POSITION // AUGUST 2025

Methane, the underestimated greenhouse gas

Sources, effects, mitigation options

German Environment Agency

Umwelt Bundesamt

Imprint

Publisher:
German Environment Agency
Wörlitzer Platz 1
06844 Dessau-Roßlau
Phone: +49 340-2103-0
Fax: +49 340-2103-2285
buergerservice@uba.de
Website: www.umweltbundesamt.de

Authors:
Johanna Appelhans, Christian Böttcher, Kai Keßler, Christian Mielke, Anja Nowack, Katja Purr, Anja Schwetje, Diana Sorg, Jens Tambke

Editors:
Patrick Gniffke
Diana Sorg
Yaman Tarakji

Design:
Atelier Hauer + Dörfler GmbH

Publication as a pdf:
www.umweltbundesamt.de/publikationen

Photo Credits:
Title: © 2022 Ansario/Shutterstock
p. 4: © 2016 KYTan/Shutterstock
p. 6: © 2021 Veranika848/Shutterstock
p. 7: © 2015 geniusksy/Shutterstock
p. 8: © 2016 Lena Wurm/Shutterstock
p. 19: © 2016 Rudmer Zwerver/Shutterstock
p. 28: © 2022 Andriana Syvanych/Shutterstock
p. 30: © 2020 elRoce/Shutterstock

As at: August 2025

ISSN 1862-4804

POSITION // AUGUST 2025

Methane, the underestimated greenhouse gas

Sources, effects, mitigation options

Table of contents

Introduction

Methane (CH_4) is the second most important greenhouse gas after carbon dioxide. Methane in the atmosphere due to human activity contributes in total approximately 0.5 degrees Celsius to net temperature increases (Intergovernmental Panel on Climate Change (IPCC) 2021). On top of this, methane is a key precursor for the formation of ground-level ozone (O_3). Ozone is linked to some health issues whilst also damaging ecosystems and crops. A reduction in methane emissions helps contribute to climate protection, public health, and also helps protect ecosystems.

Over the last few years there have been efforts at both an international and European level to significantly reduce methane emissions and set out specific mitigation targets. As methane only remains in the atmosphere for a relatively short time (between 9 and 12 years), mitigation of CH_4 can play an important role in restricting global warming in the short term. A reduction in methane emissions is one of the key objectives in the European Green Deal[1], and the EU methane strategy (COM(2020)) that was published in October 2020 provides options for mitigation of methane in the relevant sectors. The European Methane Regulation (EU Regulation (EU) 2024/1787) came into force on 5 August 2024. It requires fossil energy infrastructures operators to measure methane emissions regularly, eliminate leaks quickly and reduce the venting and flaring of gases. The regulation is part of the EU's 'Fit for 55' package[2], which aims at reducing greenhouse gas emissions in the EU by at least 55 percent by 2030. Moreover, Germany committed to reduce methane emissions by 30 percent by 2030 compared to 2020 levels at the 26th Conference of the Parties of the UNFCCC. Furthermore, the USA and the EU initiated the "Global Methane Pledge" in September 2021 (Climate and Clean Air Coalition (CCAC) et al., 2021). By signing this declaration, over 100 countries are obligated to reduce methane emissions by 30 per cent in 2030 relative to emissions in 2020.

Despite the initiatives in place to reduce methane emissions, many people remain unaware of how necessary a reduction in CH_4 emissions is and the benefits this would bring. With this paper, the German Environment Agency aims to provide information about the effects and the most important sources of methane emissions whilst specifying concrete measures to reduce methane at a national level and worldwide.

1 https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_de

2 https://www.consilium.europa.eu/en/policies/fit-for-55/

1 Political recommendations by the German Environment Agency

Germany has made progress in reducing methane emissions over the last few years. Measures that have already been put in place have achieved considerable success, particularly in the waste sector. The German Environment Agency encourages the following measures in order to achieve further reductions in methane whilst contributing to the stated initiatives for reducing CH_4:

Energy and industrial sector:

- Consistent, regular programmes for detection and repair of leaks in gas infrastructure (Leak Detection and Repair (LDAR) Programme) under the EU Methane Regulation ((EU) 2024/1787).
- Introduction of a methane emission limit for combustion engines in the EU Directive on medium combustion plants ((EU) 2015/2193)
- Introduction of a limit on methane emissions for small combustion engine plants (< 1 megawatt rated thermal input) as part of an Ordinance on the Implementation of the Federal Immission Control Act
- Development of emission control technology for reducing methane emissions from stationary combustion engines
- Transformation of the energy system as well as the application areas of heat, transport and industry and phase-out of all fossil fuels. Renewable energies and renewable electricity should be used directly where it is technically feasible.
- Lowering the demand for methane and gas: Using electricity directly is the most efficient solution. Use of fuels, such as renewable gas, should only take place where it is technically necessary.
- Phasing out gas-based heating technologies: There are sufficient fuel-free alternatives based on renewable energies such as solar power, geothermal energy and environmental heat (with heat pumps) for buildings. Gas heating systems should no longer be installed by 2026 at the latest, so phasing out such technologies when considering the use cycles should take place by 2045 at the latest.
- Electrification of equipment in the gas network: The operating equipment (compressor, preheating route) in the gas network should be electrified and be no longer operated with gas as part of rigorously transforming the energy system into something sustainable.

Agricultural sector:

- Mitigation of methane from animal digestion particularly by reducing the animal population, supplemented by the potential to mitigate methane emissions per unit of product via feed additives, feed, breeding, improving animal welfare, animal health and longevity
- Improving manure fermentation in biogas plants

Waste sector:

- Call for an end to landfilling and dumping of biowaste and organic-rich municipal waste worldwide. This is the only way to sustainably prevent the formation of methane in landfills and thereby the long-term emissions from landfills.
- Extent the separated collection and encourage and support composting, digestion or other treatment of biowaste worldwide.
- Avoid and reduce food waste at both national and global levels
- Capture and recover the energy of landfill gas
- Improve communications regarding the reduction potential of the waste sector as well as the quantification and measurement of emissions and avoided emissions

Overarching cooperation and communication:

- Setting out a mitigation target for methane as part of revising the Gothenburg Protocol under the UNECE Air Convention
- Cooperate more closely with international actors such as the “Climate and Clean Air Coalition” (CCAC), UN organisations and the Gesellschaft für Internationale Zusammenarbeit (GIZ)
- Support and improve the synergies between national targets (Nationally Determined Contributions (NDCs)), framework conditions and the implementation at a local level (towns, private sector, non-government organisations)
- Avoid methane emissions by improved support and financing, which also includes international climate protection initiatives and funds.

2 Relevance of methane

2.1 Climate impact and GWP

After carbon dioxide, methane is the second most important greenhouse gas directly caused by humans. If we consider the same mass of methane and carbon dioxide that is emitted (such as 1 tonne), the greenhouse effect of methane is 28 times that of carbon dioxide if a period of 100 years after emission is taken into consideration as a whole (Metric: GWP-100), (IPCC 2014). According to more recent research, the greenhouse effect of methane using the GWP-100 metric is 30 times that of CO_2 (IPCC 2021).

During the last 650,000 years, the concentration of methane in the atmosphere lay between 400 ppb (parts per billion) during the ice ages and 700 ppb during the warm periods. It has risen from 722 ppb in 1750 to around 1,900 ppb in 2021. The current value is unprecedented over the course of the last 650,000 years. Whilst earlier data was based on air bubbles trapped in ice or firn, since 1983 the methane concentration has been measured directly in the atmosphere in a globally representative manner. The concentration of methane has risen very clearly during this period. In total, anthropogenic methane in the atmosphere has made a contribution to anthropogenic warming of around 30 per cent in total (gross). This corresponds to a gross temperature increase of around 0.5 degrees Celsius to this day (IPCC 2021).

2.2 Role in air pollution control

Alongside nitrogen oxides (NO_X), non-methane volatile organic compounds (NMVOC) and carbon monoxide (CO), methane is a key precursor for the formation of ground-level ozone (O_3). Ozone is linked to health issues such as eye irritation, respiratory problems, inflammatory reactions in the respiratory tract and decreased lung function. Ozone can also harm ecosystems and crops. Longer periods of exposure to even moderately higher concentrations of ozone are a risk to plant growth, crop productivity, the quality of agricultural products and ecosystem services such as carbon sequestration in forests.

According to a study commissioned by the German Environment Agency (Butler et al. 2020) approximately one third of annual ground level ozone in Germany (roughly 20 micrograms per cubic metre (µg/m3)) is caused by the oxidation of methane, and just a small proportion of this (roughly 3 micrograms per cubic meter) is due to the oxidation of methane within Europe. This means that most of the methane originates from sources outside Europe. Global action is therefore required to mitigate the impact methane has on the formation of ground-level ozone.

2.3 Methane sources and sinks

Biogenic methane is produced where organic material decays in the absence of air. The gas is created by microorganisms that produce methane, known as methanogenic archaea, such as those in the digestive tracts of ruminants (enteric fermentation), but also from fermentation processes in landfill bodies. Permafrost soils that are thawing out due to climate change means decomposition of animal and plant remains in the absence of air, which also contributes to the formation of methane.

Warming of the oceans melts methane hydrate (ice with methane), releasing it. The methane that was created via biochemical transformation of organic material over millions of years as a result of immense pressure and high temperatures, is generally described as being a fossil fuel and is industrially extracted as an energy source. Methane can also arise from geothermal processes, such as in hydrothermal vents.

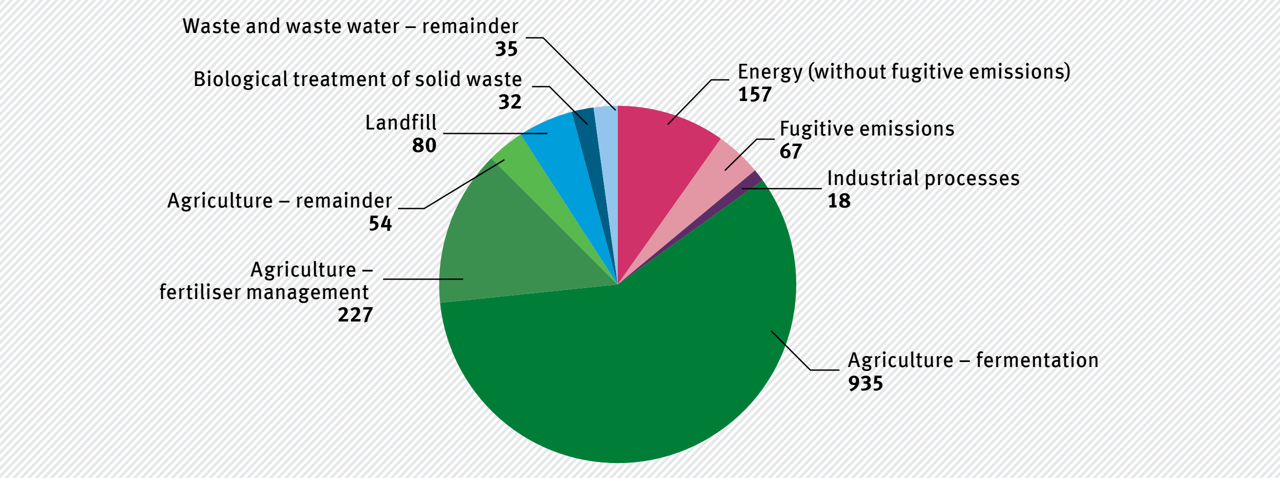
Processes that remove methane from the atmosphere are known as methane sinks. The most important sink is the oxidation of methane due to the hydroxyl radical OH in the troposphere. Soils are also a small sink for atmospheric methane: Bacteria in the uppermost soil layers use CH_4 as an energy source and break it down. Scientific investigations show that methane storage in soils is dependent on many environmental factors, such as substance discharges and climatic conditions. So far, knowledge does not suffice to reliably illustrate these interactions in models.

2.3.1 Situation in Germany

Figure 1

Methane emissions from Germany in 2023 in kt

according to reporting categories*



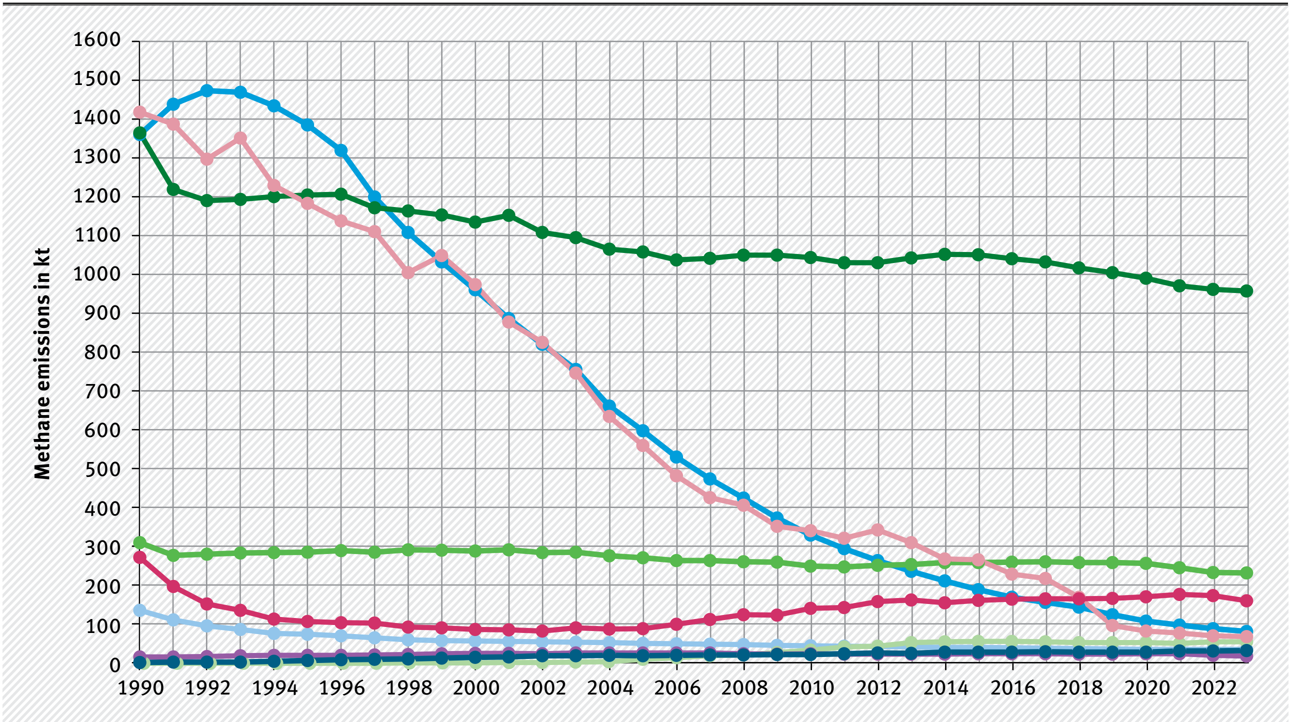
* excluding LULUCF und reported data

Source: German Environment Agency: https://www.umweltbundesamt.de/sites/default/files/medien/11867/dokumente/2025_01_14_em_entwicklung_in_d_trendtabelle_thg_v1.0.xlsx

Figure 2

Methane emissions from Germany

according to reporting categories*



Fugitive emissions 95
Agriculture – fermentation 981
Biological treatment of solid waste 28
Landfill 122
Energy (without fugitive emissions) 163
Industrial processes
Agriculture – remainder 52
Agriculture – fertiliser management 253
Waste and waste water– remainder 36

* excluding LULUCF und reported data

Source: German Environment Agency: https://www.umweltbundesamt.de/sites/default/files/medien/11867/dokumente/2025_01_14_em_entwicklung_in_d_trendtabelle_thg_v1.0.xlsx

In 1990, methane emissions accounted for around 10 per cent of total greenhouse gas emissions in Germany (converted in carbon dioxide equivalents) (UNFCCC 2025). The proportion of methane has remained stable at around 6 per cent since 2010. In absolute figures, emissions over the last thirty years have slowly, but consistently, fallen by 3.2 million tonnes and were still about 1.6 million tonnes in 2023. This corresponds to a reduction of around 66 per cent (UNFCCC 2025).

2.3.1.1 Energy

Methane emissions from the energy sector are largely due to the extraction, conversion and distribution of fuels. Whilst the coal mining sector still played a significant part in the 1990s, gas transport and distribution now contribute around 160 kilotonnes of methane (UNFCCC 2025). Ceasing coal mining operations in 2018, renewal of the gas network and the use of mine gas have saved over 1.1 million tonnes of methane. With the introduction of the Renewable Energy Sources Act (EEG 2014), along with the resulting financial support in using mine gas, direct methane emissions from decommissioned coal mines were reduced to practically nothing. The mine gas is extracted from the coal mines, supplied or processed for use as energy then provided as fuel in the natural gas network. The EEG would legally require network operators, by law, to commit to accepting the electricity generated from mine gas and to pay a feed-in tariff for it.

The emissions resulting from gas distribution have fallen slightly despite a considerable increase in the quantity of gas transported and a substantially more comprehensive distribution network compared to 1990. On the one hand, one reason for this is the renewal of the gas distribution network, particularly in eastern Germany. In particular, the proportion of cast iron pipes in the low-pressure network has been reduced and replaced by plastic pipes that cause lower emissions. Another cause of this reduction is the mitigation of various distribution losses through technological improvements (technically leak-tight fittings such as flanges, valves, pumps, compressors) as a result of following the requirements set out for emission controls (TA Luft, 2002). In total, diffuse emissions account for a large proportion of methane emissions from the energy sector. In addition, the methane slip that arises due to incomplete combustion as well as start-stop processes on equipment accounts for a high proportion of the total methane emissions within the energy sector.

2.3.1.2 Industry

Methane emissions in the industrial sector are primarily due to the chemical industry, particularly in the production of ethylene and methanol. Emission reductions can be achieved primarily through thermal afterburning of volatile organic compunds. This is the state of the art of all plants for producing basic chemicals in Germany.

2.3.1.3 Agriculture

Agriculture is the major driver of German methane emissions, totalling over 1,200 kilotonnes (2023) (UBA 2025). In particular, the digestion process in livestock (enteric fermentation) contributes 77 per cent of methane emissions from the agricultural sector. 19 per cent of agricultural methane emissions stem from fertiliser management. Fermentation of energy crops (storage of fermentation residues) have an increasing effect and now contribute around 54 kilotonnes (5 per cent) to this total (ibid.).

Total methane emissions from agriculture were reduced by about 26 per cent between 1990 and 2023 (UBA 2025). The cattle population in Germany, which causes the most methane as they are ruminants, fell by around 44 per cent between 1990 and 2023 (Federal Ministry of Food and Agriculture (BMLEH 2025a). This was primarily due to the structural changes in agriculture within eastern Germany in the 1990s as a result of the German reunification. In the same period, methane emissions from enteric fermentation only fell by around 30 per cent (UBA 2025). This is also partially due to the fact that milk output per cow also rose from 4,900 kilograms (1991) to 8,600 kilograms (2022) on average (BMLEH 2025b). Part of the reduction was compensated for by higher output from each individual animal. Emissions from digestion have therefore been stagnating for years. Emissions from fertiliser management have fallen by 25 per cent between 1990 and 2023 as nowadays more manure is used in biogas plants (UBA 2025). Furthermore, relative to 1990, more methane emissions now come from the fertilisation of energy crops (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) 2019).

The projection from the Federal Government forecasts a further small reduction in methane emissions from agriculture of around 38 kilotonnes (a fall of about 3 per cent) by 2035 relative to 2020 (BMU 2019).

2.3.1.4 Waste and waste water management

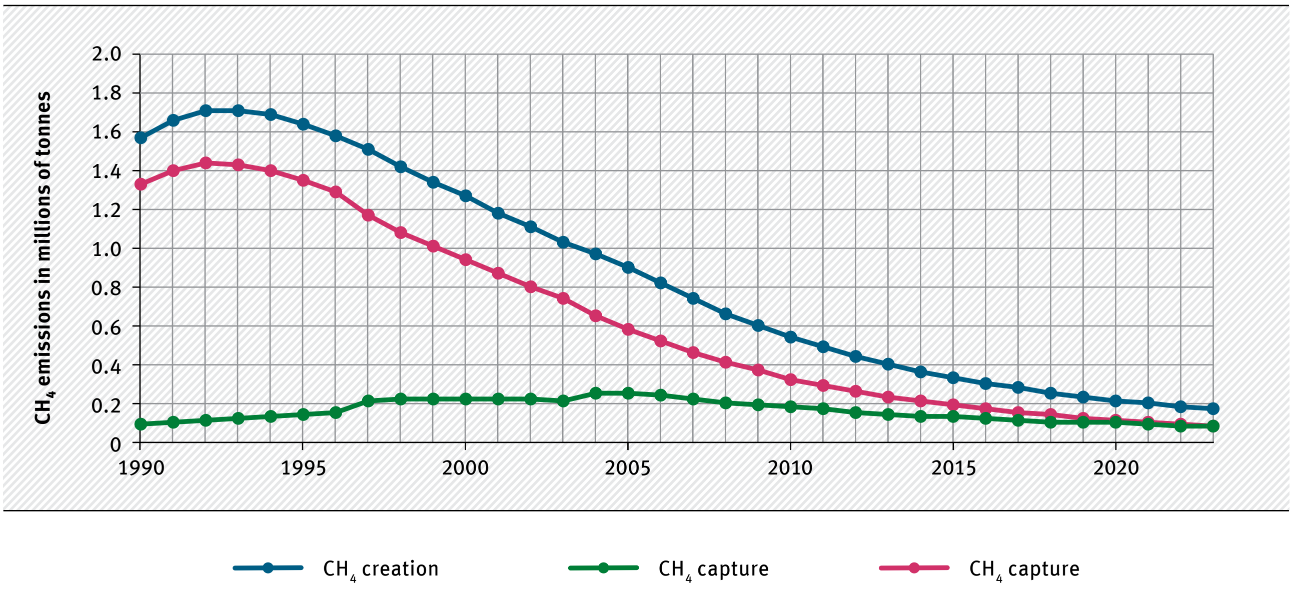
Germany is taking on an eminent role worldwide in avoiding and reducing methane emissions in the waste sector. Engineered and controlled landfills with landfill gas collection and usage were already introduced in the final quarter of the last century. The collection of landfill gas has been mandatory since 1993 and, where technically feasible, it is utilised to generate energy, whereby the efficiency of methane gas collection at landfills has also been improved.

However, the most significant contribution to methane mitigation is a result of the legally enshrined ban on landfilling untreated municipal waste, which came into force in June 2005, and led to an early transformation of the waste sector. The ban was introduced in 1993 in the Technical Guidelines for Municipal Waste (Technical Guidelines for Municipal Waste, 1993), enshrined in the Waste Disposal Ordinance in 2001 (Waste Disposal Ordinance, 2001) and is now effectively implemented today in the Landfill Ordinance (Landfill Ordinance, 2009) through waste acceptance criteria for landfills. The central control parameter for waste acceptance at landfills is the total organic carbon (TOC) content, supplemented by respiration activity and gas formation rate. Municipal waste landfills, or landfill class II (non-hazardous waste), may only accept waste with a TOC of less than 3 per cent or, in the case of mechanical biological pre-treatment, a TOC of less than 18 per cent combined with a gas formation rate GB21 < 20 ml/g and a respiration activity AT4 < 5 mg/m_3. As a result, the methane formation rate in the landfills was sustainably reduced in the long term (see Figure 3).

As Figure 3 shows, the decisive reduction in emissions is not resulting from the capture of methane gas from landfills, which is always subject to technical limitations, but is mainly a result of the strict acceptance criteria for waste in landfills. As of 2005, all landfilled waste is pre-treated in such a way that the formation of methane in the landfill body is minimised. As a result, gas formation and methane emissions are naturally and continuously decreasing. Only waste disposed before the ban that is still biodegradable causes decreasing methane emissions for decades to come. The data in Figure 3 demonstrate therefore that the 94 per cent decrease in methane emissions from landfills from 1.33 million tonnes of methane in 1990 to 0.08 million tonnes in 2023 is essentially due to the landfill ban of untreated municipal waste in force since 2005 through strict waste acceptance criteria for landfills. This can also be seen

Figure 3

Methane emissions from landfills



Source: German Environment Agency

in Figure 4, here in 1000 tonnes of CO_2 equivalents. A transition period of 12 years allowed sufficient time for the waste management sector to react to the upcoming transformation by setting up the necessary treatment plants.

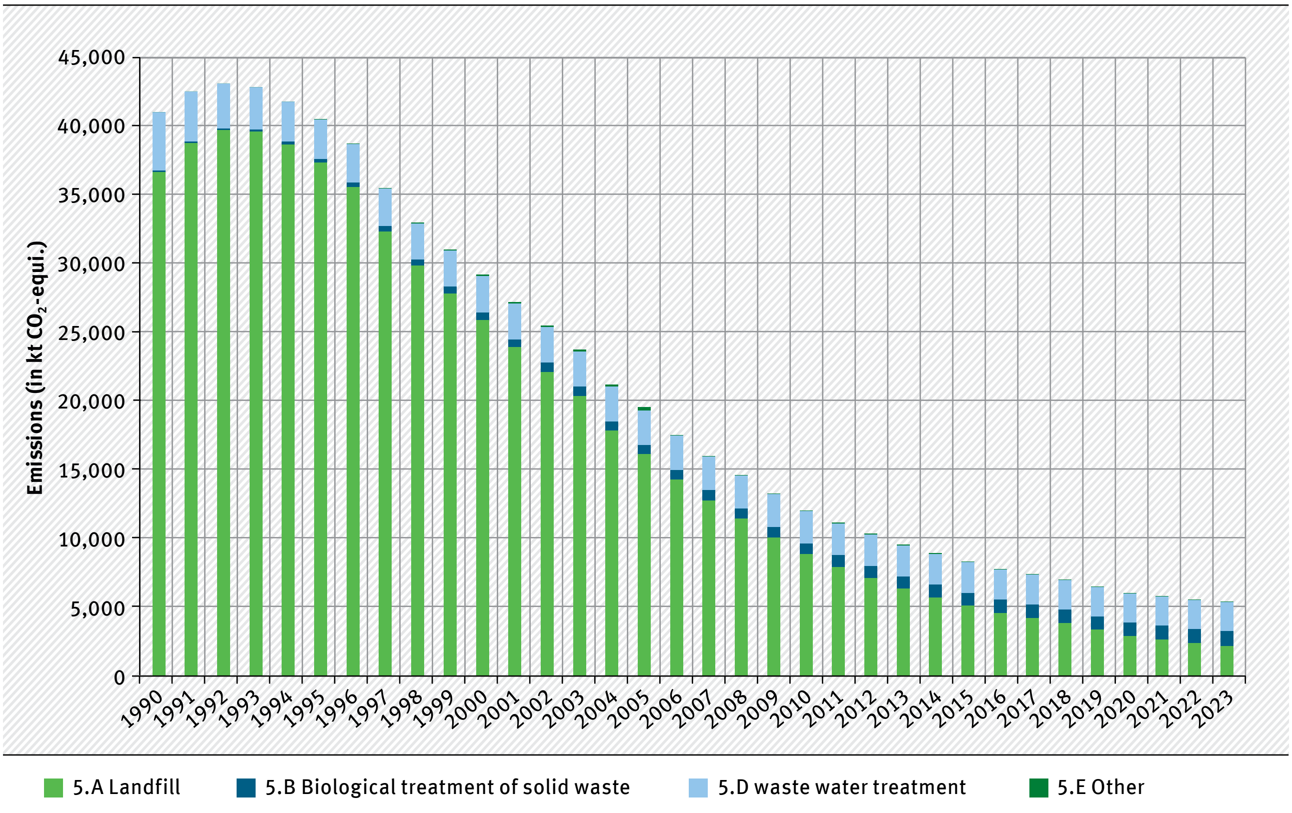
As part of this transformation, the environmentally desirable expansion of the separate collection of organic waste and of biological treatment capacities (anaerobic digestion and/or composting) for this separately collected organic waste was and is being driven forward. This has resulted in an increase in methane emissions from biological waste treatment, which cannot be completely avoided despite all technical and organisational efforts and is mainly caused by improper operational management, fermentation processes, open digestate storage or operational malfunctions. Methane emissions from biological waste treatment have therefore risen from 0.002 million tonnes as methane in 1990 to 0.032 million tonnes as methane in 2022. Figure 4 shows this increase in 1000 tonnes of CO_2 equivalents.

In Germany, the proportion of anaerobic digestion in treatment of biowaste will further increase, accompanied by a corresponding reduction of composting only. Nevertheless, the emissions from biowaste treatment are to be kept at a consistently low level through continuous improvements in the state-of-the-art technology and emission reduction.

In order to accelerate the natural reduction of methane emissions from landfills, the National Climate Protection Programme since 2013 promotes measures that go beyond state of the art. That is necessary because the methane formation decreases with increasing landfill age, making effective landfill gas capture and utilisation difficult to impossible. The active aeration of more than 50 old landfills intends to reduce the remaining emissions. For landfills that have not yet reached that stage, optimisation of landfill gas collection beyond the state of the art is currently supported from 2019 to 2026. In addition, the federal government's waste prevention programme with the participation of the federal states from 2013 (Federal Ministry for the Environment, 2013) and its update

Figure 4

Annual greenhouse gas emissions from the waste and waste water management sector



Source: German Environment Agency

in 2021 (Federal Ministry for the Environment, 2020) aims to reduce food waste.

The development towards a circular economy with prevention, waste separation, composting and biogas utilisation, mechanical biological treatment, recycling and energy recovery of waste has made significant mitigation contributions as waste management not only avoids methane, but also contributes to climate protection in other sectors such as the energy sector or industry. Methane is also produced by waste water and sewage sludge treatment.

Waste water from the municipal sector consists of domestic waste water and indirect discharge from industry (approximately 30 per cent based on population equivalents), and it is generally treated in centralised wastewater treatment plants via the activated sludge process. A substantially lower proportion of waste water (around 3 per cent relative to the residents connected to the centralised systems) is treated in small sewage treatment plants or collected in drainless tanks until subsequent transportation and treatment in a wastewater treatment plant. The main source of methane emissions in the waste water sector is sewage sludge treatment or digestion (Becker et al. 2012).

An increased connection rate to the public sewage system and waste water treatment (due to the requirements set out in the EU Council Directive on urban waste water treatment (EU-RL 91/271/EEC)) and the abolition of open sewage sludge digestion are key reasons for the reduction in methane emissions within waste water disposal. The latter was still practised until the beginning of the 1990s in the federal states of the former East Germany.

Comprehensive measurements are required for a more detailed appraisal of methane emissions from waste water treatment in the opinion of the German Environment Agency. Specific reduction measures can be derived based on these measurements.

The waste and waste water management sector together emitted around 5.5 million tonnes of methane in CO_2 equivalents in 2023. Emissions were reduced by about 87 percent between 1990 and 2023. Figure 4 shows the proportions for waste and waste water management of the total in the sector emissions in kilotonnes of CO_2 equivalents.

2.3.2 Situation in Europe

2.3.2.1 Energy

Trends in methane emissions across Europe are similar to those in Germany. Emissions from fuel transformation and provision are also dominant within the energy sector. However, the methane slip that arises due to incomplete combustion as well as the stopping and starting of engines is at around 30 per cent, which also plays a part. Whilst in particular, methane emissions from stationary furnaces have almost tripled in the energy sector, which is primarily due to the switch from burning solid fuels in combustion engines for the combustion of gaseous fuels containing methane, emissions from the provision of fuels have been reduced by over 70 per cent. Above all, the lessening importance of coal mining as well as the modernisation of the natural gas supply network have played a substantial part. In total, methane emissions in the energy sector in the EU-27 were reduced by almost 61 percent between 1990 and 2021 (UNFCCC 2025).

2.3.2.2 Industry

In the industrial sector, the chemical industry is also the main source of methane emissions across Europe. Between 1990 and 2021, emissions in the industrial sector were reduced by about 8 percent, mainly due to higher environmental standards in the Member States (UNFCCC 2025).

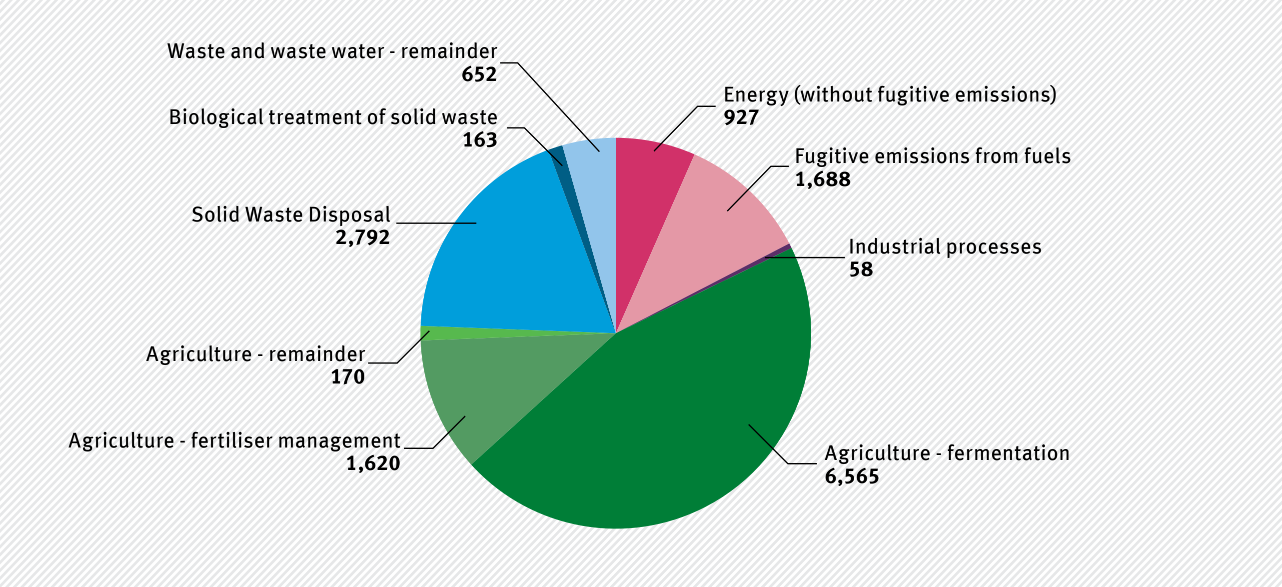
2.3.2.3 Agriculture

At about 8,200 kilotonnes, agriculture was the primary cause of methane emissions in Europe in 2023. Alongside livestock farming and fertiliser management (around 98 per cent in total), paddy cultivation also causes some of these emissions with 80 kilotonnes (EuroStat 2025). Relative to 1990, methane emissions have fallen by 25 per cent (EuroStat 2025 and Food and Agriculture Organisation of the United Nations (FAO) 2022). A substantial reduction (more than 10 per cent) came about particularly in the early 1990s as a result of a fall in livestock numbers due to structural changes in eastern Europe along with more efficient use of manure. There are only marginal changes within rice cultivation. Emissions from biogas plants have risen the most over the last 20 years, and this is dominated by Germany (UNFCCC 2025).

Figure 5

Methane emissions from the European Union (EU27) in 2021 in kt

according to reporting categories*



* excluding LULUCF

Source: UNFCCC: https://di.unfccc.int/flex_annex1https://di.unfccc.int/flex_annex1

2.3.2.4 Waste and waste water management

Despite a significant decrease in methane emissions compared to 1990, landfills (solid waste disposal) remain the second largest emitter of methane in the EU with about 2,800 kilotonnes of methane emissions in 2021, and therefore the entire waste and waste water sector also remains the second largest emitter with in total about 3,600 kilotonnes of methane emissions as shown in Figure 6. Member States, which transposed and implemented the EU Landfill Directive (EU 1999) at national level applying landfill bans, pre-treatment requirements and/or acceptance criteria at landfills have significantly reduced their methane emissions in the sector and thus make a decisive contribution to meeting the EU climate protection targets. The unabated high landfill rate of untreated waste in some Member States is unfortunately the decisive factor for the overall high methane emissions from the waste sector, both at national level in these states and for the EU climate balance as a whole.

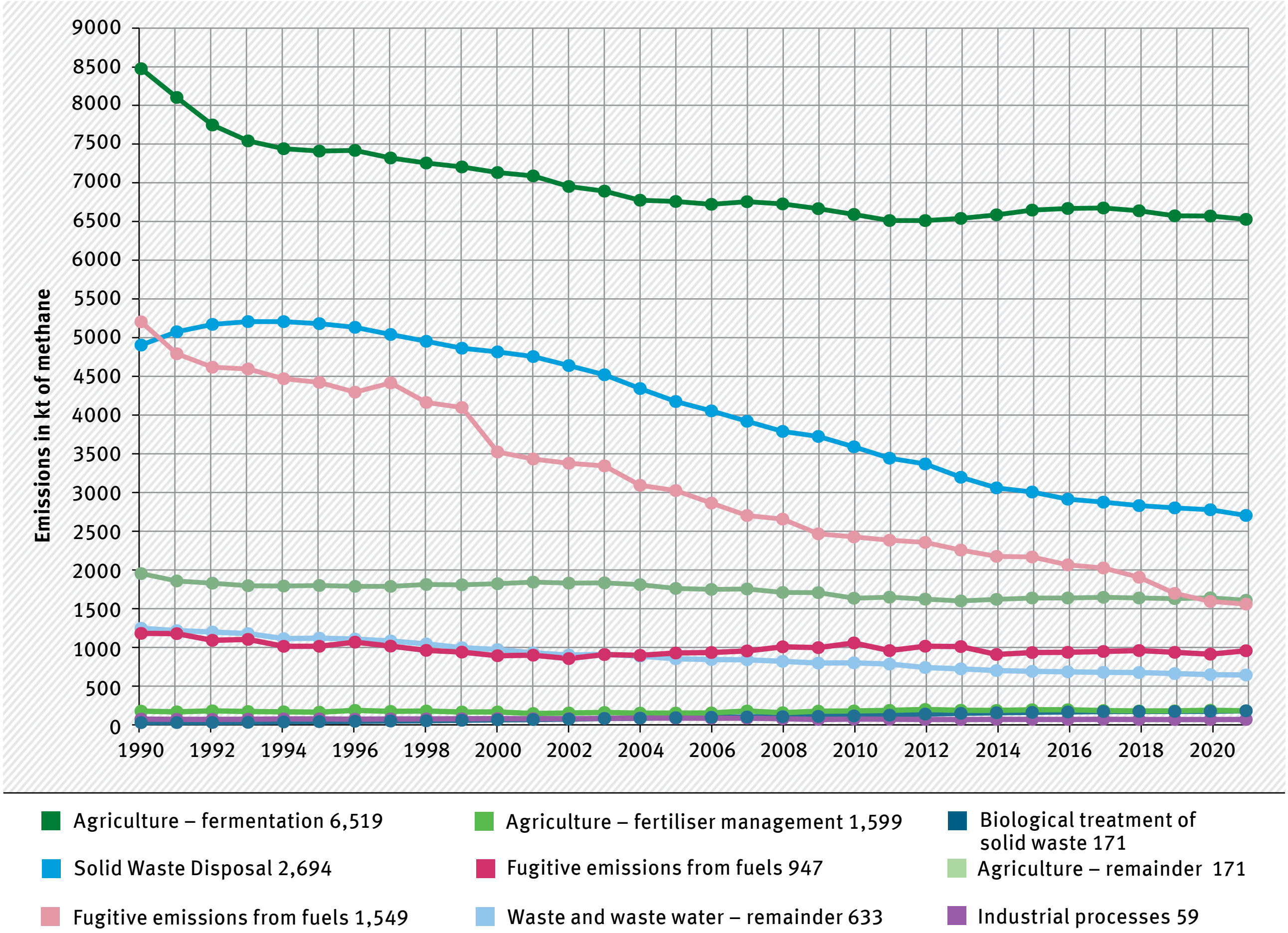
The increase in treatment capacities for biodegradable waste by composting and fermentation plants is also a source of methane emissions, for example in the event of improper operation or malfunctions, which is why emissions from biological waste treatment have risen.

According to the EU Landfill Directive (EU 1999), the landfilling of untreated municipal waste is to be reduced to 10 per cent by 2035. This will further contribute to the mitigation efforts in the sector. However, without a comprehensive landfill ban, and with derogation periods available for some Member States, the EU's technically possible emission reduction maximum is still unlikely to be exploited legally and politically.

A reduction in methane emissions of over 50 per cent was achieved in previous years due to technical improvements in waste water treatment as well as the increase in collection points for waste water to the sewer system. Increased recycling of sewage sludge and gases for gaining energy is clear from the data.

Figure 6

Methane emissions from the European Union (EU 27)
according to reporting categories*



* excluding LULUCF

Source: UNFCCC GHG Data Interface

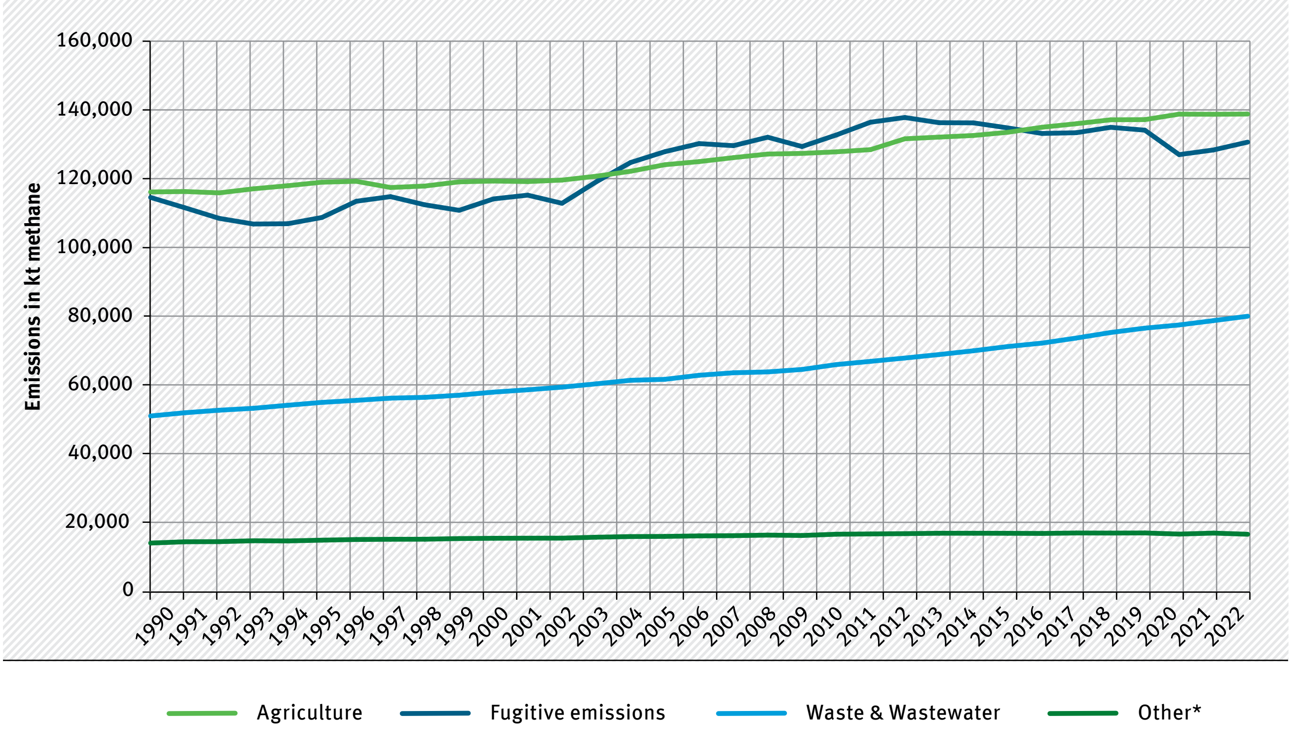
2.3.3 Situation worldwide

Around 60 per cent of global methane emissions originate from anthropogenic sources (United Nations Environment Programme (UNEP) and CCAC 2021). Agriculture is responsible for most emissions. It caused nearly 40 per cent of methane emissions worldwide that were due to humans. Nearly 36 per cent of global anthropogenic CH_4 emissions originate from the extraction and transportation of fossil fuels and nearly 22 per cent is from the waste and waste water sector (Boston University 2025), particularly from landfill and waste treatment (UNEP and CCAC 2021). Whilst all stated sources of methane play a part in all regions worldwide, there are noticeable regional differences. As an example, methane emissions from coal extraction are especially relevant in China. CH_4 emissions from the extraction and transportation of oil and natural gas are particularly prevalent in the Middle East, Russia and North America. Methane from agriculture, and particularly from livestock farming here, plays a part in all regions of the world, especially in Latin America and Southern Asia. CH_4 emissions from rice cultivation are particularly prevalent in South East Asia (UNEP and CCAC 2021).

Figure 7

Methane emissions worldwide

according to reporting categories*



**other includes for example emissions from industry and energy except fugitives

Source: Boston University: https://visualizingenergy.org/global-anthropogenic-methane-emissions-1970-2022/

2.3.3.1 Energy

Different strategies have been used to lower methane emissions worldwide, and a few countries have set out reduction measures and anchored them in law. Some countries focus on voluntary activity by companies whilst others use financial penalties for methane losses. Some examples of such can be found below:

Norway is the first country to introduce a carbon tax. Amongst other things, this is based on the emissions trading price and increases considerably until 2030. In 2021 this was 590 Norwegian kroner (about 57 euro) and this should rise continuously to approx. 2,000 kroner (about 193 euro) per tonne of CO_2 equivalent. Methane emissions from the provision of fossil fuels in Norway have hardly changed since 1990 and are around 21 kilotonnes annually (Bioenergy International 2021; Norwegian Petroleum 2021). For an oil and gas producer, this is a comparatively low value (UNFCCC 2025).

Russia is another country that has passed laws that aim to reduce methane emissions. Standards for avoiding emissions are specified by the Ministry of Energy and monitored by the Ministry of Natural Resources and Environment on site. If emissions arise from the infrastructure then a fine must be paid. These depend on the level and duration of such emissions. However, these fines range from 50 to 1,250 roubles per tonne emitted (around 0.60 - 14.40 euro, exchange rate as of August 2021 Finanzen.Net (2021)) and are comparatively low. Some regions in Russia have therefore increased the fines considerably (for example, the Yamal region of Russia has increased these by a factor of 4), which has led to substantial investments in technology for avoiding emissions (Evans und Roshchanka 2014). Methane emissions in the Russian energy sector have fallen by 35 per cent since 1990 and were around 6,900 kilotonnes in 2019 (UNFCCC 2025). Households and small-scale users have a large impact (80 per cent), as does the electricity and heating sector (32 per cent). Extraction of fossil fuels has fallen by 32 per cent in the same period, but still dominates the energy sector with a total of 6,763 kilotonnes. In this case, the main drivers are oil and gas extraction as well as transportation of natural gas, each causing around 1,200 kilotonnes of methane annually (UNFCCC 2025).

Even the **USA** has agreed on a plan to lower emissions. According to legislation passed in 2015, emissions from oil and gas producers must fall by 40 per cent in 2025 relative to emissions in 2012. Amongst others, the reduction measures cover a series of standards for avoiding methane through improved detection of leaks. The Department of Energy has received a bigger budget to develop new standards. Methane emissions from the energy sector were extremely high in 2019, amounting to 10,700 kilotonnes (The White House - Office of the Press Secretary 2015). 96 per cent of this is due to the extraction and provision of fossil fuels. Whilst emissions from coal extraction have almost halved since 1990, this trend is far less evident for both oil and gas (-16 per cent), and over the last few years emissions have indeed tended to increase. Extraction of natural gas (around 3,750 kilotonnes) is the main driver of emissions, followed by extraction of crude oil and the transport of natural gas (around 1,500 kilotonnes each) (UNFCCC 2025).

China has, until now, only regulated methane from coal mines but more for safety reasons and less due to environmental matters. For the first time ever, 2021 saw regulations of methane emissions in the energy sector covered in the five-year plan (You 2021). The biggest energy supplier, China National Petroleum Corporation (CNPC), has pledged to reduce methane emissions by 50 per cent in 2025 relative to 2017 (Xu and Aizhu 2020). In total, methane emissions in China due to the provision of fossil fuels initially rose slowly from 6,275 kilotonnes in 1990, then increased rapidly (Climate Watch 2025)[3].

In a similar manner to the USA and as part of the European Green Deal, the **European Union** (EU) aims to improve detection of leaks to avoid methane emissions whilst also supporting the voluntary “Oil and Gas Methane Partnership“ (OGMP)[4]. Furthermore, the EU is pushing for an independent, international observer role as part of the United Nations Environmental Program, which should check the data reported from companies in the natural gas sector. On 5 August 2024, the European Methane Regulation (EU Regulation (EU) 2024/1787) also came into force, requiring operators of fossil energy infrastructure to regularly measure methane emissions, quickly eliminate leaks, and reduce venting and flaring of gases.

2.3.3.2 Industry

Process-related methane emissions in the industrial sector play a minor part worldwide. However, the trend is upwards, and it is mainly driven by emerging economies, especially China, from the late 1990s onwards (Climate Watch 2025) [5]. In particular, rapid expansion of the petrochemical sector with the production of fuels and base chemicals has a major impact, as does the metal industry, albeit to a lesser extent.

2.3.3.3 Agriculture

In 2022, agriculture caused around 40 per cent of methane emissions worldwide that were due to humans. The largest share of agricultural emissions here is also due to livestock farming as a result of enteric fermentation. This sector, along with fertiliser management, together make up around 31 per cent of worldwide anthropogenic methane emissions. Rice cultivation adds another 7 per cent to the total. Less than 1 per cent is due to combustion of agricultural waste (FAOStat 2025a and Boston University 2025)).

Methane emissions from the agriculture sector have continuously risen from around 91,000 (1961) to about 139,000 kilotonnes (2022) (FAO 2025a). In this period, countries in the Organisation for Economic Cooperation and Development (OECD) saw a slight reduction - after a peak in the 1970s - down to around 26,000 kilotonnes. On the other hand, methane emissions from the world’s least developed countries tripled to around 26,000 kilotonnes, and also increased in countries that recorded a substantial improvement in prosperity such as China, Brazil, or India (ibid.). The key reason for this is the increasing world population along with changes in eating habits. The latter contains an increasing proportion of animal products, particularly in the countries of the Global South (“developing and emerging countries”).

3 The figures stated are in millions of tonnes of CO_2 equivalents. To ensure comparability, this data from the GWP-100 in the IPCC’s Assessment Report 4 has been divided by 25.

4 The Oil and Gas Methane Partnership is an initiative from the Climate and Clean Air Coalition that is led by the UN Environment Programme, which aims to reduce methane emissions from within the energy sector.

5 The figures stated are in millions of tonnes of CO_2 equivalents. To ensure comparability, this data from the GWP-100 in the IPCC’s Assessment Report 4 has been divided by 25.

These developments led to an increase in animal populations (UBA 2021). The population of cows and buffalos rose from 1 billion in 1961 to 1.8 billion, whilst the population of sheep and goats rose from 1.3 billion to 2.4 billion. Land used for paddy cultivation has also increased from 115 million hectares in 1961 to 168 million now in order to cope with the ever increasing demand for food (FAO 2025b).

2.3.3.4 Waste and waste water

The Global Methane Pledge (GMP) (CCAC 2021), which was launched in 2021, calls on signatory countries to reduce global methane emissions in 2030 by over 30 per cent compared to 2020 levels in order to support the implementation of the Paris Climate Agreement. Germany is one of the champions of the GMP since 2023 and is also a signatory of the "Reducing Methane from Organic Waste (ROW)"[6] declaration, which was initiated by the COP29 Azerbaijan Presidency in support of the GMP.

The Climate and Clean Air Coalition (CCAC) in charge of supporting the implementation of the GMP estimates that the waste and waste water sector is responsible for 20 per cent of anthropogenic methane emissions (2005) and is the third largest CH_4 emitter worldwide after the fossil fuel industry and agriculture (CCAC 2021). According to the CCAC, landfills and dump sites are currently the third largest source of man-made methane emissions (11 per cent). Waste is also the fastest growing anthropogenic source of methane globally.[7] Figure 7 clearly illustrates this trend.

If no measures are taken to expand climate and resource-friendly waste management internationally, the annual global municipal waste generation will increase from around 2 billion tonnes in 2016 to an estimated 3.4 billion tonnes in 2050, and the waste sector would thus emit around 2.6 billion tonnes of CO_2 equivalents in 2050 (Kaza, Yao, Bhada-Tata, & Woerde, 2018). Waste management is still underdeveloped, particularly in a global context. Here, landfill gas emissions resulting from the uncontrolled dumping or regulated landfilling of untreated municipal and commercial waste are the main source of methane. However, due to technical and economic conditions, only a maximum of 50 per cent of landfill gas can be effectively captured and utilised, meaning that most of the methane escapes uncontrolled into the atmosphere.

According to the CCAC, up to 90 per cent of methane emissions in the sector could be reduced by 2050 using the technologies available today. The timely implementation of several reduction strategies, from halving food waste to diverting biodegradable waste away from landfill and towards high-quality utilisation (compost, biogas, insect protein, animal feed, etc.) as well as retrofitting existing landfills, is described as crucial for this.

Based on waste water treatment experiences in Germany, developments towards centralised treatment and closed sewage sludge digestion appear to be expedient.

6 https://cop29.az/en/media-hub/news/cop29-presidency-publishes-final-texts-of-declarations-and-pledges-for-upcoming-un-climate-summit
7 https://www.ccacoalition.org/content/waste-sector-solutions

3 Mitigation strategies

3.1 Targets for methane reduction

Up until now, there have been no binding mitigation targets for methane. Methane is only indirectly considered as part of all greenhouse gases in the form of CO_2 equivalents.

In September 2021 the USA and EU started off the "Global Methane Pledge" (CCAC 2021), which is a declaration on the part of countries to commit to a substantial decrease in methane emissions. The declaration aims to reduce methane emissions in all signatory countries by 2030, across all sectors and collectively, by at least 30 per cent relative to 2020. However, this is not a binding mitigation target. Germany has also signed the Global Methane Pledge in October 2021. In its new strategy, (CCAC 2020) the CCAC has also set out a target for reducing methane emissions: A 40 per cent reduction in global emissions relative to emissions in 2010 should be achieved by 2030. This aim is also not binding.

Furthermore, setting out a mitigation target for methane as part of revising the Gothenburg Protocol under the UNECE Air Convention is discussed. The German Environment Agency is in favour of such a mitigation target based on a sound impact assessment using up-to-date data.

In August 2024, all EU member states except Hungary agreed to implement the EU Methane Regulation. This regulation aims to identify and quantify methane emissions in Europe and repair leaks as well as to reduce global methane emissions by increasing requirements for exporting countries.

3.2 Measures for the mitigation of methane

Current data shows that around 95 per cent of global methane emissions comes from sources outside Europe (COM(2020) 663 final). However, Germany and the EU are indirectly involved in causing methane emissions in countries exporting natural gas due to natural gas imports. Methane-intensive foods are also imported. According to various EU countries, South America is the second most important source of imported beef and Asia is also so for rice and rice products. Most mutton is imported from New Zealand (United Nations (UNO) 2021). Worldwide cooperation is necessary to reduce global methane emissions. Germany should get involved in financially supporting international projects, in entering into partnerships and supporting other countries through knowledge transfer.

3.2.1 Energy sector and industry

There is great potential for mitigation of methane in the energy sector worldwide. Easily implemented and cost-effective measures to reduce methane emissions such as resolving leaks in the natural gas infrastructure are available, particularly in extracting and distributing fossil fuels. Methane emissions from combustion plants can also be reduced via technical measures. In principle, a transformation of the whole energy system is required, as is the phasing out of all fossil fuels if a considerable reduction in methane emissions is to be achieved.

3.2.1.1 Extraction and distribution of fuels

In Germany, methane emissions from the extraction and distribution of fuels have fallen considerably due to stopping hard coal mining, replacing the natural gas network, and the use of mine gas over the last few years.

In order to quickly discover and quantify progress and problematic cases, the German Environment Agency suggests that more frequent surveying, inspections and quantification of emissions from gas infrastructure (Leak Detection and Repair (LDAR)) should take place. Furthermore, the German Environment Agency explicitly supports the measures for reducing emissions that are stated in the German Technical and Scientific Association for Gas and Water (DVGW) research report (Große and Köllmer 2019). On top of this, the Oil and Gas Methane Partnership has published comprehensive technical documents showing where emissions occur as well as how these can be quantified and avoided (CCAC 2017). The German Environment Agency welcomes this and hopes that reporting is standardised across Europe in line with these standards.

Comprehensive measurements were carried out on the infrastructure in the transport network during 2020 and 2021. This showed that over 90 per cent of total emissions occurred at 0.5 per cent of the measured leaks. Natural gas companies plan to reduce methane emissions by 50 per cent by the end of 2025 for the entire German network relative to 2015 figures (Vereinigung der Fernleitungsnetzbetreiber Gas e.V. 2021). The German Environment Agency has stated that regular surveying of infrastructure should take place, especially of parts that are responsible for high emissions, and that leaks should be resolved promptly.

3.2.1.2 Technical adaptations to plants and to the use of fuels

Fuel is not completely combusted in combustion engines, particularly when using gaseous fuels (including natural gas, biogas, biomethane, landfill gas and sewage gas). A small proportion of fuel, which in the case of natural gas is over 90 per cent methane, and in the case of biogas, sewage gas and landfill gas is also largely methane, escapes into the atmosphere without being combusted. What is known as the methane slip represents a problem for all combustion engines that use fuels containing methane gas due to the high greenhouse gas potential inherent in methane.

Major sources of unburned methane emissions in gas engines are the slip during valve overlapping, misfiring, and crevices in combustion chambers, as well as incomplete combustion, especially with inhomogeneous fuel mixtures (de Zwart et al. 2012). Important variables regarding methane emissions in exhaust gas include the overlaps of the entry and exit times of the valves, the combustion chamber geometry, the fuel-to-air ratio and the combustion chamber temperature.

Lambda-1 engines, which stoichiometrically combust the fuel, are generally equipped with 3-way catalytic converters and have lower methane emissions compared to lean-burn engines and pilot injection engines that burn the fuel with excess air. This is shown, amongst others, in the various emission limits set out in the 44th Federal Immission Control Ordinance (44th BImSchV). The emission limit of the 44th BImSchV for lean-burn engines and pilot injection engines of 1.3 grams of total carbon per standard cubic metre of exhaust gas applies to natural gas engines from 2025 onwards and the reduction is expected to be realised just via the engine itself. The emission limit of the 44th BImSchV for Lambda-1 engines of 0.3 grams of total carbon per standard cubic metre can be met with the use of a 3-way catalytic converter.

As Lambda-1 engines usually have lower electrical efficiency compared to lean-burn engines, then CO_2 emissions per quantity of energy generated may be higher than from a lean-burn engine. When comparing both technologies, the greenhouse gas emissions must be compared as CO_2 equivalents. Research in this field has been carried out by the University of Applied Sciences Amberg-Weiden (Trötsch et al. 2022).

From a climate protection perspective, methane emissions are unacceptably high from all gas engine types, so the process for methane-specific exhaust purification is extremely important. A reduction of methane emissions can be achieved with lean-burn engines using exhaust purification systems featuring oxidation catalysts. Gaseous hydrocarbons in the exhaust gas are oxidised to make carbon dioxide and water. In particular, effective mitigation of methane requires high exhaust temperatures of around 550 degrees Celsius. 3-way catalytic converters can be further developed for Lambda-1 engines regarding the reduction of methane. At the moment, both exhaust gas aftertreatment technologies are not ready for the market as there was no motivation for development due to the lack of a demanding methane emission limit. Quantitative statements regarding the reduction potential that can be achieved cannot be made at the moment for this reason.

A reduction to values as measured for the exhaust gas from coal-fired powerplants (at and below 10 milligrams per cubic meter at 6 per cent of oxygen (O_2)) could currently only be achieved viapost-combustion. Post-combustion plants are predominantly used in areas where high levels of organic compounds can be found in the exhaust air. The flammable materials contained in the exhaust air are oxidised at temperatures between 650 and 820 degrees Celsius. The resistance of post-combustion relative to catalyst poisons such as chlorine or sulphur compounds is an advantage of this exhaust purification process. The disadvantage of this process is that it is not compatible with flexible operation of the plants, occasionally for only a few hours per day, due to the continuous provision of the high temperatures required in the post-combustion system. This technology also has high investment costs and the addition of further fuel might be necessary so that operating temperatures for post-combustion can be reached (Böhm et al. 2010). Furthermore, a great deal of space is required for the facilities needed for post-combustion in accordance with the current state of knowledge. Particularly in the case of large combustion engines with their large exhaust gas flows, the additional space required as well as the additional investment costs linked to the process make deployment of this process considerably more difficult. This is why the technology of post-combustion for combustion engines is currently only used in niche applications such as landfill gas engines. Effective exhaust purification should be developed urgently and methane limits should be adapted to it. On the one hand, this technology is required to reduce greenhouse gas emissions during a transitional period in which natural gas cogeneration plants are still in operation. On the other hand, methane-specific exhaust purification systems are required in combustion engines even with the use of biomethane, biogas or power to gas (PtG) that contains methane, otherwise the methane emissions are so high that climate neutrality cannot be achieved. Exhaust purification should also prevent increased methane emissions by the replacement of coal-fired power plants with gas engine systems . These methane emissions reduce the advantage of natural gas firing relative to coal regarding greenhouse gas emissions by approximately one third if a natural gas combustion engine system exploits the emission limit set out in the 44th Federal Immission Protection Ordinance for total carbon (as an indicator for methane).

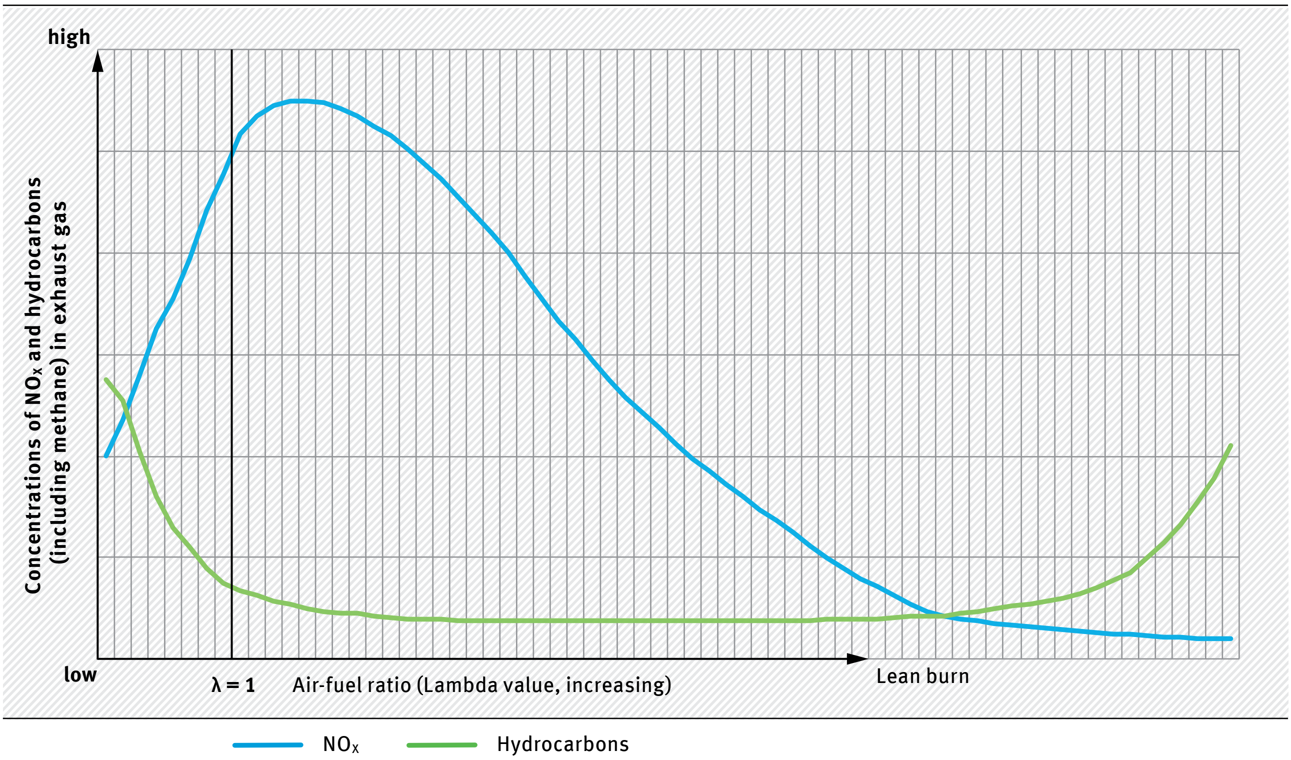
If catalytic converters for reducing methane emissions are not yet ready for the market, then emissions from lean-burn engines and pilot injection engines can only be lowered with engine-related measures. In this case, the interplay of nitrogen oxides (NO_X) and methane emissions is of particular importance.

Engines that reduce methane and nitrogen oxide emissions purely through the engine (without exhaust gas treatment) work with a high quantity of excess air to reduce the level of NO_X. After a certain quantity of excess air, methane emissions start to rise (see Figure 8).

This problem can arise, particularly with combustion engines that should be converted at a later point in time to run on hydrogen generated from renewable sources (H2-ready devices). As hydrogen burns at a higher temperature than natural gas,

Figure 8

Typical trends for emissions (NO_X and hydrocarbons) depending on the Lambda value



Source: German Environment Agency, own illustration

NO_X emissions are also higher compared to the burning of natural gas. Purely motor-driven reduction of NO_X would result in the engine being operated with even more excess air. “Temporary” natural gas operations may result in higher methane emissions compared to a natural gas engine that is not suitable for using hydrogen.

It must be made sure that H2-ready devices, if running on natural gas (for as long as hydrogen is not yet available) do not emit more methane than devices designed to run on natural gas. This applies to combustion engine plants in particular. In order to ensure this, the following legislative measures are necessary:

- Introduction of a methane emission limit for combustion engines in the EU Directive on medium combustion plants
- Introduction of a limit on methane emissions for small combustion engine plants (< 1 megawatt rated thermal input) as part of an Ordinance on the Implementation of the Federal Immission Control Act.

As fuels containing methane such as gas from PtG, biogas or landfill gas will still play a (small) role in a “greenhouse gas neutral” Germany, then methane emissions from stationary combustion engine plants must be reduced further by making use of exhaust gas purification. Research and development is required to this effect.

Lean-burn engines that use exhaust gas purification (in the form of selective catalytic reduction (SCR in short)) for the mitigation of nitrogen oxide can run with less excess air; this results in lower methane emissions than a purely engine-related reduction in NO_X with a high quantity of excess air. An advantage of this variant is the higher degree of electrical efficiency. In many cases operators of SCRs can finance it solely due to the higher electricity proceeds.

The applicable NO_X emission limits in EU Directive 2015/2193 on medium combustion plants in combustion engines with gaseous fuels can be met with purely motor-related measures, for new natural gas engine systems with an enhanced lean-burn feature alone. As the EU Directive does not contain any emission limits for methane then it is suspected that the methane emissions of such systems are high.

In order to reduce both the NO_X and methane emissions, a methane emission limit must therefore be included in the EU Directive for medium combustion plants (EU-RL 2006/123/EC); at the same time the NO_X limit should be lowered so that it can only be met if exhaust gas purification, namely SCR, is in use. In Germany this is already the case for large combustion plants (13th BImSchV) as well for medium-sized combustion plants (44th BImSchV). For systems below 1 megawatt rated thermal input, federal limits should still be introduced.

3.2.1.3 Cross-sectoral transformation of energy supply

Gas, and mainly natural gas, is used in practically all applications in our current economic system: especially in space and process heat supply, in the chemical industry, in electricity supply and also mobility in vehicles powered by natural gas[8,9]. To successfully constrain climate change, a transition away from fossil fuels to renewable energies is inevitable. The primary aim in the context of the precautionary principle is to avoid greenhouse gas emissions whilst also keeping usage and consumption of resources and all negative environmental effects as low as possible. Many changes are required in both the economy and in society – both regarding the demand for energy and goods as well as the production thereof. In order to use energy and natural resources efficiently, renewable energies and particularly renewable electricity should be used directly where it is technically feasible. With high energy losses, a synthetic, renewable gas (synthetic methane) can be produced by using renewable electricity and synthesis via power-to-gas technologies (Purr et al. 2016; 2019). Biomethane is only available to a limited extent due to reasons of resources and climate protection, an example being that there is not enough materially useful waste and residual material available to produce biogenic gases. A substantial proportion of future gas requirements will have to be generated via power to gas (PtG). Fuels are a valuable product in a sustainable energy system that is based on renewable energies, and should only be used where it is not otherwise technically possible. The more energy – also in the form of gas – that

8 Natural gas has been discussed as an alternative fuel for a few years, particularly in long-haul road transport. Despite some growth, the proportion of newly registered trucks with such technology is still very low indeed. At the moment, it is not currently clear for how long this trend will continue, if at all.

9 The use of liquified natural gas is also encouraged by some actors within the maritime transport sector, but it remains unclear if relevant proportions can be achieved relative to fuel requirements.

we need, the more photovoltaic and wind energy systems we require for electricity generation and therefore also need more resources to provide it.

With the strategies of such a sustainable transformation in the energy and economic system, gas requirements and the methane emissions arising from such requirements will fall considerably as a result. The German Environment Agency showed in its study “Resource-Efficient Pathways towards Greenhouse-Gas-Neutrality – RESCUE” how gas requirements can fall to 140 terawatt hours before greenhouse gas neutrality is reached[10].

The primary aspect here is the adjustment to supplying space heat. In general, the aim is to raise the available and very high energy efficiency potential whilst also lowering the energy demand. Whilst it is technically possible to use renewable gas, synthetic methane or hydrogen to heat up buildings using fuel cells or boilers, there are sufficient fuel-free alternatives based on renewable energies such as solar power, geothermal energy, environmental heat (with heat pumps) and unavoidable waste heat. Heat pumps are more energy efficient and with one unit of renewable electricity, they replace around three units from fossil fuels. Heating with synthetic methane or hydrogen will become correspondingly rather more expensive - and based on current knowledge it will cause energy costs to be two or three times higher than using a heat pump in the medium to long term. The German Environment Agency recommends ending the use of fuels in buildings. No more oil-based heating systems should be installed as quickly as possible. Gas heating systems should no longer be installed by 2026 at the latest when considering the more ambitious climate protection targets. When considering usage cycles then gas-fired heating should be phased out by 2045 (Purr et al. 2021).

Heating networks must also fulfil what applies to houses with an internal heating system: They must be switched over to greenhouse gas neutral fuels by 2045. Changing the fuel to direct usage of renewable electricity and environmental heat also applies in this case, such as by using efficient combinations of solar power and environmental heat together with large heat pumps as well as cogeneration units. Renewable hydrogen or synthetic methane is required for the latter. If hydrogen is used instead of synthetic methane as a fuel, then the fugitive methane emissions that arise during transportation of methane and when operating cogeneration units are avoided. Hydrogen has only about one-fifth of the climate impact of methane and is therefore more climate friendly if it leaks out into the atmosphere. The course has already been set here, such as the CHP pilot projects as part of the Kraft-Wärme-Kopplungsgesetz (Combined Heat and Power Act) (KWKG 2020) or the envisaged support of “hydrogen ready” CHP plants as per the national hydrogen strategy (Bundesministerium für Wirtschaft und Energie (BMWi) 2020). At the same time, leaks should always be kept to a minimum via technical measures and effective monitoring regardless of whether methane or hydrogen can escape from them.

Gas containing methane will be used, but to a far lesser extent than now, in both the industrial as well as the commercial, retail and service sectors with the premise that energy supply is wholly based on renewable energy (Purr et al. 2019). Gas is used as a heat supply in a wide range of production processes. Decarbonisation of this process heat supply should, if possible, primarily take place via electrification. Heat pumps are an extremely efficient choice in low to medium temperatures. On the other hand, electrification of high temperature processes (such as heating furnaces for steel tempering, glass melting tanks) must take place, based on current knowledge, via more direct use of electrical energy (such as resistance heating or electric arcs). In some areas, electrification is either not possible or is only possible with extremely high investment in technology, such as specific requirements for the furnace atmosphere at the incredibly high temperatures required (> 1,600 degrees Celsius). Renewable synthetic fuels (hydrogen and methane) are used at this point.

Even in transportation, using electricity directly is the most efficient solution and should be prioritised. Natural gas only plays a minor role in this sector even now. Scientific studies and scenarios for the future do not provide any signs that this situation will change. Synthetic methane or biogenic gases from residual and waste materials are not expected to be of relevance in the upcoming transformation of transport.

10 Scenario GreenSupreme. If energy efficiency measures and measures for efficient sector coupling are not rigorously implemented or if they are delayed, then gas requirements will be higher. An example is scenario GreenLate with around 330 terawatt hours in the long term.

The crux for transforming the energy supply is rapid decarbonisation of electricity supply with an ambitious expansion of renewable energies. The Federal Government's plans of increasing the proportion of total electricity consumption from renewable energies to 80 per cent by 2030 is an important step in this regard (SPD; GRÜNE; FDP 2021). At the same time, supply gas from fossil fuels must be incrementally phased out by 2035 (Federal Ministry for Economic Affairs and Climate Action (BMWK) 2021). This incremental fuel switch to generating power from hydrogen should already be addressed by amending regulations and assistance instruments in the instant climate protection programme in the first half of 2022. Modern H2-ready gas power plants and cogeneration units, along with recently converted coal-fired power plants that can now handle highly efficient, flexible electricity generation from gaseous fuels (green hydrogen), ensure supply security.

From the perspective of an efficient energy transition across all applications, all necessary steps along with the switch in fuel from natural gas to hydrogen to supply electricity by 2035 result in substantial synergies for the methane strategy. The switch in fuel and subsequent use of renewable electricity means that methane consumption falls across sectors and that the associated emissions also fall during use as a result. As a result, it will no longer be cost-effective to operate at least one third of the distribution network (Wachsmuth et al. 2019). As a result, fugitive methane emissions arising from transport and usage will also fall. Fugitive methane emissions in the existing gas network in the future can be reduced further by electrifying the operating equipment (compressor, preheating route) and no longer running it on gas (Wachsmuth et al. 2019). This is just a logical extension of the premises outlined above when looking at the transformation into a sustainable energy system.

3.2.2 Agriculture

Methane from the digestion of ruminants is an intermediate step in the CO_2 carbon cycle (air) – organically bound carbon (plants) – methane (air) – CO_2 (air). The emitted methane becomes CO_2 after decomposition, then subsequent binding to plants ultimately results in a CO_2 sink. However, this is staggered and the warming impact of methane is far stronger relative to CO_2. There is no baseline value for climate-neutral livestock populations that would justify a form of "permanent right to pollute" for a country (Flessa and Osterburg 2021). The increasing methane concentrations in total, the high climate warming potential of methane and the ambitious climate protection targets with a short timeframe of 10 to 30 years demand that the great potential there is in lowering methane emissions from the agricultural sector must be exploited as far as possible (ibid.). The most important measure in the agricultural sector is, alongside anaerobic fermentation of manure, the mitigation of methane from animal digestion. This can be most effectively carried out by reducing animal populations – both in Germany and worldwide (German Environment Agency 2021)

If measures also achieve lowered consumption of products of animal origin in Germany at the same time, then displacement effects (such as increased imports) are avoided. Nevertheless, a target for reducing the number of livestock in Germany cannot be linearly derived from consumption targets. Instead, the maximum sustainable number of livestock for Germany and regions with intensive livestock farming should be derived from environmental, conservational and climate protection targets. A reduction target for the number of livestock must be clear in the long-term, whilst also being transparently communicated and implemented. Options include a maximum livestock density at an farm or regional level, funding programmes for operational restructuring and negotiable production rights based on the Dutch model.

When implementing the measures recommended by the Borchert Commission for improving animal welfare (Kompetenznetzwerk Nutztierhaltung – competence network for animal welfare), populations may fall in the short-term as more space must be provided in existing barns (BMEL 2020; Grethe et al. 2021).

Alongside reducing livestock numbers, all technical and management measures should be used in order to improve ecological efficiency of livestock production, in other words reducing methane emissions per kilogram of meat or milk. For example, these include improving animal welfare, animal health and longevity, amended housing systems and manure removal systems, emerging methane-inhibiting feed additives as well as the recording of feed efficiency and mitigation of methane emissions in the breeding goal. Such accompanying measures can be encouraged with more research and more financial incentives for operations and companies. However, they should be part of an integrated overall political strategy that takes the safeguarding of both animal welfare and the environment equally into account.

Increased fermentation of manure in biogas plants and gas-tight storage of fermentation residues can also play an important role in the mitigation of methane emissions from manure. These should be buttressed with state investment subsidies or legal requirements. Supporting the fermentation of manure must not result in increased production capacity for manure (more animals) or energy crops. According to estimates, the quantity of manure digested in biogas plants in Germany could double (Scholwin et al. 2019). There are still uncertainties about the potential unwanted release of methane from biogas plants and in the formation of microbial resistance in the manure of animals treated with antibiotics. Further research is necessary here.

3.2.3 Waste and waste water management

Strict criteria and parameters for the acceptance of waste at landfills would be expedient for the effective reduction of methane emissions at EU level. These could be implemented as part of the BREF LAN process (reference document on best available technology for landfills) and/or in a future revision of the EU Landfill Directive and thus in the associated Council Decision (2003/33/EC) (Decision 2003/33/EC). A complete landfill ban for untreated waste would largely and more clearly support the achievement of the EU's climate protection targets and can be realised with the technologies currently available. Despite some resulting methane emissions, separate collection and biological treatment of kitchen and green waste should be promoted in the EU, particularly in order to achieve the recycling targets and support a high-quality circular economy.

Restricting or even stopping the landfill of organic waste is imperative to internationally reduce levels of methane in the waste sector. To exploit the potential for reducing methane in the waste sector it is necessary to develop an integrated recycling economy whilst taking the entire product lifecycle into account. The primary aim should be to avoid waste and if waste is inevitable, to separate it and ideally recycle it or alternatively convert it into energy. Depending on the initial situation and the support provided, this aim may be implemented in the short or medium-term, providing substantial additional benefits to the environment, public health, value creation and the green economy.

In particular, this can be achieved by avoiding food waste at every stage of the life cycle, ideally with continuous monitoring and also with separate collection and treatment of biowaste through composting, fermentation, energy-related use or using it as animal feed. Compost and fermentation residues should be subject to quality control to be used to improve soils and also to be used as a replacement for peat and artificial fertiliser. They can make a further contribution to climate protection when used in agriculture, in landscaping, and also in nature-based climate change adaptation in urban areas (greenery).

In addition, any remaining landfill gas must be captured and utilised as comprehensively and as early as possible, as landfills and dump sites continue to emit methane for decades after their closure. This approach is also in line with the goals and strategies of the Climate and Clean Air Coalition (CCAC) and other international organisations addressing climate change in the waste sector (see also Chapter 2.3.3.4).

The minimisation of biodegradable waste going to landfill or dumping and the development of integrated waste management systems aiming at the best utilisation of resources and energy is therefore a central component of a methane reduction strategy in the sector and could also include the substitution effects of recycling and energy recovery on CO_2 emissions in other sectors (industry, cement, power plants) due to the synergies. According to studies of the German Environment Agency, emerging and developing countries can reduce their national greenhouse gas emissions by up to 15 per cent by implementing waste management measures (Dehoust et al. 2010).

Detailed evaluations of emissions are necessary, particularly via measurements of various aspects of waste water infrastructure, to expediently develop reduction measures for waste water treatment.

In order to implement all these measures, it is necessary to build on cooperation with international actors both within the EU as well as on bilateral and multilateral initiatives, such as the Climate and Clean Air Coalition (CCAC), UN organisations, the Gesellschaft

für Internationale Zusammenarbeit (GIZ), the International Solid Waste Association (ISWA) or the NDC partnership[11]. Above all, support from climate protection initiatives, climate funds, and by the development cooperation should be included.

It is also important to support and enhance the synergies between national aims and framework conditions with implementation at a local level. Communications regarding the emission reduction potential of the waste sector as well as the quantification of emissions could also be improved.

Furthermore, corresponding strategies and legislation should be developed at an international level or be updated at EU level.

11 The Paris Climate Agreement of 2015 sets out that contracting states must set out and implement nationally determined contributions (NDCs) regarding climate protection. The global NDC partnership that was initiated in 2016 supports developing countries in setting out and implementing their nationally determined contributions.

4 Recording and transparent reporting of methane emissions

There is great uncertainty regarding quantification of global methane emissions, especially from natural sources of methane. However, there are a few emissions inventories that record emissions data for all regions of the world and are divided into source groups.

Methane emissions can be measured at source. In addition, there are models that simulate the formation and dispersion of methane in the atmosphere. Satellite observation programmes can also be used to detect methane sources. As there is too little data and information worldwide about the potential to reduce emissions, the EU Commission and the United Nations Environmental Programme have decided to establish an International Methane Observatory (IMEO) (UNEP 2021), which started its work in spring 2021.

4.1 Earlier reporting about the Framework Convention on Climate Change and the Kyoto Protocol

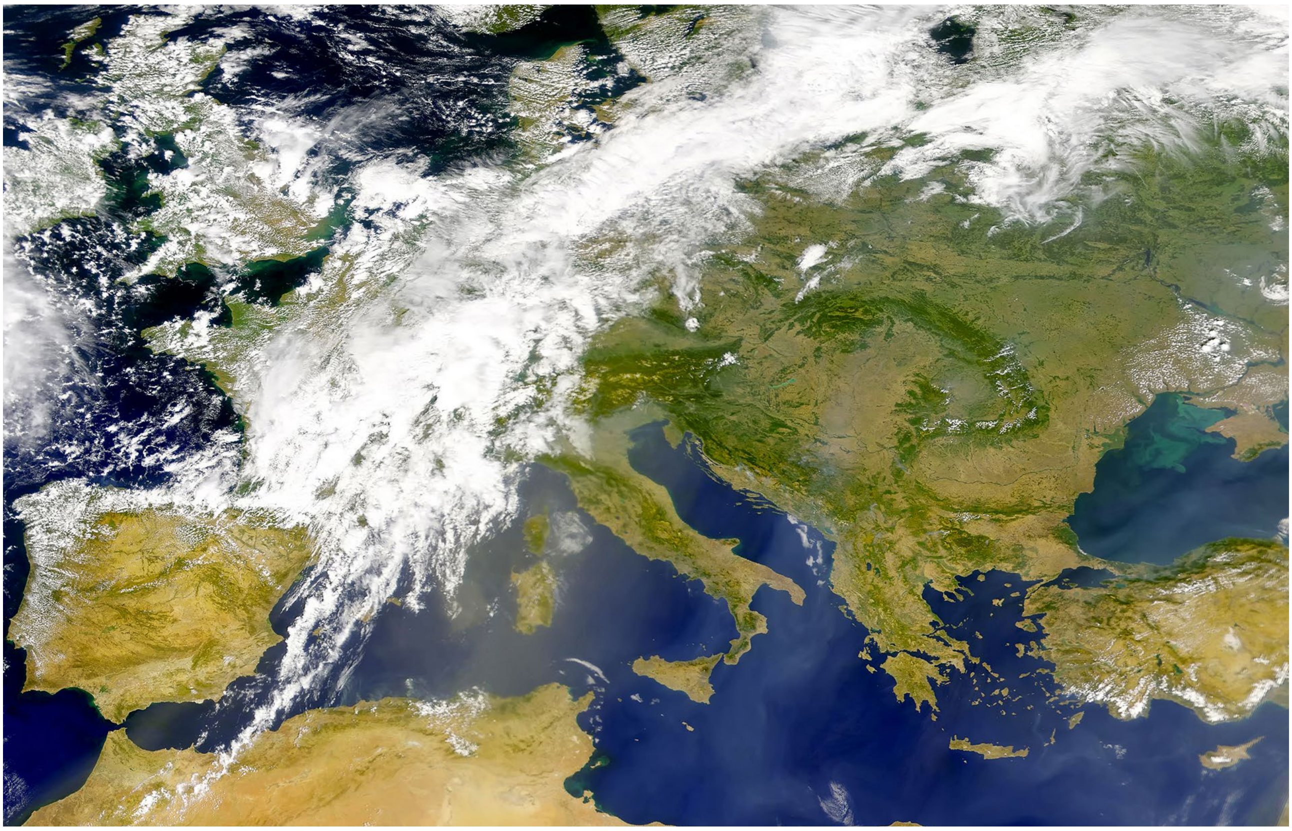
Reporting on greenhouse gases and therefore also on methane emissions currently takes place annually as per the United Nations Framework Convention on Climate Change (UNFCCC) for Annex I parties. According to this, all countries listed in Annex I of the Framework Convention on Climate Change must prepare a National Inventory Document (NID) containing in-depth and complete information about the entire process behind preparation of greenhouse gas inventories. These reports are transparently reported (UNFCCC 2025). The IPCC Guidelines from 2006 are still the basis for reporting emissions (IPCC 2006). These specify how emissions can be estimated as accurately as possible. The formula activity data x emissions factor = emission is used in the majority of cases. The activity data describes the variable behind a specific emission process: “kilometres travelled by a vehicle” or “quantity of a fuel used”. The emissions factor states how high the average emissions are based on the activity, such as the quantity of CH_4 escaping per kilometre of gas pipeline. Countries report the emissions in a standard table format (CRT – Common Reporting Tables) for all years from 1990 onwards.

Countries that are not in Annex I prepare a National Communication (NC) every four years (UNFCCC 2022). The scope of the NC is considerably less comprehensive than the reporting provided by Annex I states. It is rather difficult to compare emission reports due to the different reporting years and also the different IPCC guidelines that are applied (in some cases, the guidelines date from 1996).

4.2 Detection of methane with the help of satellites

Worldwide detection of methane from satellite data is a remote sensing application that has become increasingly important due to rapid developments in the fields of satellite platforms, algorithm developments and sensor technology. However, the on-board spectrometers in this case do not directly measure the methane concentration. In fact, the sensor registers the light absorption in narrow wavelengths over part of the electromagnetic spectrum from 300-2,500 nanometres. Specific light absorption in narrow absorption ranges within the detection area of the sensor is labelled as a characteristic spectral fingerprint. It is possible to deduce the proportion of methane in the atmosphere with the aid of this spectroscopic measurement as well as complex radiative transfer modelling. Additional modelling approaches are required to draw further conclusions about the methane concentrations from the satellite measurements of methane emissions.

In this case, the particular orders of magnitude of the satellite measurements must be taken into consideration: TROPOMI onboard Sentinel5P is able, as a global atmosphere monitoring satellite (swath width 2,600 kilometres), to deliver methane concentration data products on a scale of around 7 kilometres per pixel, whereas spatially higher resolution missions such as EnMAP or PRISMA do not provide any direct methane concentration data products on an operational basis (Apituley et al. 2021). However, there is the opportunity to develop these data products (swath width of 30 kilometres, pixel size of 30 metres) as part of scientific research and to make these available (Guanter et al. 2021).



In addition, there is already a company in Canada that offers methane data products on a commercial basis using their own fleet of satellites since 2016 (GHGSAT 2021). GHGSat specialises in providing spatially high-resolution methane data products, such as for the oil and gas industry, coal mining, and predominantly relating to landfills within the waste sector. Future developments in methane detection in both the satellite or drone sector are developed with a particular focus on user requirements, science, and research funding.

4.3 Harmonisation of reporting

The EU strategy for mitigation of methane emissions as part of the European Green Deal requires standardised and comparable reports for methane emissions. Amongst other things, the International Methane Emission Observatory (IMEO) was created as part of the United Nations Environmental Programme (UNEP 2021). The aim is, amongst other things, to verify the emissions reported by infrastructure operators and to use them for emissions reporting by countries. If no reports are issued then the institute will calculate emission values based on satellite data. The EU Methane Regulation prescribes a very precise LDAR programme (leak detection and repair) for operators, which is intended to significantly reduce methane emissions through frequent monitoring and rapid replacement of leaking components.

The EU will use this data for their emissions inventory. Data must also be used by individual member states so that two systems do not run in parallel. The German Environment Agency welcomes these plans and will also use the data from national operators in the emissions inventory.

Literature

Apituley, A; Pedergnana, M; Sneep, M; Veefkind, JP; Loyola, D; Hasekamp, O (2021): Sentinel-5 precursor/TROPOMI Level 2 Product User Manual Methane. Download at: https://sentinel.esa.int/documents/247904/0/Sentinel-5P-Level-2-Product-User-Manual-Methane/1808f165-0486-4840-ac1d-06194238fa96, as of: 30.05.2022

Becker, A; Düputell, D; Gärtner, A; Hirschberger, R; Oberdörfer, M (2012): Emissionen klimarelevanter Gase aus Kläranlagen (Emissions of climate-relevant gases from sewage treatment plants). Immissionsschutz(4), p. 182-188. DOI: https://doi.org/10.37307/j.1868-7776.2012.04.07

13. BImSchV - Verordnung über Großfeuerungs-, Gasturbinen- und Verbrennungsmotoranlagen from 6 July 2021 (BGBl. [German Federal Gazette] I p. 2514), replaces V 2129-8-13-2 v. 2.5.2013 I 1021, 1023, 3754 (BImSchV 13 2013)

44. BImSchV – Verordnung über mittelgroße Feuerungs- Gasturbinen- und Verbrennungsmotoranlagen from 13 June 2019 (BGBl. [German Federal Gazette] I p. 804), amended by Article 3, paragraph 1 of the Regulation dated 6 July 2021 (BGBl. [German Federal Gazette] I p. 2514)

Bioenergy International (2021): Norwegian government presents its 2021-2030 climate action plan. https://bioenergyinternational.com/policy/norwegian-government-launches-climate-action-plan, as of: 30.05.2022

BMEL – Federal Ministry of Food and Agriculture (2020): Kompetenznetzwerk Nutztierhaltung: Recommendations from the Kompetenznetzwerk Nutztierhaltung network. Download at: https://www.bmel.de/SharedDocs/Downloads/DE/_Tiere/Nutztiere/200211-empfehlung-kompetenznetzwerk-nutztierhaltung.pdf;jsessionid=21CFE3A55BD3568ED568332A7C9F980F.live832?__blob=publicationFile&v=3.

BMLEH – Federal Ministry of Agriculture, Food and Regional Identity (2025a): Agriculture tables. Viehbestand (Livestock). Download at: https://www.bmel-statistik.de/fileadmin/daten/3100200-0000.xlsx

BMLEH – Federal Ministry of Agriculture, Food and Regional Identity (2025b): Agriculture tables. Leistungen der kontrollierten Milchkühe und der Kühe insgesamt. (Output of monitored dairy cows and cows in general). Download at: https://www.bmel-statistik.de/fileadmin/daten/3110300-0000.xlsx

BMU – Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (2019): Projektionsbericht der Bundesregierung 2019 für Deutschland gemäß Verordnung (EU) Nr. 525/2013. (2019 projection report from the Federal Government for Germany in accordance with Regulation (EU) no. 525/2013). Bonn. Download at: https://cdr.eionet.europa.eu/de/eu/mmr/art04-13-14_lcds_pams_projections/projections/envxnw7wq/Projektionsbericht-der-Bundesregierung-2019.pdf.

BMU – Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (2020): Abfallvermeidungsprogramm des Bundes unter Beteiligung der Länder - Fortschreibung (Waste Prevention Programme of the German Government with the Involvement of the Federal States - Update). Download at: https://www.bmuv.de/download/abfallvermeidungsprogramm-des-bundes-unter-beteiligung-der-laender-fortschreibung-wertschaetzen-statt-wegwerfen.

BMU – Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (2013): Abfallvermeidungsprogramm des Bundes unter Beteiligung der Länder (Waste Prevention Programme of the German Government with the Involvement of the Federal States). Bonn. Download at: http://webde/gruppen/bibliothek/Onlinebuecher/EB008107.pdf.

BMWi – Federal Ministry for Economic Affairs and Energy (2020): Die Nationale Wasserstoffstrategie (The National Hydrogen Strategy). Berlin. Download at: https://www.bmbf.de/bmbf/shareddocs/downloads/files/die-nationale-wasserstoffstrategie.pdf;jsessionid=5385CA013649DAFAF73F58DAD9F0A6D7.live382?__blob=publicationFile&v=1.

BMWK – Federal Ministry for Economic Affairs and Climate Action (2021): Eröffnungsbilanz Klimaschutz (Climate protection opening statement). Berlin. Download at: https://www.bmwi.de/Redaktion/DE/Downloads/Energie/220111_eroeffnungsbilanz_klimaschutz.pdf?__blob=publicationFile&v=22Bundesregierung.

Böhm, W; Danner, J; Dutzi, R; Schlichter, E; Stöcklein, F (2010): Ermittlung des Standes der Emissionsminderungstechnik bei Verbrennungsmotoranlagen, Ermittlung technischer Grundlagen für immissionsschutzrechtliche Anforderungen an diese Anlagen (Determining the state of emission reduction technology for combustion plants, determining the technical foundations for emission control-related requirements on these plants): Sub-project 5, package 3: Natural gas Dessau-Roßlau. German Environment Agency.

Boston University (2025): https://visualizingenergy.org/global-anthropogenic-methane-emissions-1970-2022/, as of: 02.07.2025

Butler, T; Leitao, J; Lupascu, A (2020): Consideration of methane emissions in the modelling of ozone concentrations in chemical transport models: final report. Texts 67/2020. Dessau-Roßlau. Download at: https://www.umweltbundesamt.de/en/publikationen/consideration-of-methane-emissions-in-the-modelling.

CCAC – Climate & Clean Air Coalition (2017): Oil and Gas Methane Partnership Technical Guidance Documents. Download at: https://www.ccacoalition.org/en/content/oil-and-gas-methane-partnership-technical-guidance-documents, as of: 20.05.2022

CCAC – Climate & Clean Air Coalition (2020): The Climate and Clean Air Coalition 2030 Strategy. Download at: https://www.ccacoalition.org/en/resources/climate-and-clean-air-coalition-2030-strategy, as of: 20.05.2022

CCAC – Climate & Clean Air Coalition (2021): Global Methane Pledge. https://www.globalmethanepledge.org/, As of: 20.05.2022

Climate Watch (2025): Data Explorer. World Resources Institute. Washington, DC. https://www.climatewatchdata.org., as of: 17.06.2025

COM(2020) 663 final – Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on an EU strategy to reduce methane emissions

de Zwart, M; van Dijk, G; Klimstra, J (2012): Methane emissions from gas engines driving combined heat and power installations. Journal of Integrative Environmental Sciences 9, p. 14. DOI: https://doi.org/10.1080/1943815X.2012.691885

Decision 2003/33/EC: Council Decision of 19 December 2002 establishing criteria and procedures for the acceptance of waste at landfills pursuant to Article 16 of and Annex II to Directive 1999/31/EC. Download at: https://eur-lex.europa.eu/eli/dec/2003/33(1)/oj/eng

Dehoust, G; Schüler, D; Vogt, R; Giegrich, J (2010): Klimaschutzpotenziale der Abfallwirtschaft: Am Beispiel von Siedlungsabfällen und Altholz (Climate-saving potential of the waste sector: residential waste and waste wood as an example). Texts 06/2010. Dessau-Roßlau. Download at: https://www.umweltbundesamt.de/sites/default/files/medien/461/publikationen/3907.pdf.

EEG 2014 – Renewable Energy Sources Act from 21 July 2014 (BGBl. [German Federal Gazette] I p. 1066), amended by Article 1 of the Law from 22 December 2014 (BGBl. [German Federal Gazette] I p. 2406)

European Council Directive 91/271/EEC of 21 May 1991 concerning urban waste-water treatment

European Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste

EU Directive (EU) 2015/2193 of the European Parliament and of the Council of 25 November 2015 on the limitation of emissions of certain pollutants into the air from medium combustion plants

EU Regulation (EU) 2024/1787 of the European Parliament and of the Council of 13 June 2024 on the reduction of methane emissions in the energy sector and amending Regulation (EU) 2019/942. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32024R1787

Evans, M; Roshchanka, V (2014): Russian policy on methane emissions in the oil and gas sector: A case study in opportunities and challenges in reducing short-lived forcers. Atmospheric Environment 92, p. 199-206. DOI: https://doi.org/10.1016/j.atmosenv.2014.04.026

FAO – Food and Agriculture Organisation of the United Nations (2025a): FAOSTAT: Climate Change - Emissions. https://www.fao.org/faostat/en/#data/GT, as of: 17.06.2025

FAO – Food and Agriculture Organisation of the United Nations (2025b): FAOSTAT: Crops and livestock products. https://www.fao.org/faostat/en/#data/QCL as of: 05.06.2025

Finanzen.Net (2021): Finances - converting currencies. https://www.finanzen.net/devisen/euro-russischer_rubel-kurs, as of: 30.05.2022

Flessa, H; Osterburg, B (2021): Stellungnahme zur Veröffentlichung „Landwirtschaft und Klimawandel: Stimmt die Rechnung" von Friedrich Kuhlmann im Band 99, Ausgabe 2, 2021. (Statement to the publication of "Agriculture and climate change: do the figures add up" by Friedrich Kuhlmann in Volume 99, issue 2, 2021). Zeitschrift für Agrarpolitik und Landwirtschaft volume 99(2), p. 5. DOI: https://doi.org/10.12767/buel.v99i2.369

GHGSAT (2021): Global Emissions Monitoring. https://www.ghgsat.com/en/, as of: 30.05.2022

Grethe, H; Martinez, J; Osterburg, B; Taube, F; Thom, F (2021): Klimaschutz im Agrar- und Ernährungssystem Deutschlands: Die drei zentralen Handlungsfelder auf dem Weg zur Klimaneutralität (Climate protection in the German agricultural and nutrition system: Three central fields of action on the path towards climate neutrality). Gutachten für die Stiftung Klimaneutralität (Report for the Stiftung Klimaneutralität foundation). Berlin. Download at: https://www.stiftung-klima.de/app/uploads/2021/06/2021-06-01-Klimaneutralitaet_Landwirtschaft.pdf, as of: 16.12.2021

Große, C; Köllmer, A (2019): Abschlussbericht G 201813 2019-09 Gas. Erstellung eines Leitfadens mit Maßnahmen zur technischen Reduzierung von Methanemissionen im Gasverteilnetz (ME-Red DSO) (Preparation of guidelines with measures for technical reduction of methane emissions in the gas distribution grid). DBI Gas und Umwelttechnik GmbH. Leipzig. Download at: https://www.dvgw-regelwerk.de/plus/#technische-regel/dvgw-g-201813/affa2e, as of: 30.05.2022

Guanter, L; Irakulis-Loitxate, I; Gorroño, J; Sánchez-García, E; Cusworth, DH; Varon, DJ; Cogliati, S; Colombo, R (2021): Mapping methane point emissions with the PRISMA spaceborne imaging spectrometer. Remote Sensing of Environment 265, p. 112671. DOI: https://doi.org/10.1016/j.rse.2021.112671

IPCC – Intergovernmental Panel on Climate Change (2006): 2006 IPCC Guidelines for National Greenhouse Gas Inventories. National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (Publ.). IGES, Japan. Download at: https://www.ipcc-nggip.iges.or.jp/public/2006gl/, as of: 16.12.2021

IPCC – Intergovernmental Panel on Climate Change (2014): Klimaänderung 2014: Synthesebericht (Climate Change 2014: Synthesis Report). Beitrag der Arbeitsgruppen I, II und III zum Fünften Sachstandsbericht des Zwischenstaatlichen Ausschusses für Klimaänderungen (IPCC) (Contribution from working groups I, II and III to the Fifth Assessment Report from the Intergovernmental Panel on Climate Change (IPCC)). Principal authors, Pachauri, HK and Meyer, LA (Publ.). IPCC, Geneva, Switzerland. German translation by the German IPCC Coordination Office, Bonn, 2016. Download at: https://www.ipcc.ch/site/assets/uploads/2018/02/IPCC-AR5_SYR_barrierefrei.pdf, as of: 16.12.2021

IPCC – Intergovernmental Panel on Climate Change (2021): Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte, V; Zhai, P; Pirani, A; Connors, SL; Péan, C; Berger, S; Caud, N; Chen, Y; Goldfarb, L; Gomis, MI; Huang, M; Leitzell, K; Lonnoy, E; Matthews, JBR; Maycock, TK; Waterfield, T; Yelekçi, O; Yu, R; Zhou, B (Publ.). Cambridge University Press. In print. Download at: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf, as of: 16.12.2021

Kaza, S; Yao, L; Bhada-Tata, P; Woerde, FV (2018): What a waste 2.0: A Global Snapshot of Solid Waste Management to 2050. World Bank Group. Washington. Download at: https://olc.worldbank.org/system/files/What%20a%20Waste%202.0%20Overview.pdf, as of: 16.12.2021

KWKG 2020 - Combined Heat and Power Act from 21 December 2015 (BGBl. [German Federal Gazette] I p. 2498), amended by Article 88 of the Law from 10 August 2021 (BGBl. [German Federal Gazette] I p. 3436)

Landfill Ordinance (2009): Verordnung über Deponien und Langzeitlager: https://www.gesetze-im-internet.de/depv_2009/

Norwegian Petroleum (2021): Emissions to air. https://www.norskpetroleum.no/en/environment-and-technology/emissions-to-air/, as of: 30.05.2022

Purr, K; Osiek, D; Lange, M; Adlunger, K; Burger, A; Hain, B; Kuhnhenn, K; Lehmann, H; Mönch, L; Müschen, K; Proske, C; Schmied, M; Vollmer, C (2016): Integration of Power to Gas/Power to Liquids into the ongoing transformation process. Position. Dessau-Roßlau. Download at: https://www.umweltbundesamt.de/publikationen/integration-von-power-to-gaspower-to-liquid-in-den.

Purr, K; Günther, J; Lehmann, H; Nuss, P; Kropf, A (2019): Wege in eine ressourcenschonende Treibhausgasneutralität – RESCUE: Langfassung. ("Resource-Efficient Pathways towards Greenhouse-Gas-Neutrality – RESCUE: Long Version") Climate Change 36/2019. Dessau-Roßlau. Download at: https://www.umweltbundesamt.de/rescue.

Purr, K; Wehnemann, K; Balzer, F; Erxleben, F; Hendzlik, M; Kahrl, A; Lange, M; Lünenbürger, B; Joscha, S; Weyland, M (2021): Treibhausgasminderung um 70 Prozent bis 2030: So kann es gehen! (Reducing greenhouse gases by 70 per cent by 2030: this is how it is done!) Position. Download at: https://www.umweltbundesamt.de/publikationen/treibhausgasminderung-um-70-prozent-bis-2030.

Scholwin, F; Grope, J; Clinkscales, A; Daniel-Gromke, J; Rensberg, N; Denysenko, V; Stinner, W; Richter, F; Raussen, T; Kern, M; Turk, T; Reinhold, G (2019): Aktuelle Entwicklung und Perspektiven der Biogasproduktion aus Bioabfall und Gülle: Abschlussbericht (Current developments and perspectives in biogas production from biowaste and mature: Final Report). Texts 41/2019. Dessau-Roßlau. Download at: https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2019-04-15_texte_41-2019_biogasproduktion.pdf.

SPD; GRÜNE; FDP (2021): Mehr Fortschritt Wagen - Bündnis für Freiheit, Gerechtigkeit und Nachhaltigkeit: Koalitionsvertrag 2021 – 2025 zwischen SPD, BÜNDNIS 90/DIE GRÜNEN und FDP. (Dare for more progress - Alliance for Freedom, Justice and Sustainability: 2021-2025 coalition contract between the SPD, BÜNDNIS 90/DIE GRÜNEN and FDP). Download at: https://www.bundesregierung.de/resource/blob/974430/1990812/04221173eef9a6720059cc353d759a2b/2021-12-10-koav2021-data.pdf?download=1, as of: 25.02.2022

Technical Guidelines for Municipal Waste (1993): Technische Anleitung Siedlungsabfall, Dritte Allgemeine Verwaltungsvorschrift zum Abfallgesetz: https://dip.bundestag.de/vorgang/dritte-allgemeine-verwaltungsvorschrift-zum-abfallgesetz-ta-siedlungsabfall-g-sig-12021554/144154?f.deskriptor=Abfallgesetz&rows=25&pos=15

The White House – Office of the Press Secretary (2015): FACT SHEET: Administration Takes Steps Forward on Climate Action Plan by Announcing Actions to Cut Methane Emissions [Press Release]. 14.01.2015. https://obamawhitehouse.archives.gov/the-press-office/2015/01/14/fact-sheet-administration-takes-steps-forward-climate-action-plan-anno-1

Trötsch, R; Becker, M; Lechner, R (2022): Methanemissionen und ihr Einfluss auf die THG-Bilanz von Erdgas-BHKW - Brückentechnologie ja oder nein? (Methane emissions and their impact on the greenhouse gas balance of natural gas cogeneration plants - yes or no as a bridging technology?) BWK Energie 1-2(74), p. 3. https://www.ingenieur.de/fachmedien/bwk/energieversorgung/methanemissionen-und-ihr-einfluss-auf-die-thg-bilanz-von-erdgas-bhkw/

UBA – German Environment Agency (2021): Prospects for environmentally sound livestock farming in Germany. Texts 33/2021. Dessau-Roßlau. Download at: http://www.umweltbundesamt.de/publikationen/perspektiven-fuer-eine-umweltvertraegliche.

UBA – German Environment Agency (2025): Nationale Trendtabellen für die deutsche Berichterstattung atmosphärischer Emissionen 1990 – 2023. (National trend tables for German reports on atmospheric emissions between 1990 - 2020). Dessau-Roßlau. Download at: https://www.umweltbundesamt.de/sites/default/files/medien/11867/dokumente/2025_01_14_em_entwicklung_in_d_trendtabelle_thg_v1.0.xlsx

UNEP – United Nations Environment Programme (2021): International methane emissions observatory (IMEO). https://www.unep.org/explore-topics/energy/what-we-do/international-methane-emissions-observatory, as of: 30.05.2022

UNEP – United Nations Environment Programme and CCAC - Climate & Clean Air Coalition (2021): Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions. Nairobi. Download at: https://www.ccacoalition.org/en/file/7941/download?token=q_bCnfYV, as of: 15.12.2021

UNFCCC – United Nations Framework Convention on Climate Change (2021): National Inventory Submissions 2021. https://unfccc.int/ghg-inventories-annex-i-parties/2021, as of: 28.02.2022

UNFCCC – United Nations Framework Convention on Climate Change (2022): National Communication submissions from Non-Annex I Parties. https://unfccc.int/non-annex-I-NCs, as of: 30.05.2022

UNFCCC – United Nations Framework Convention on Climate Change (2025): National Inventory Submissions 2025. https://unfccc.int/ghg-inventories-annex-i-parties/2025, as of: 25.06.2025

UNO – United Nations (2021): UN Comtrade database. https://comtrade.un.org/data, as of: 20.05.2022

Vereinigung der Fernleitungsnetzbetreiber Gas e.V. (2021): Methane emissions. https://fnb-gas.de/energiezukunft/methanemissionen/, as of: 11.10.21

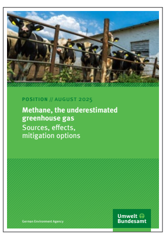
Wachsmuth, J; Michaelis, J; Neumann, F; Wietschel, M; Duscha, V; Degünther, C; Köppel, W; Zubair, A (2019): Roadmap Gas für die Energiewende – Nachhaltiger Klimabeitrag des Gassektors. (Gas roadmap as part of the energy transition - sustainable climate contribution from the gas sector). Climate Change 12/2019. Dessau-Roßlau. Download at: https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2019-04-15_cc_12-2019_roadmap-gas_2.pdf#page=138&zoom=100,72,345.

Waste Disposal Ordinance (2001): Verordnung über die umweltverträgliche Ablagerung von Siedlungsabfällen und über biologische Abfallbehandlungsanlagen: https://www.bgbl.de/xaver/bgbl/start.xav?start=%2F%2F*%5B%40attr_id%3D%27bgbl101s0305b.pdf%27%5D#/switch/tocPane?_ts=1751453392594

Xu, M; Aizhu, C (2020): China's CNPC targets 50% slash in methane emission intensity by 2025. https://www.reuters.com/article/us-china-cnpc-carbon-idINKBN2430P7, as of: 30.05.2022

You, L (2021): China to Reduce Emissions of Methane, a Powerful Greenhouse Gas. https://www.sixthtone.com/news/1006954/china-to-reduce-emissions-of-methane%2C-a-powerful-greenhouse-gas, as of: 30.05.2022

List of Figures


POSITION // AUGUST 2025
Methane, the underestimated greenhouse gas
Sources, effects, mitigation options
German Environment Agency
Umwelt Bundesamt