values as in literature, methane emissions from biogas and biomethane have been underestimated.

This study highlights the importance of detecting, measuring, and mitigating methane emissions from biogas plants, which are hard to predict. It is established that methane emissions originate both from structural sources associated with technology design and from operational sources due to plant management. An analysis on various detection and measurement technologies, ranging from on-site leak detection devices to remote sensing technologies, shows that emissions sources can be identified with a high level of accuracy.

The main sources of biomethane emissions have been identified at the sections of biogas production (anaerobic digester), digestate management, biogas upgrading to biomethane, and at the exhaust of the CHP engine. Default values available in the RED II Annex VI already contain methane emission factors from digestate management, upgrading and CHP, but a review based on the most recent findings from literature and projects shows that the current estimations may not fully account for all sources of emissions, particularly fugitive and operational emissions.

Therefore, the report proposes updated emissions factors, including a methodology to account for them. This considers the integration of best technologies and practices to mitigate the actual emissions associated with biogas production and use. According to successful EU-funded initiatives and national programmes such as those in Denmark or Sweden, the introduction of LDAR (Leak Detection and Repair Programs) has shown positive results in addressing unavoidable leaks and reducing emissions through the adoption of best practices. Such programs have demonstrated the effectiveness of measures to reduce methane emissions, incentivizing operators to monitor and mitigate GHG emissions effectively.

To implement such proposal within the RED framework, two scenarios are proposed: a best practice scenario, which would apply if the plant participates in a voluntary emissions monitoring program, and a standard practice scenario, which would apply otherwise. For digestate management, the study proposes default emission factors for various practices, including closed digestate storage, actively aerated composting, and open digestate storage or composting. For biogas upgrading, it is recommended that emission factors be adjusted based on the technology used, with specific categories for emissions under 0.2% and between 0.2% and 1% of the produced biomethane. For CHP units, the report recommends maintaining the current emission factor. To be eligible for best practice emission factors, biogas operators must adhere to a voluntary LDAR program. This program would include regular plant inspections, leak detection and quantification by external professionals, maintenance and repair plans, and operator training or access to best management practice documents.

The impact assessment of the proposed measures indicates that the implementation of LDAR programs and best practices would enable most biogas and biomethane pathways to meet or even exceed the sustainability thresholds established by RED II.

Feedback from industry, experts and associations, such as the European Biogas Association (EBA) and the International Council on Clean Transportation (ICCT), supports the recommendations and highlights the importance of measuring, reporting, and verifying practices and the use of best available technology to reduce methane emissions.

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List of abbreviations and definitions

Abbreviations	Definitions
AD	Anaerobic Digestion
BATs	Best Available Techniques
bcm	billion cubic meters
BMP	Biomethane Potential
CHP	Combined Heat and Power
CO	Carbon Monoxide
COP	Conference of the Parties
ETS	Emission Trading System
FFC	fossil fuel comparator
FQD	Fuel Quality Directive
GHG	Greenhouse Gas
GWP	Global Warming Potential
IF	Infra-Red
IPCC	Intergovernmental Panel on Climate Change
LDAR	Leak Detection And Repair
LCA	Life Cycle Assessment
LHV	Lower Heating Value
MJ	Mega Joule (10^6 J)
MRV	Monitoring, Reporting and Verification
MS	EU Member State(s)
MSW	Municipal Solid Waste

Abbreviations	Definitions
NG	Natural Gas
OGI	Optical Gas Imaging
OGO	Off-gas Oxidation
OGV	Off-gas Venting
PRV	Pressure Relief Valve
RED	Renewable Energy Directive 2009/28/EC
RED II	Renewable Energy Directive 2018/2011- RED recast
RMP	Remaining Methane Potential (identical to the BMP for digestate)
TDLAS	Tuneable Diode Laser Absorption Spectrometry
TOC	Total Organic Compounds
UN	United Nations
VOC	Volatile Organic Compounds
VS	Voluntary schemes

Terms	Definitions
Accidental emissions	Unintentional release of emissions as a result of events that may occur due to abnormal conditions or as a consequence of an emergency.
Channelled emissions	Emissions into the atmosphere through an emission point such as a stack or a chimney.

Terms	Definitions
Diffuse emissions	Non-channelled emissions to air. Diffuse emissions include fugitive and non-fugitive emissions from various small, scattered sources (e.g. components leaks such as bulk storage, valves, etc.). Non-fugitive emissions can arise from bulk storage, loading/unloading systems, atmospheric vents, open vessels and tanks, open gutters, sampling systems, waste, sewers and water treatment ponds.
Emission factor	The percentage of methane loss, hence the ratio between methane emitted and methane produced.
Fugitive emissions	Non-channelled, unintentional emissions of methane into the atmosphere caused by loss of tightness of equipment, which is designed or assembled to be tight. Fugitive emissions can arise from: moving equipment, such as agitators, compressors, pumps, valves (manual and automatic); static equipment, such as flanges and other connections, open-ended lines, sampling points.
Hydraulic Retention Time (HRT)	It is a parameter used for biological processes and is defined as the average time that a volume of an influent (such as, for example wastewater) spends in a tank or bioreactor).
Leaks, Leakages	Emissions through a crack or hole or seal of a component (tank, pipe, etc.) that should be sealed.
Methane losses	All emissions of the methane that is lost as operational and structural emissions, channelled or diffuse emissions, etc.
Operational emissions	All emissions that occur during the operational or in-use phase of a plant and that are due to the way the plant is operated.
Residual Methane Potential (RPM)	Residual Methane Potential refers to the amount of methane gas that can be produced through anaerobic decomposition of biogenic material after the initial anaerobic digestion process has taken place. It is typically expressed in terms of the volume of methane gas produced per unit mass of residual organic matter.

Terms	Definitions
Structural emissions	Emissions due to the design of a plant or the nature of a technology such as open digestate storage, exhaust gases of a CHP or upgrading slip. This category includes channelled emissions and emissions from storage operations.

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