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Part 1: Basic elements for avoiding greenhouse gases and generating climate-neutral energy (technical toolbox)

Chapter 2-12

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2.12 Greenhouse gases other than CO_2

2.12.1 Climate gas methane – status quo and options for reducing emissions

2.12.1.1 Introduction

Methane is one of the most important climate gases with a negative climate impact many times greater than that of CO_2. The concentration of methane in the atmosphere, like that of CO_2, has been increasing continuously since the beginning of industrialisation. The shares of the most important climate gases worldwide (shown in CO_2 equivalents) are as follows (Figure 188). Methane is in second place:[594]

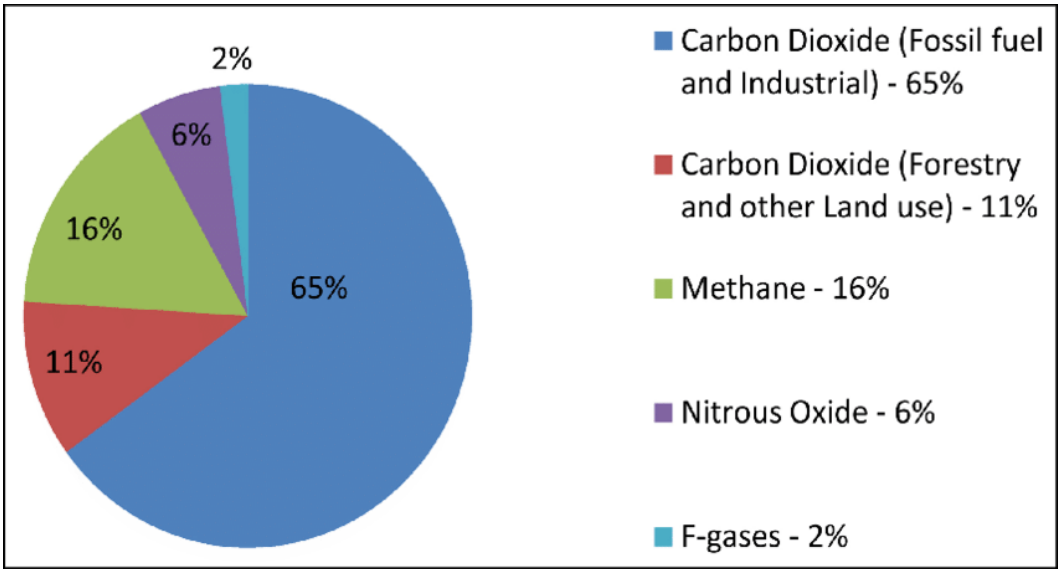

Figure 188: Shares of the most important greenhouse gases in global emissions.

Source: IPCC Report (2014)

Methane has a 16 % share of global climate gas emissions in CO_2 equivalents. Approximately 60 % of methane emissions are anthropogenic in nature; in addition to agriculture (25 %), they are mainly caused by the extraction and use of fossil fuels (23 %). Methane emissions arise from both natural and – to a greater extent – anthropogenic sources.

As a result of the Ukraine war and its impact on natural gas supply in Europe, the use of liquefied natural gas (LNG) and the development of a corresponding infrastructure are becoming particularly important. The production, transport and injection of LNG into existing natural gas networks results in considerable additional methane emissions. This topic is dealt with separately in sub-section 2.6.

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[594] Cf. IPCC, (2014).

Controlling and reducing anthropogenic methane emissions has a high leverage effect with regard to limiting global warming.

A major unknown is the natural release of methane from permafrost areas and through the decay of methane hydrates. Methane emissions from these sources are diffuse, accelerated by global warming and ultimately cannot be stopped. There is no reliable information on the size of the deposits.

The target agreed in the Paris Climate Agreement to limit global warming due to climate change by 1.5 °C compared to pre-industrial times can only be achieved if current annual methane emissions are reduced by at least 45 % by 2030.[595]

Over 100 countries signed the Global Methane Pledge at COP26, committing to reduce their methane emissions by at least 30 % from 2020 levels within ten years.

The initiators of the Global Methane Pledge speak of a possible reduction in global warming of at least 0.2 – 0.3 °C by the year 2050 if the agreement is adhered to globally with regard to methane.[596]

2.12.1.2 Methane in the atmosphere

The methane content of the atmosphere has risen from 730 ppb (parts per billion) in 1750 to over 1,800 ppb today.[597] This is an increase of 150 % and, as with carbon dioxide (CO_2), the highest level for at least 800,000 years, as determined by analysing gas inclusions in drill cores.[598]

The increase in methane concentration in the atmosphere has reached a record value of 1876 ppb in 2021, whereby the attribution to anthropogenic or natural emission sources is not clear.[599]

Figure 189 shows the long-term development and a forecast that would be consistent with achieving the 1.5 °C target:[600]

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[595] Cf. Loulerque et al., 2008.

[596] Cf. COP26, (2021).

[597] 1 ppb corresponds to 0.72 microgram methane per Nm^3

[598] Cf. Loulerque et al., 2008.

[599] Cf. Copernicus Climate Change Service, (2022).

[600] Cf. Dlugokencky, n.d.

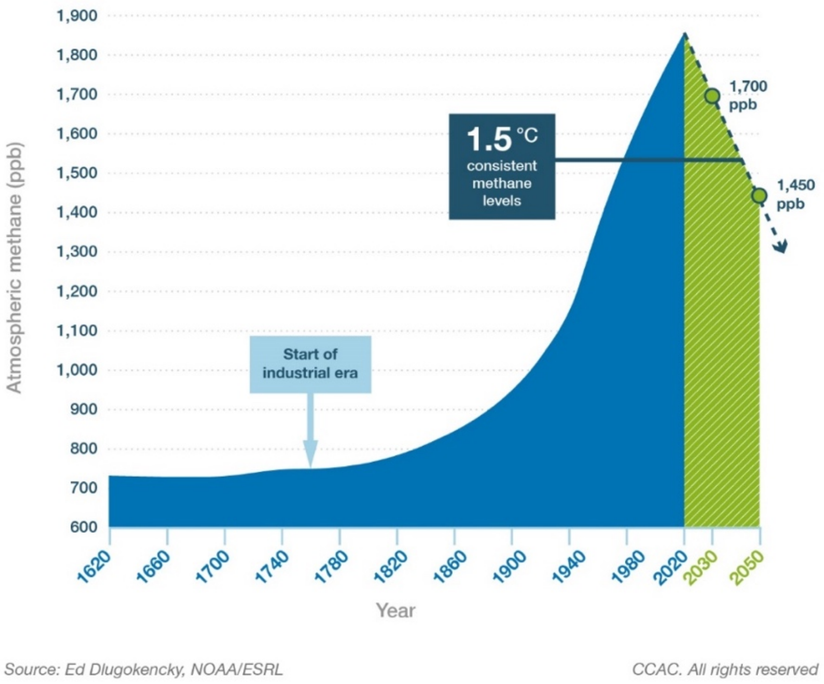

Figure 189: Proportions of methane in the atmosphere.

Source: Climate and Clean Air Coalition (2020).

Figure 190 and Figure 191 show the increase in atmospheric methane content over the last 40 years to almost 1,900 ppb and the annual changes.[601]

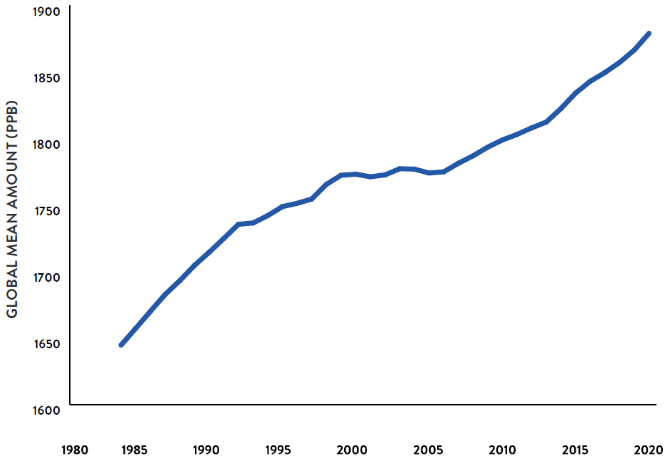

Figure 190: Increase in global mean methane content in the atmosphere.

Source: Climate and Clean Air Coalition (2020), p. 18

In 1992, for example, the eruption of the Pinatubo volcano is said to have caused a sharp drop in methane concentration through the emission of aerosols and SO_x into the stratosphere and subsequently an acceleration of photochemical decay processes.

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[601] Cf. C3S, (2021)

There are attempts to explain the strong fluctuations in the increase in methane content in the atmosphere since 1980, some of which are contradictory.

After an approximate state of equilibrium between methane emissions and sinks in the years 2000 – 2005, the methane content has been rising significantly again since then.

The increase since 2007 is attributed on the one hand to the progressive intensification of agriculture, especially in Asia and Africa, stronger emissions from tropical wetlands, but also to the exploitation of shale gas through fracking, especially in the USA.[602]

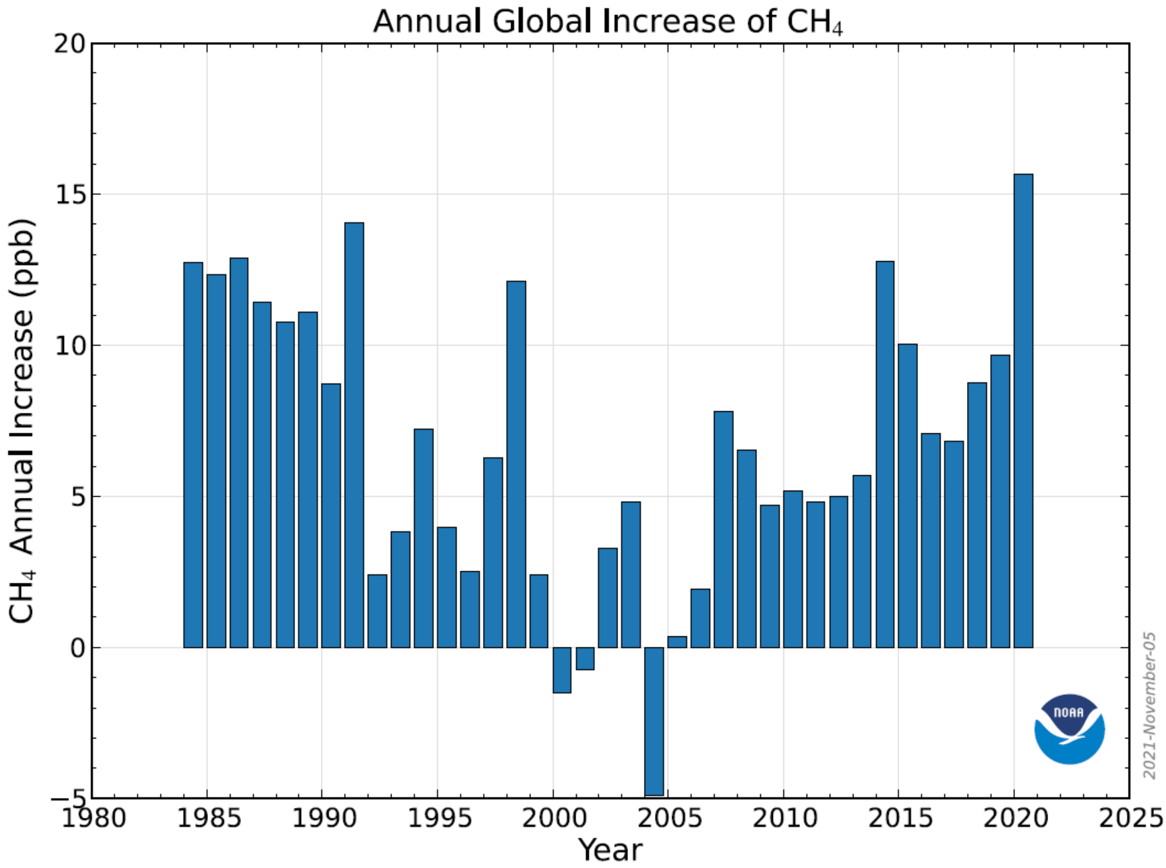

Figure 191: Annual increase in methane content in the atmosphere.

Source: Dlugokencky (n.d.).

The average residence time of methane in the atmosphere is 12.4 years, which is much shorter than that of CO_2 (120 years). Nevertheless, methane is 25 times more harmful as a climate gas than carbon dioxide,[603] although the factor is initially much higher and gradually settles to the level of about 25. The Environmental Protection Agency expects a factor in the range 84 – 87 in the first 20 years.

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[602] Cf. Howarth, (2019).

[603] Cf. Facts and Figures Natural Gas, 2nd version, March 2020, DVGW Bonn. methane-emissions-natural-gas-facts-dvgw.pdf

2.12.1.3 Methane emissions

Approximately 40 % of global methane emissions come from natural sources such as wetlands, lakes, but also thawing permafrost areas, 60 % from anthropogenic sources, e.g. from the extraction of coal, oil and gas, landfills, but above all from agriculture.

Total emissions are estimated at about 600 Mt (year 2017), of which about 370 Mt from anthropogenic sources and about 230 Mt from natural sources.[604]

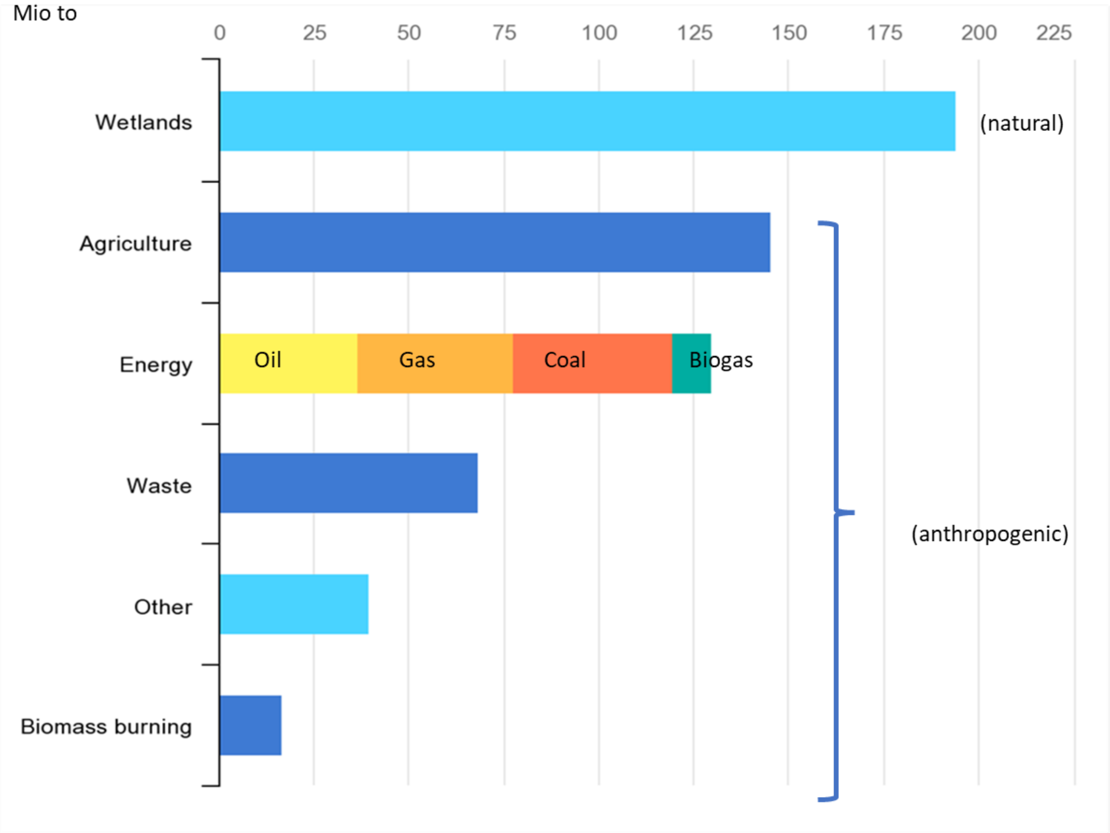

Figure 192: CO_2 emissions in Mt from various sources.

Source: IEA (2020).

The distribution of emission sources is shown in Figure 192 based on a slightly lower total emission of 570 Mt for (2020) assumed by the IEA.[605]

Following a slightly different categorisation, methane emissions arise at[606]

- 30 % from livestock farming and processing of manure,
- 22 % in the production and use of gas and oil,

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[604] Cf. Jackson, (2020)
[605] Cf. IEA, (2020)
[606] Cf. Climate and Clean Air Coalition, (2021)

- 18 % from waste recycling and landfills,
- 11 % from coal mining, blast furnace gas,
- 8 % from rice cultivation,
- 8 % from the combustion of biomass and biofuels,
- and various smaller sources.

Geographically and from the respective emission sources, methane emissions in 2020 are distributed according to a UNEP survey as shown in Figure 193:[607]

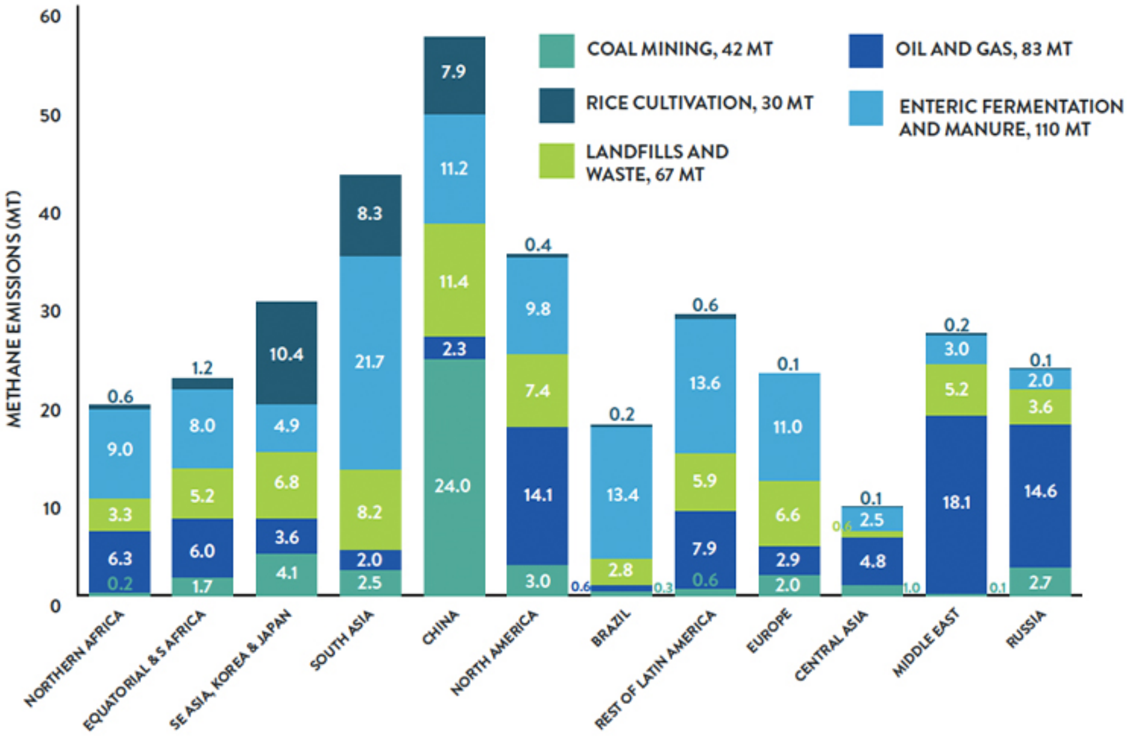

Figure 193: Methane emissions by geographical region.

Source: Climate and Clean Air Coalition (2020), p. 33.

In Germany, annual methane emissions amount to about 1.9 Mt. The main emitters are agriculture, wastewater and waste treatment. Since 1990, emissions have decreased by almost 60 %, which is attributed to smaller landfills, reduced livestock and decreasing coal production (see Figure 194).

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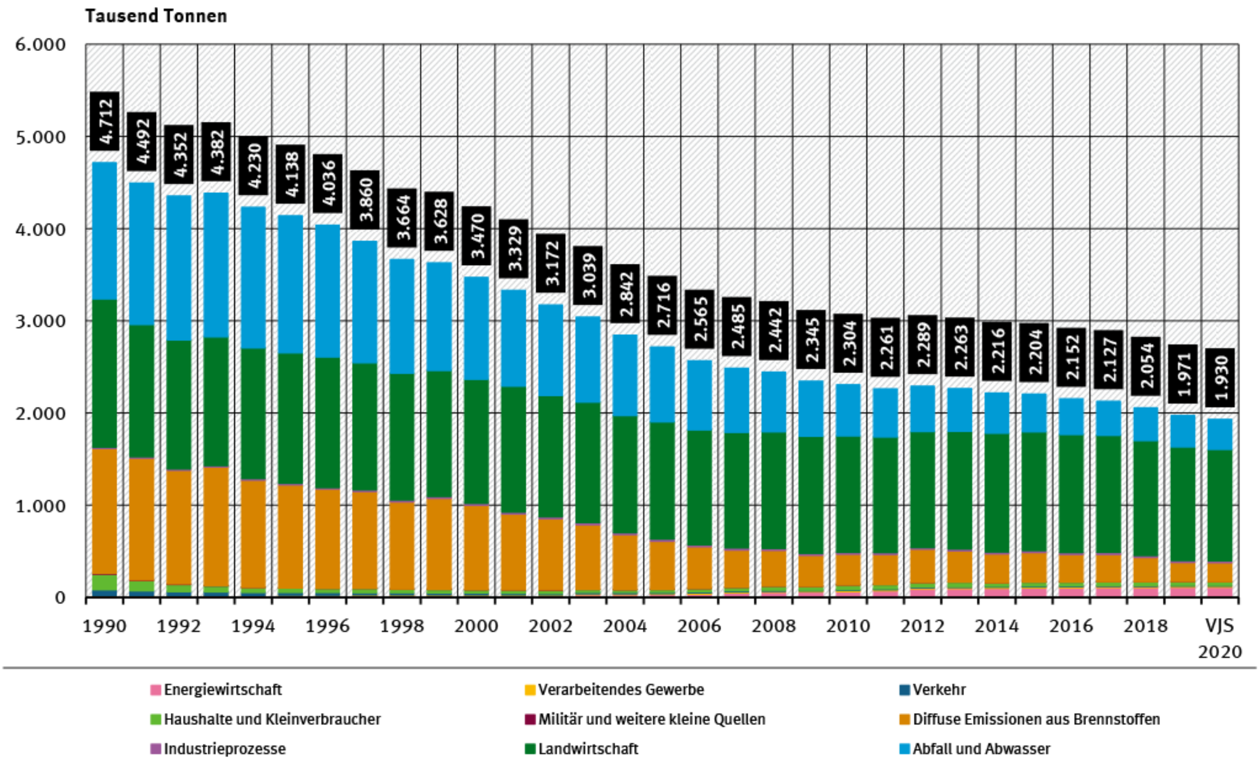
[607] Cf. Saunois (2020a)



Emissionen ohne Landnutzung, Landnutzungsänderung und Forstwirtschaft
Verkehr: ohne land- und forstwirtschaftlichen Verkehr
Haushalte und Kleinverbraucher: mit Militär und weiteren kleinen Quellen (u.a. land- und forstwirtschaftlichem Verkehr)

Quelle: Umweltbundesamt, Nationale Treibhausgas-Inventare 1990 bis 2019 (Stand 12/2020) sowie Vorjahresschätzung (VJS) für das Jahr 2020 (PI 07/2021 vom 15.03.2021)

Figure 194: Methane emissions by category and in the years 1990 to 2020.

Source: UBA, 15.3.2021.

2.12.1.4 Methane sinks, methane balance and forecasts

In connection with the changes in methane concentration in the atmosphere after the eruption of the Pinatubo volcano in 1992, natural methane sinks were investigated in more detail. Essentially, methane is degraded by chemical reaction with OH radicals and ozone in the troposphere (approx. 80 %), to a lesser extent in the stratosphere (15 %).

The most important sink is the chemical reaction with the hydroxyl radical OH in the troposphere:

$$OH^{\bullet} + CH_4 \Rightarrow CH_3^{\bullet} + H_2O$$

The reaction of methane with OH radicals leads to the formation of water and methyl radicals, which are ultimately converted to CO_2 via a few more intermediate steps.

This process removes about 500 Mt of methane from the atmosphere per year.

The uptake of methane in the soil or oceans and bacterial degradation, on the other hand, is negligible (5 %).[608]

The total amount of methane degraded via sinks is estimated to be less than 600 Mt/a in total.

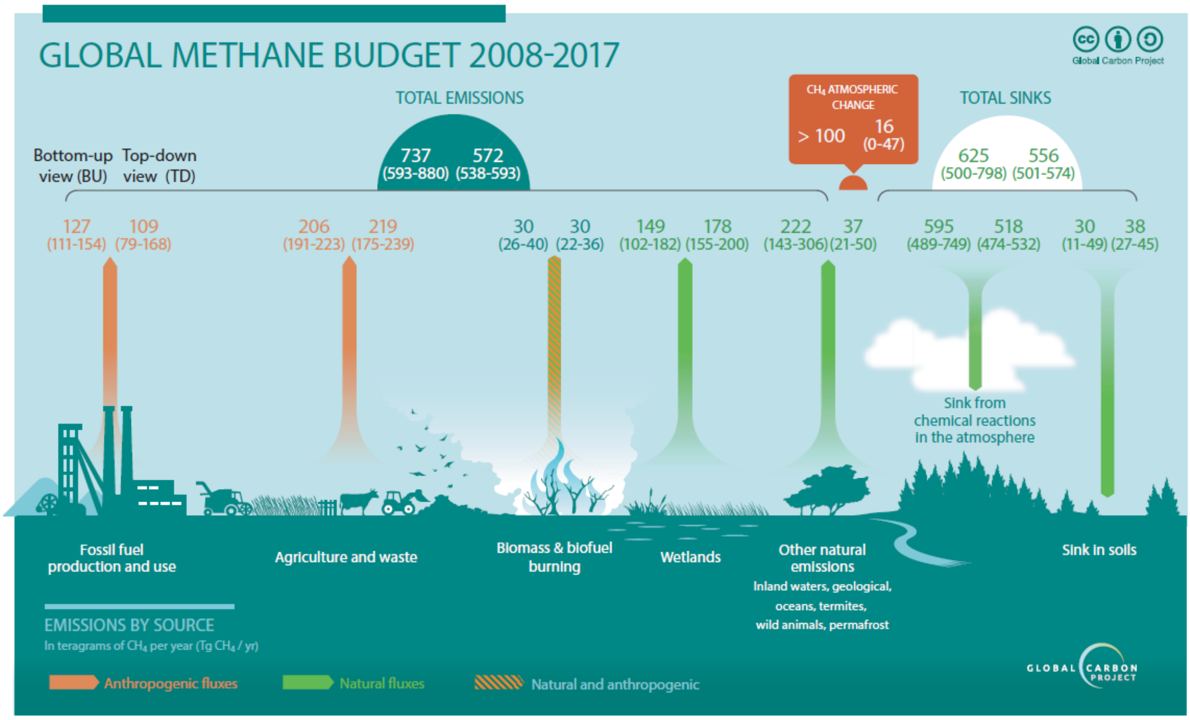


Figure 195: Global methane emissions from 2008 to 2017.

Source: Saunois et al., (2020).

The total balance of emissions and sinks has been broken down in extensive international carbon cycle studies directed by the Penn State Earth System Science Center (ESSC) and NOAA (National Oceanic and Atmospheric Administration of the US Department of Commerce) for the period 2008 – 2017 (cf. Figure 195). The quantity ranges are largely consistent with all other sources cited.

Projections into the future in relation to global warming are difficult because, despite countermeasures, with the current anthropogenic share of approx. 60 %, the development of natural emissions, including methane bound in permafrost and as methane hydrate, is difficult to quantify.

Climate models within the framework of the Global Carbon Project assume a further increase in methane concentrations in the atmosphere unless global warming can be limited to 0.9 – 2.3 °C (year 2100 compared to years 1850 – 1900) (see Figure 196).[609]

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[608] Cf. Nechita-Banda (2015)
[609] Cf. Global Carbon Project, (n.d.)

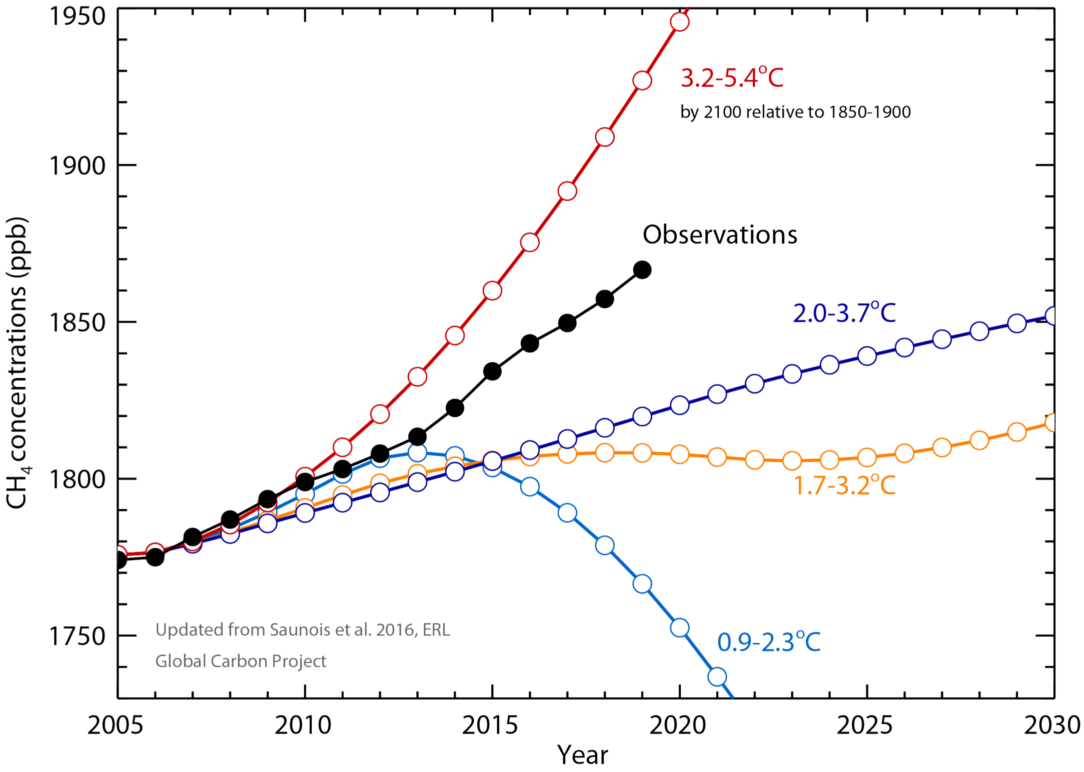

Figure 196: Measured and modelled methane concentrations in the atmosphere.

Source: Global Carbon Project, n.d.; Saunois et al, (2020).

2.12.1.5 Permafrost and methane hydrate

There are contradictory statements on the potential methane formation from thawing permafrost areas. The figures range from no more than 20 Mt/a (Siberia)[610] to 130 – 160 Gt in this century (i.e. an average of 1.6 – 2 Gt/a).[611] The wide range is due to the uncertainty as to which areas will be affected depending on regional differences in global warming. Forecasts depending on global warming are correspondingly uncertain.

More detailed model calculations for so-called Yedoma permafrost (50 – 90 % ice, 2 % organic carbon) assuming global warming of less than 2 °C by the end of this century (RCP 2.6 Scenario) are tangential to the model described in Figure 197 and the amounts of carbon sequestered per m^2. According to these model calculations, they lead to methane emissions of approx. 620 – 1,340 Mt.[612]

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[610] Cf. Anisimov & Zimov, (2021)
[611] Cf. Schuur et al., (2015)
[612] Cf. Yokohata et al., (2020)

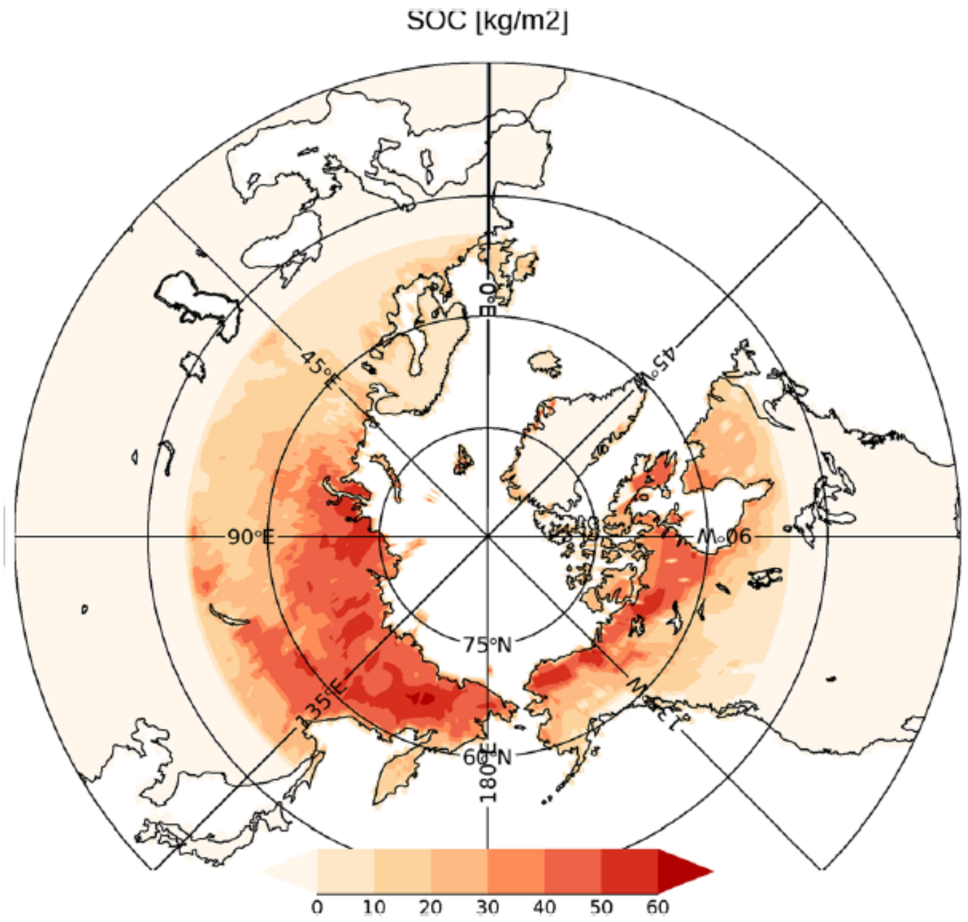

Figure 197: Area of permafrost soils and potential of CH_4 per area.

Source: Yokohata (2020)

In order to extract methane from permafrost soils, experimental wells have been drilled in Siberia and Canada, among other places, but these have not led to commercial production.

Examples are the exploration in Mallik in the Mackenzie Delta in Canada[613] in Qilian/China[614] and in Siberia.

2.12.1.6 Methane hydrate (methane ice)

Methane hydrate is a solid (clathrate) of methane and water that is stable at low temperatures and high pressures. The phase diagram is shown in Figure 198.

1 m^3 methane hydrate can contain up to 170 m^3 gas. The trapped methane comes mainly from the decomposition of biomass by microbial methanogenesis into methane (and CO_2).

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[613] Cf. Moridis et al., 2004.
[614] Cf. Li et al., 2012.

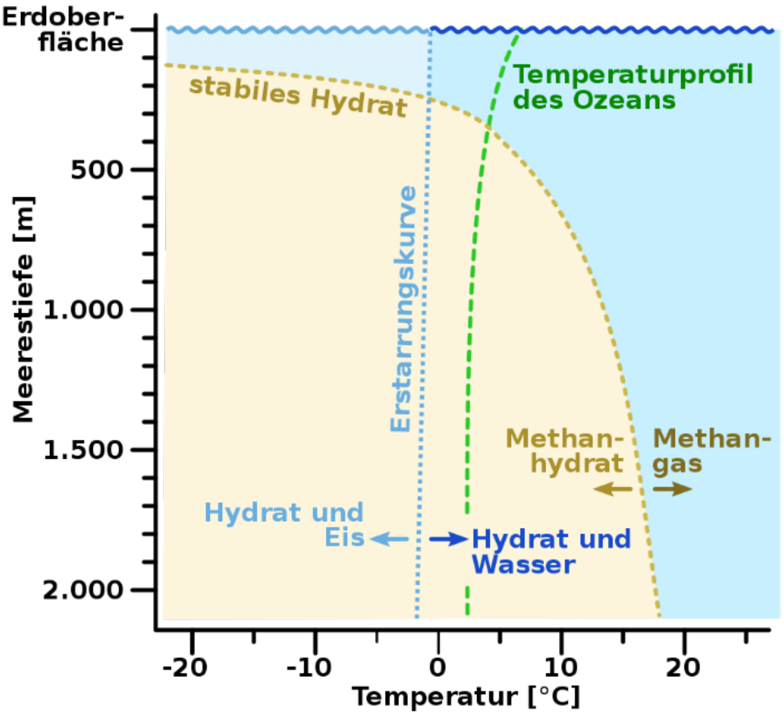

Figure 198: Phase diagram of methane hydrate.

Source: Capitanio et al., (2017).

Methane hydrate is found in large quantities in the continental slopes of oceans at depths of usually 500 to 2,000 metres. When warm ocean currents shift towards methane fields and warm the water by about 5 °C, large amounts of methane can be released (so-called blow-out effect).

Methane hydrate deposits are found on almost all ocean coasts worldwide (see Figure 199). The total deposits are not known, estimates range from 1,000 to 530,000 Gt of carbon, in any case many times the existing fossil fuel reserves are involved.[615]

It is not known to what extent methane is actually released from methane hydrates to a greater extent due to the warming of the oceans. It is assumed that there is a balance between methane decay and new formation due to increased pressure as a result of rising sea levels.

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[615] Cf. World Ocean Review, (2010); Treude, (2021).

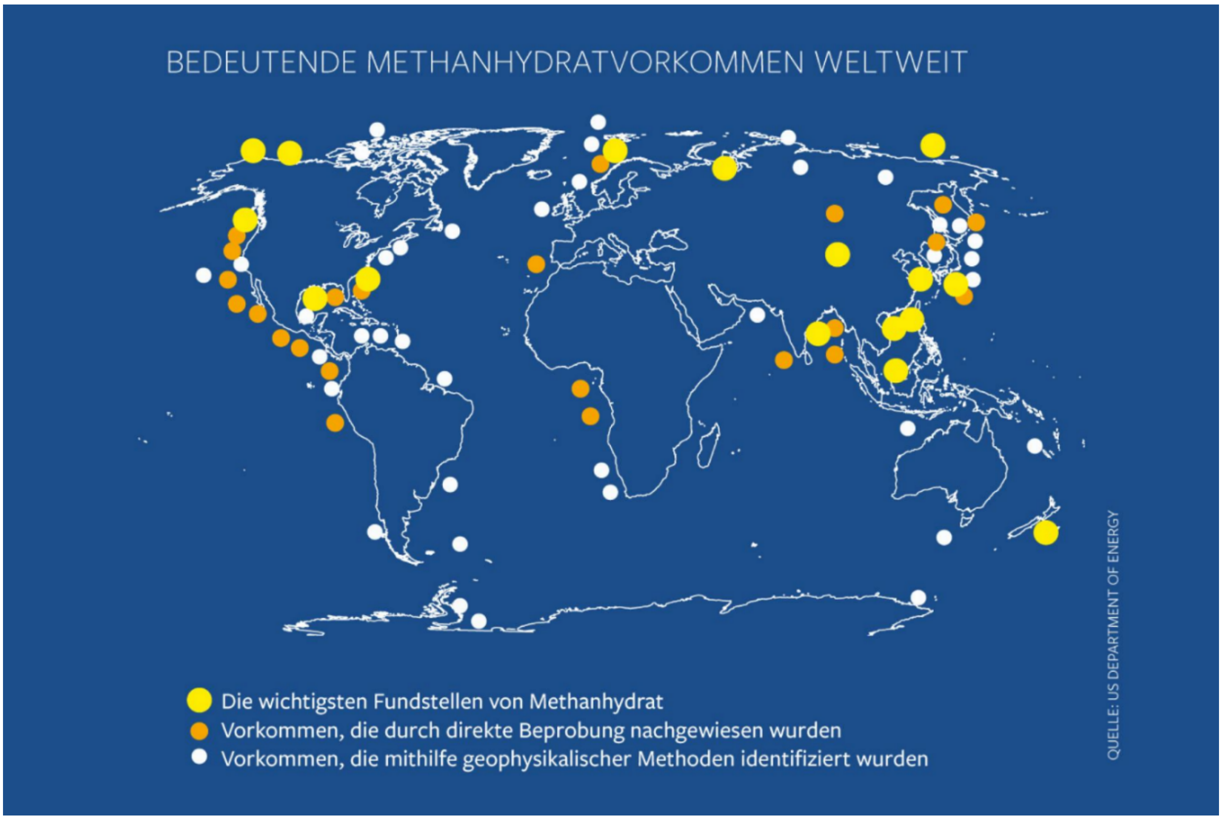

Figure 199: Worldwide methane hydrate deposits.

Source: Kroker, 2015.

Methane hydrates are considered an inertially reacting tipping element in the course of global warming; quantity forecasts from model calculations are rather speculative. Some publications speak of an elusive "time bomb".

The industrial extraction of methane from the mining of methane hydrates has so far only taken place in the form of test wells, such as a production of 300,000 m^3 from May to July 2017 at a depth of 1,266 m in the South China Sea near the Chinese coast.[616] Japan, India and the USA have also carried out corresponding tests, but commercial use has not developed due to the complex extraction technology, the risk of uncontrolled methane leakage as a result of landslides and ultimately for cost reasons.

2.12.1.7 Options for reducing methane emissions

Methane emissions are often diffuse in nature compared to CO_2 emissions and are therefore more difficult to capture and therefore more difficult to mitigate. In the USA alone, 600,000 natural gas and oil wells, a global livestock population of about 1.5 billion cattle and 6,000 abandoned coal mines emit methane.

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[616] Cf. Li et al, (2018).

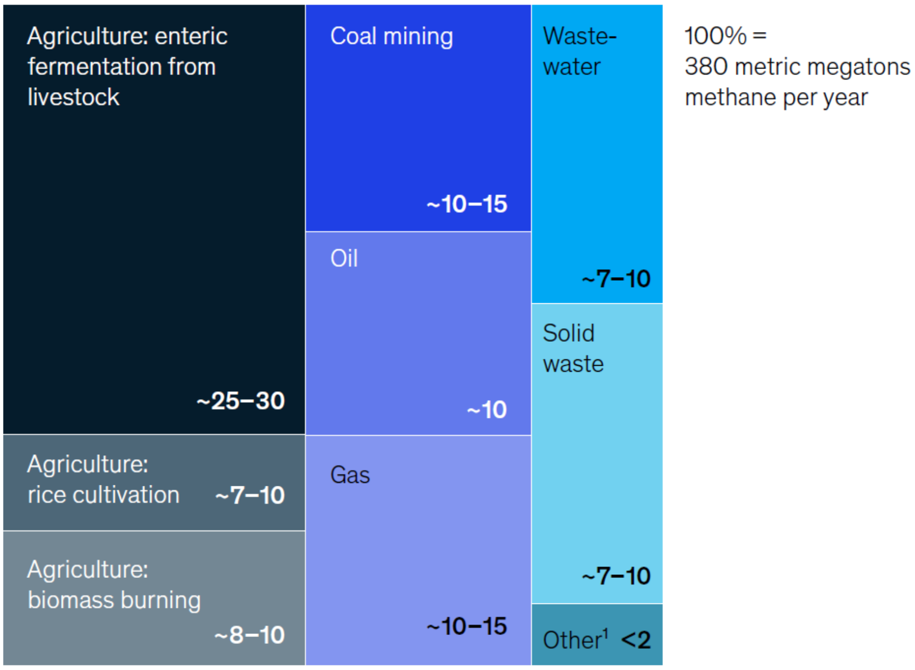

Figure 200: Origin of methane emissions.

Source: McKinsey, (2021).

The individual sectors and their contributions to anthropogenic methane emissions in 2020 are shown in Figure 200.[617]

Concrete remedial measures are essentially the sealing of leaks and the capture of residual gases in fossil energy production and landfills. Gradual reductions in methane emissions are possible in agriculture and livestock farming.

With known measures and technologies, methane emissions could be reduced by up to 57 % in this decade, a quarter of this at no additional net cost by increasing efficiencies, closing leakages and recovering methane.[618] This would only be achievable if all emission sources were addressed simultaneously, globally and at high financial cost.

New measuring methods based on infrared laser techniques allow the detection and concentration determination of methane leaks from aircraft and drones. This method is used in the American oil and gas industry, but also in Russian gas production areas.[619]

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[617] Cf. Moridis et al., 2004; Global Methane Initiative, (2020).
[618] Cf. Ocko et al., (2021).
[619] Cf. Johnson et al, 2021; Yakovlev et al, (2020).

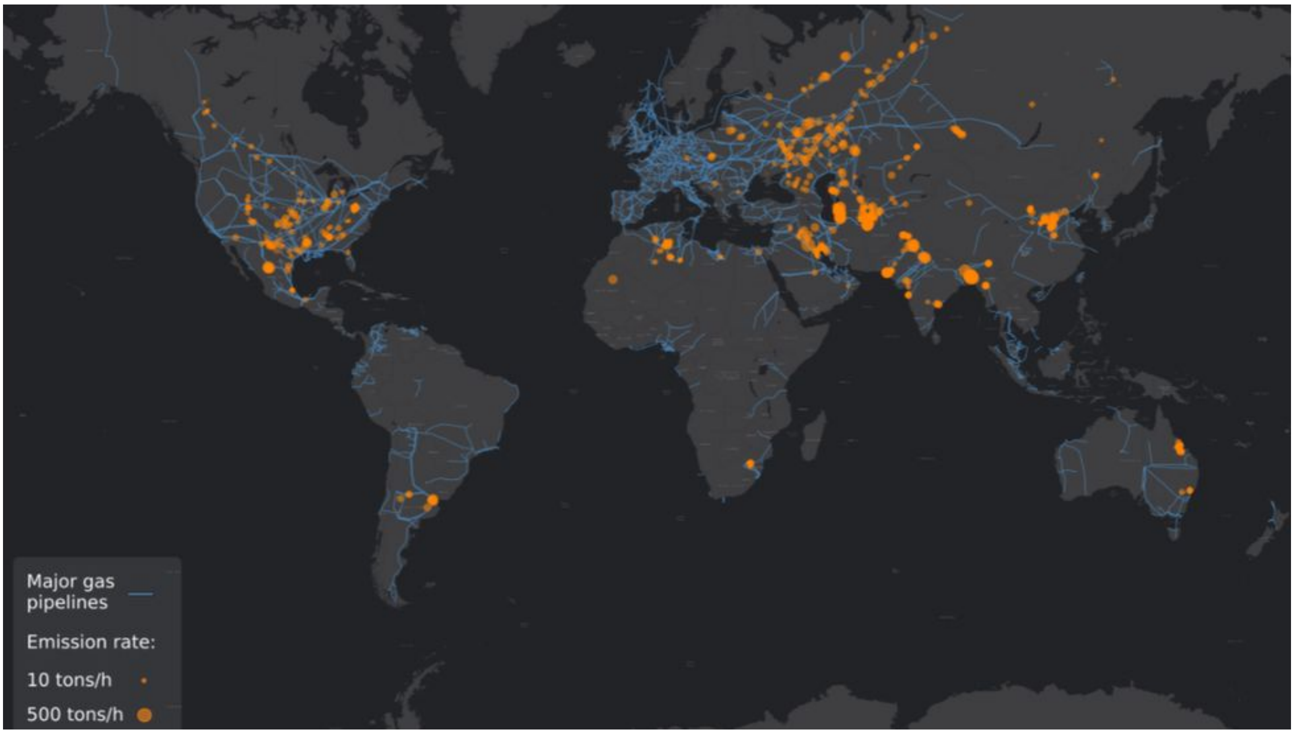

Figure 201: Search for methane leaks using satellite systems.

Source: Tropomi, o J.; Lavaux, (2022).

Satellite-based analyses, such as with the TROPOspheric Monitoring Instrument of the Copernicus Sentinel-5 Precursor satellite, are able to detect methane leaks on a daily basis in grids of approximately 20 x 20 km. In 2019 and 2020, for example, more than 1,800 methane leaks were recorded along natural gas fields as well as pipelines, often of several tonnes of methane per hour (see Figure 201).

2.12.1.8 Methane emissions in the oil and gas industry

Methane emissions arise from the conventional extraction of natural gas and crude oil as associated gases as well as from unconventional sources such as shale gas, so-called "tight gas" from gas-permeable sediments and coal associated gas.

Methane losses in the oil and gas industry are estimated by the IEA to be around 75 Mt/a. In the case of natural gas, the loss rate is up to 1.7 % of the total volume produced; in Russia, the losses are said to be up to 2.5 % of the volume produced.

Emissions from fracking with methane losses are particularly high, estimated at up to 3.7 % for the US. [620]

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[620] Cf. Vaughan, (2020).

The numerous leaks extend into urban networks. For example, around 286 t of methane are released into the atmosphere every year through the Hamburg gas grid alone.[621]

From a loss rate of 3.2 %, natural gas contributes more to climate change than coal.[622]

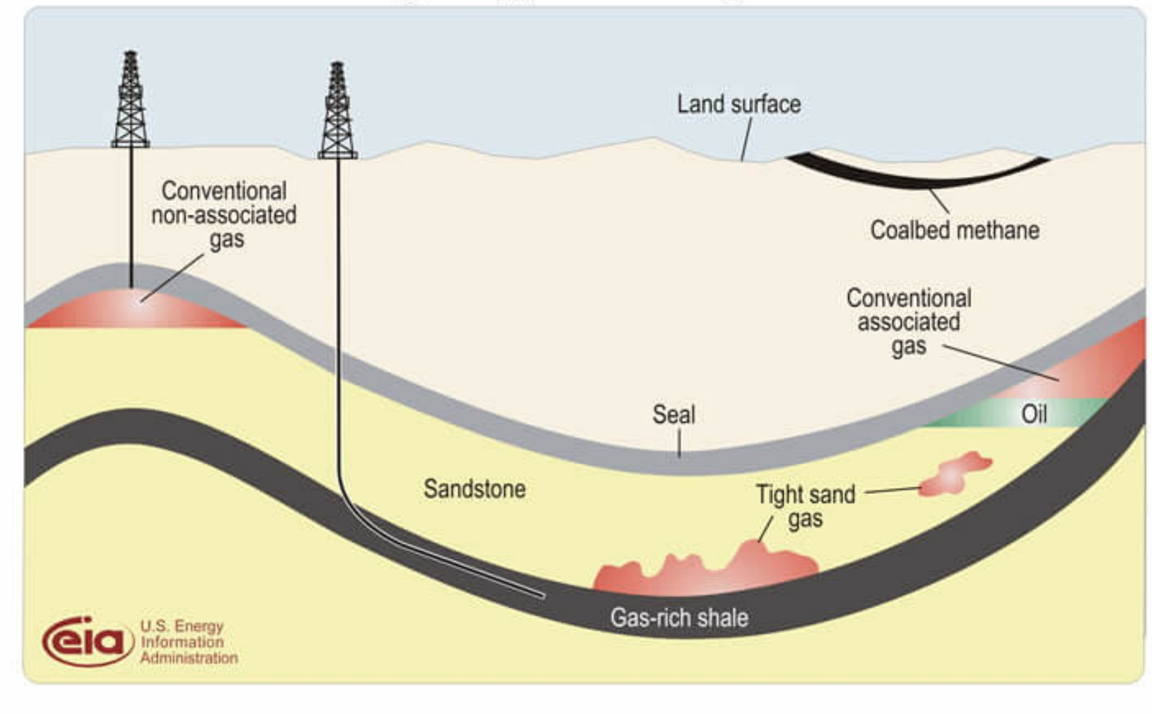

Figure 202: Schematic representation of natural gas reservoirs.

Source: EIA, 2013.

The main measures to reduce methane emissions are the search for and closure of leaks in wells, pipelines, pumps and compressors along the entire natural gas and oil process chain. This mainly concerns the recovery of associated gases, renewal of flares and methane recovery from tanks and blowdown vessels to filling stations and local gas networks.

2.12.1.9 Methane emissions in coal mining

Emissions of methane from coal mining, both underground, in opencast mines, but also from disused mines, are considerable (see Figure 203). Estimates by the IEA are around 40 Mt/a,[623] a study by the US JBCRI states 114 Mt/a from active and disused coal mining.[624] Only a small part is captured and used for energy.

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[621] Cf. PM Environmental Defense Fund Europe, (2020).
[622] Cf. Traber, (2019).
[623] Cf. IEA, (2019)
[624] Cf. Kholod et al., (2020)

This would make coal-related emissions higher than those of the oil and gas industry.[625] China is the geographical focus of emissions.

The removal of mine gases ("firedamp", coal seam gas) during underground coal mining by ventilation ("ventilation") has long been state of the art for safety reasons. However, the methane content is too low for further utilisation and can be oxidised to CO_2 via catalytic waste gas purification.

However, mine gas also escapes from coal mines that have already been shut down but not flooded. This can be extracted and thermally utilised. In Germany, the quantity is estimated at approx. 1.5 million m^3/a and generates an output of 200 MW.[626]

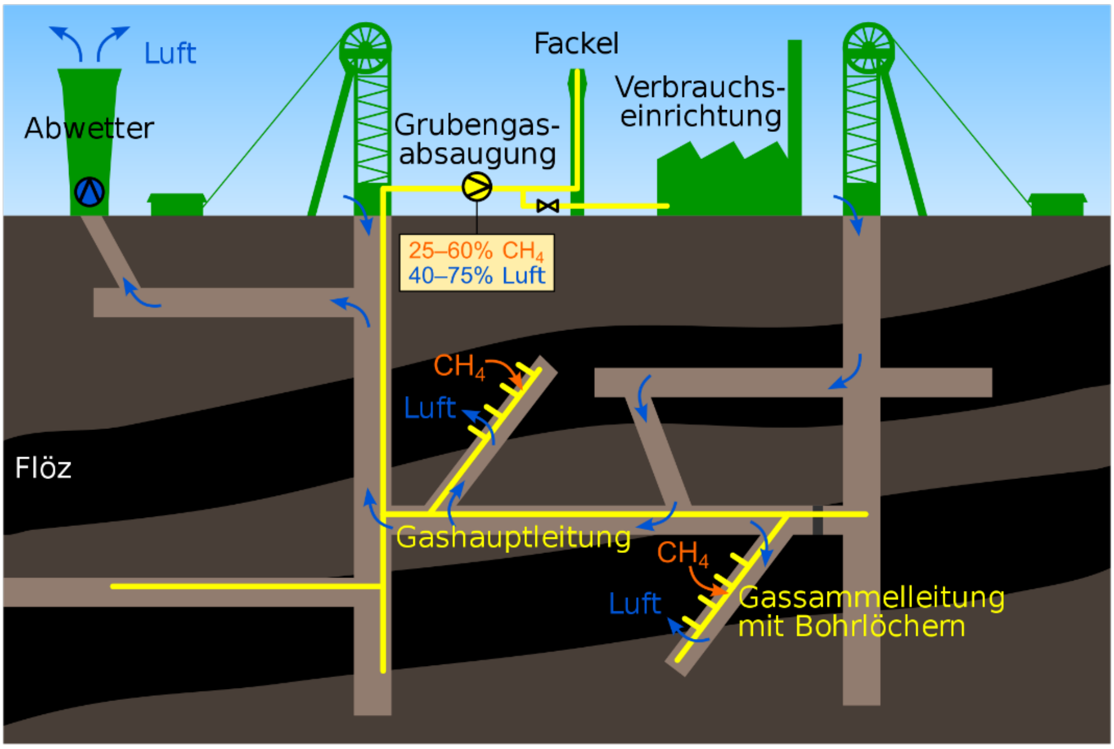

Figure 203: Schematic representation of methane emissions in a coal mine.

Source: Wikipedia, (2010).

2.12.1.10 Methane emissions from animal husbandry

Apart from a general change in dietary habits, i.e. less meat consumption or a switch to pigs and poultry instead of e.g. beef, measures to reduce methane formation in ruminants are difficult. There are feed additives (terpenes, calcium nitrate, linseed oil) that curb fermentation, but with limited effect. DSM is setting up a first production plant in Scotland for Bovaer® (3-

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[625] Cf. Gabbatiss, (2020)

[626] Cf. Grumptmann, (2018).

nitrooxy-propanol) in Dalry, Scotland, after 10 years of development and testing in South America.[627] The feed additive reduces methane emissions from ruminants by 30 %.

In manure management, methane can be collected by covering and subsequent treatment under anaerobic conditions, e.g. in biogas plants, and utilised for energy.

2.12.1.11 Methane emissions from rice cultivation

Rice is a staple food for over 3.5 billion people. According to the FAO, around 90 % of the world's rice harvest comes from South Asia and Southeast Asia. China and India are the world's largest producers with corresponding significance for the climate.

Wet rice cultivation in natural or artificially flooded fields is common. In permanently flooded rice fields, methane is produced by microorganisms that decompose plant residues (methanogenesis). Draining a field at certain times of the growth cycle can reduce methane emissions by up to 50 % without reducing rice yield. A further reduction in methane emissions could also be achieved by selecting appropriate rice varieties.[628]

Since 2011, there has been a "Platform for Sustainable Rice" (SRP) which was introduced by UNEP and the International Rice Research Institute (IRRI) with the aim of promoting climate and environmentally friendly cultivation methods and – since 2015 – introducing corresponding standards. Measures to inhibit methanogenesis and thus reduce methane emissions include water management, the use of other rice varieties, fertilisation with gypsum containing phosphates (calcium sulphate) and other sulphates.

2.12.1.12 Landfill gas

Landfill gas is produced from all organic components of waste through fermentation and decomposition to a gas mixture of CO_2 and methane. In orderly landfills, the gas can be collected and used centrally for energy by covering the landfill and installing collectors (see Figure 204).

Worldwide methane emissions from landfills were estimated to be around 30 Mt in 2012,[629] with total emissions from "wild" landfills unknown.

For every tonne of unseparated household waste, about 150 – 200 m^3 of landfill gas is produced, about 60 % of which consists of methane.

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[627] Cf. DSM, (2021).
[628] Cf. Proplanta, n.d.
[629] Cf. Zhao, 2019

In Germany, all landfills together released about 300 Mt of methane per year in 2012. This is roughly equivalent to the methane emissions of three million cattle. According to a 2012 study, the capture rate in Germany is about 57 %, while in Spain, for example, it is only 18 %. [630]

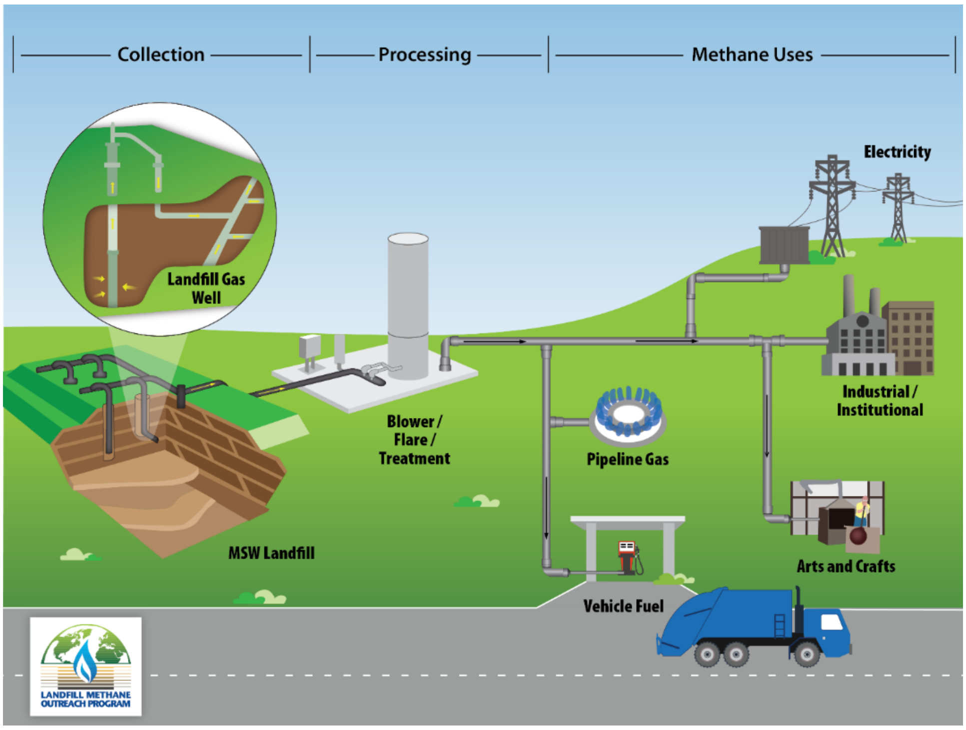

Figure 204: Schematic representation from the capture of methane emissions to recycling.

Source: EPA, n.d.

2.12.1.13 Wastewater

Wastewater generates about 34 Mt of methane annually worldwide, with about 90 % of wastewater being untreated.

Simple wastewater treatment plants usually operate aerobically, i.e. "aerate" the wastewater. Incorrect operation and anaerobic conditions produce an estimated 3 Mt of methane, i.e. approx. 10 % of the above-mentioned total emissions.

Improvements are achieved through additional, anaerobically operating clarification stages and separation of the methane produced. The yield of the methane-containing "digester gas" is increased in digesters at elevated temperatures (approx. 35 °C). In this process, the organic contents of the sewage sludge are decomposed in four phases (hydrolysis, acidification,

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[630] Cf. Reiser (2021)

acetogenic and methanogenic phase) to form an energetically usable product gas with a typical composition of 60 – 70 % methane and 26 – 36 % CO_2.[631]

In Germany, around 1,491 GWh of electricity was generated from sewage gas in 2018. It thus had a share of 0.7 % in the total electricity supply from renewable energies. Of the more than 9,000 German sewage treatment plants, 1,274 plants put the digester gas to use, 8 % of which generated n electricity.[632]

2.12.1.14 Oxidation of methane from diffuse sources and at low concentrations

Recent developments allow the removal of methane in the range of atmospheric methane trace concentrations by catalytic oxidation to CO_2 at moderate temperatures of 200 – 300 °C. Copper-doped zeolites with a modernite structure are used.[633]

Enzymatic oxidation of methane traces, among others to methanol using methane monooxygenase, is also known but not very effective.[634] Both options are at the development stage.

2.12.1.15 Summary and outlook

The most detailed study on the status and mitigation measures of methane emissions is the UNEP/CCAC study "Global Methane Assessment and Costs of Mitigating Methane Emissions" published in 2021.[635]

With known technical possibilities, methane emissions could be reduced by 180 Mt/a by the end of the decade. This would correspond to a reduction of the greenhouse effect by 0.3 °C.

Measures that have already been planned and initiated comprise approx. 120 Mt/a, with the oil/gas/coal sector contributing half – also because they are the least diffuse emission sources.

In several other studies, the potential for methane emission reduction by 2030 is given as 29 – 57 Mt/a for oil and gas, 12 – 25 Mt/a for coal, 29 – 36 Mt/a for waste and wastewater, 6 – 9 Mt/a for rice cultivation and 4 – 42 Mt/a for livestock. This would be an average of about 113 Mt/a, with wide fluctuation ranges in each case.

This may also be due to the fact that priorities vary geographically and mitigation measures are addressed with different intensity:

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[631] Cf. Gebhart, (2018).

[632] Cf. Kröll, (2020).

[633] Cf. Brenneis et al., (2021).

[634] Cf. Smith et al., 2009.

[635] Cf. UNEP/CCAC 2021

Table 48: Sectors with high CO_2 emissions by country/continent.

Country/Continent	Sector with the highest CO_2 emissions
Europe	Waste and waste water
Africa	Animal husbandry, coal/oil/gas
China	Coal, agriculture
Asia without China	Waste, waste water, agriculture
Middle East	Oil/Gas
North America, Russia	Oil/Gas/Coal
South America	Agriculture (incl. expansion of agricultural land)

2.12.1.16 Costs

Reliable, general figures are not possible due to the heterogeneity of the emission sources and the respective measures. In some sectors, especially in the oil and gas sector, even negative costs, i.e. revenues from the reduction of losses, are given.

The UNEP/CCAC study[635] estimates an average cost of 600 USD/t of reduced methane emissions, focusing on oil/gas (520 USD/t), coal (190 USD/t) and agriculture (830 USD/t). The costs for waste/wastewater are much higher.

2.12.1.17 Relevance for GES

Methane is the second most important climate gas after CO_2 . Reducing methane emissions along value chains, especially the so-called upstream emissions, are relatively easy to achieve for less diffuse anthropogenic sources such as in the oil and gas sector and some areas of agriculture such as rice cultivation and livestock farming, and have a high leverage effect.

A well thought-out strategy to reduce methane emissions must therefore be an imperative part of today's climate protection activities, even if "methane neutrality" is ultimately unattainable.

To be considered, but difficult to quantify, are the risks of uncontrolled methane release from natural sources in the course of general climate changes leading to thawing of permafrost areas and warmer ocean currents and decomposition of methane hydrates.

2.12.2 Special case of methane: Scope and control of LNG upstream emissions

2.12.2.1 Composition and properties of LNG

Liquefied natural gas (temperature approx. –162 °C) consists of approx. 95 % (molar) methane, other components are approx. 2.5 % CO_2 , approx. 2 % ethane and propane and small proportions of higher hydrocarbons as well as N_2.[636] LNG has only one six-hundredth of the volume of gaseous natural gas with the following additional properties:

1,000 kg LNG corresponds to approx. 1,400 m^3 natural gas
1 m^3 LNG corresponds to approx. 630 m^3 natural gas
Density of LNG: approx. 450 kg/m^3
Energy density of LNG: 2,200 MJ/m^3 or 610 MWh
Calorific value (Ho): approx. 15 kWh/kg, calorific value (Hu): approx. 13.5 kWh/kg
Ignition limits in air: 5 – 15 vol % CH_4

Table 49: Some physical and chemical properties of LNG.

2.12.2.2 Supply routes: Global trade in natural gas (via pipeline) and LNG

The only data currently available on supply routes pre-date the major shifts resulting from the Ukraine war and the corresponding forecasts.

The global transport volumes of natural gas via pipelines and as LNG in billion m^3 are summarised in Figure 205.[637] According to this, the share of pipeline transport is just under 60 %, and transport by LNG 40 % (2021: 515 bn m^3) in relation to gaseous natural gas.[638]

Figure 205 shows the international trade flows for LNG in 2021 with a focus on Southeast Asia/Australia and Indonesia and Middle East/Qatar (production) and China as well as Europe (as recipient).

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[636] Cf. Sagroll, 2015.
[637] Cf. BP, (2022).
[638] Cf. Sönnichsen, (2022).

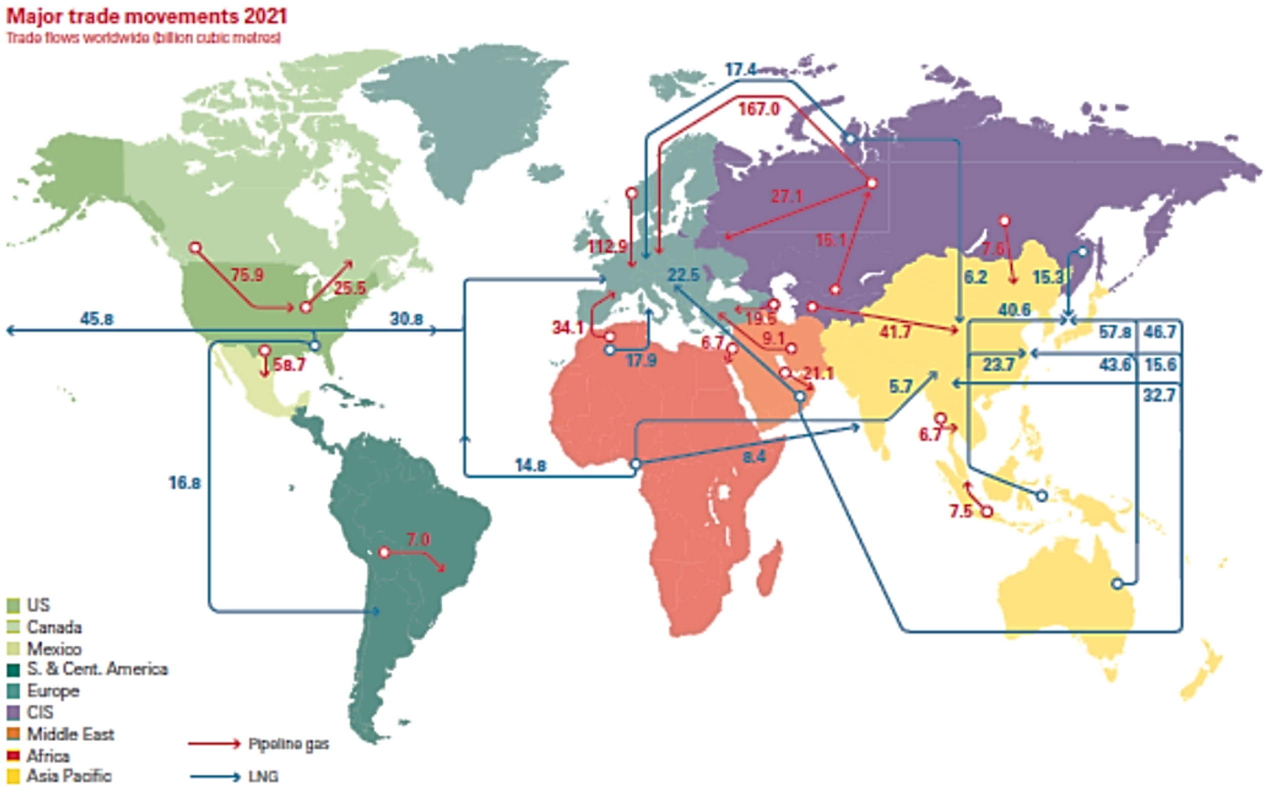

Figure 205: Global supply chains for natural gas via pipelines and as LNG.

Source: BP, (2022).

In total, just over 370 Mt of LNG was traded globally in 2021, with Australia, Qatar, the US and Russia the largest producers, while China, Japan, India and Europe were the largest importers (see Figure 206).[639]

Liquefaction capacities in 2021 amounted to approx. 460 Mt and are being strongly expanded worldwide. An additional 200 Mt of annual liquefaction capacity is planned and under construction, and further projects of over 1 Gt have been announced (see Figure 206).

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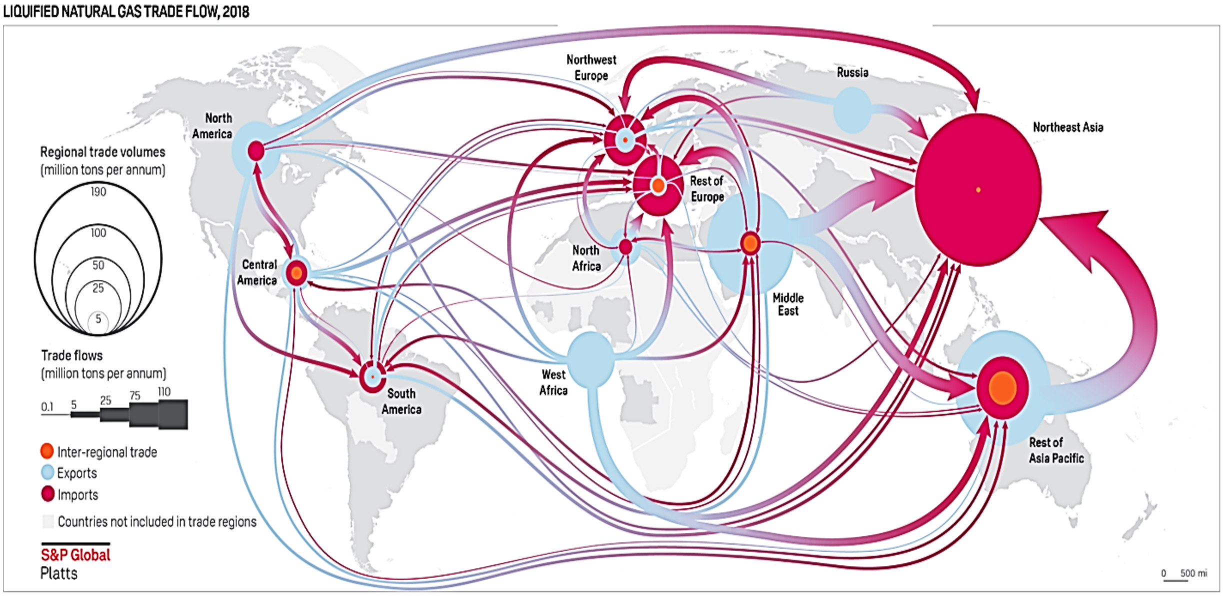
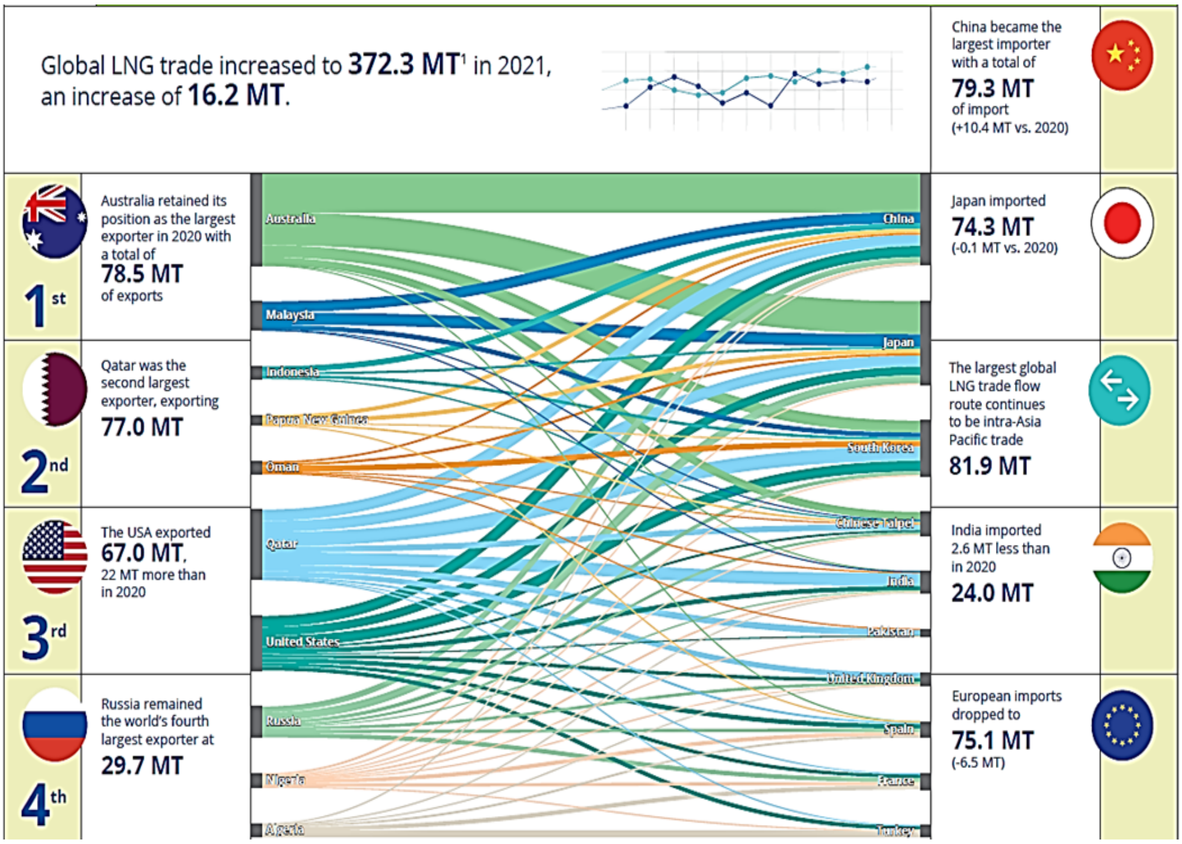
[639] Cf. IGU, (2022)



Source: S&P Global Platts

Figure 206: LNG transport worldwide.

Source: Sönnichsen, (2022).


Global LNG trade increased to **372.3 MT**[1] in 2021, an increase of **16.2 MT**.

China became the largest importer with a total of **79.3 MT** of import (+10.4 MT vs. 2020)

Australia retained its position as the largest exporter in 2020 with a total of **78.5 MT** of exports

Japan imported **74.3 MT** (-0.1 MT vs. 2020)

Qatar was the second largest exporter, exporting **77.0 MT**

The largest global LNG trade flow route continues to be intra-Asia Pacific trade **81.9 MT**

The USA exported **67.0 MT**, 22 MT more than in 2020

India imported 2.6 MT less than in 2020 **24.0 MT**

Russia remained the world's fourth largest exporter at **29.7 MT**

European imports dropped to **75.1 MT** (-6.5 MT)

Figure 207: Main exporters and importers of LNG.

Source: IGU, (2022).

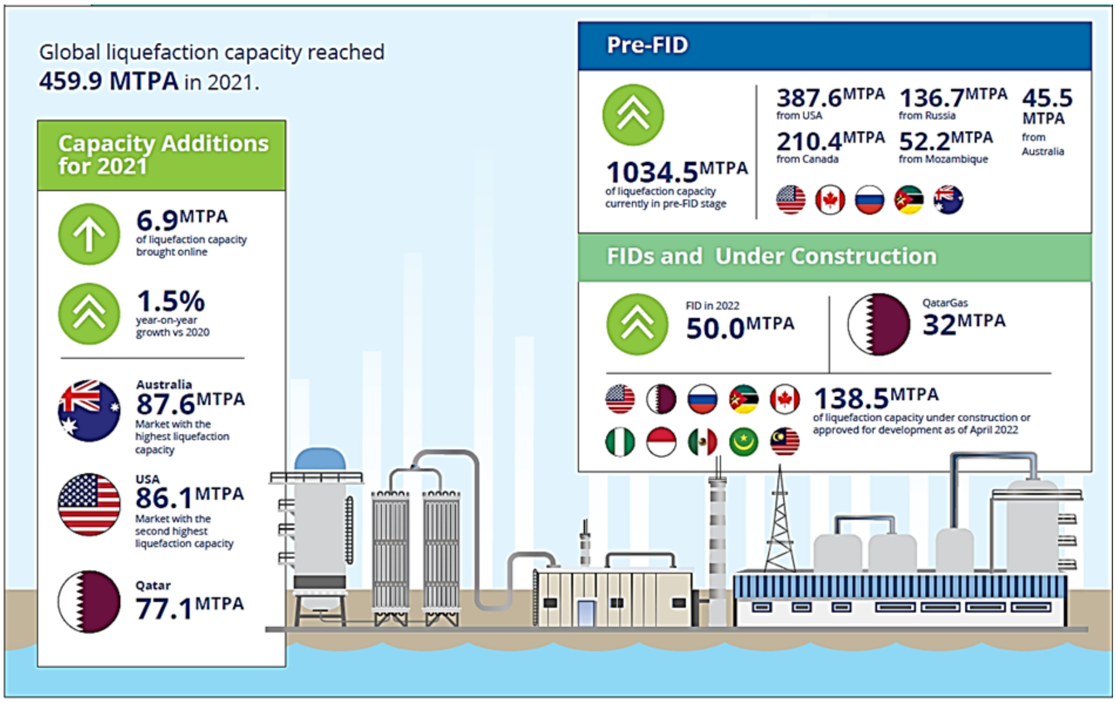


Figure 208: Liquefaction capacities for the production of LNG (as of 2021).

Source: IGU, (2022).

The LNG terminals with LNG regasification have a significant overcapacity of 903 Mt of LNG worldwide. This corresponds to a utilisation rate of approx. 43 %, whereby part of the overcapacity is determined by the seasonality of consumption (see Figure 209).

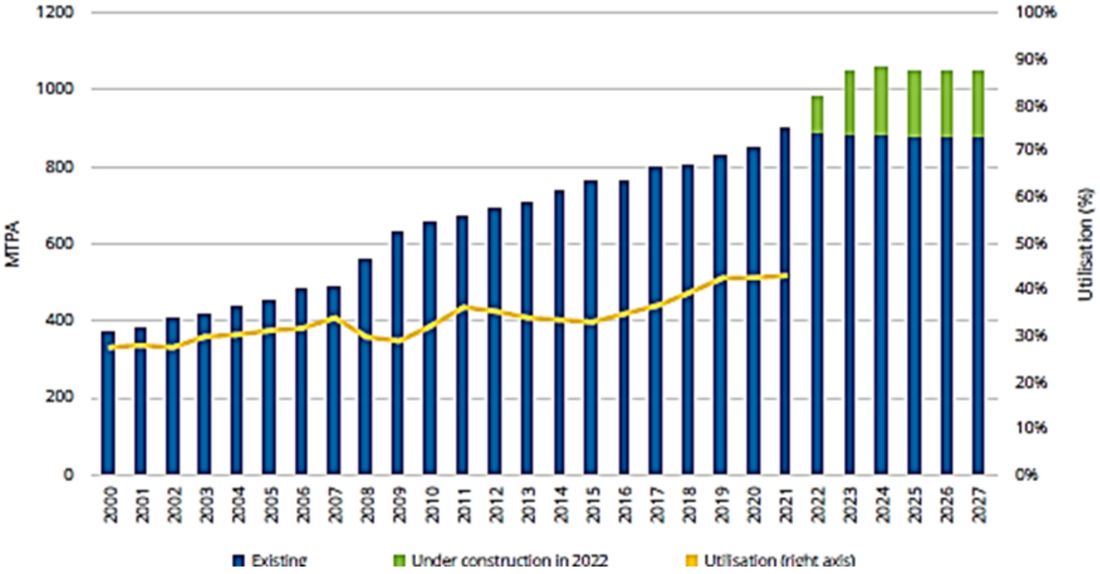


Figure 209: Capacity and utilisation of LNG terminals worldwide.

Source: IGU, (2022).

Currently, only a small expansion of this capacity is planned (which could change as a result of the Ukraine war).

The LNG tanker fleet currently consists of 640 vessels with an average capacity of 180,000 m^3 LNG (approx. 81,000 t LNG or 114 million m^3 methane/natural gas). A further 216 ships have been commissioned.

The main transport routes are Australia – China or Japan and Qatar – South Korea with a travel time of up to one month.

2.12.2.3 Situation in Europe

In terms of Europe, before the start of the Ukraine war, the supply of natural gas by pipeline was dominant, with only about 13 % (approx. 75 Mt in 2021) imported as LNG, see Figure 210.[640]

There was also no need for additional pipelines (Nordstream 2) and LNG terminals – despite the strong dependence on Russian natural gas. Accordingly, a supply structure was created mainly in the east-west direction (pipelines). Especially in southern Europe (Spain, Portugal), and partly also in England, LNG terminals emerged mainly to compensate for insufficient pipeline capacities (see Figure 211).

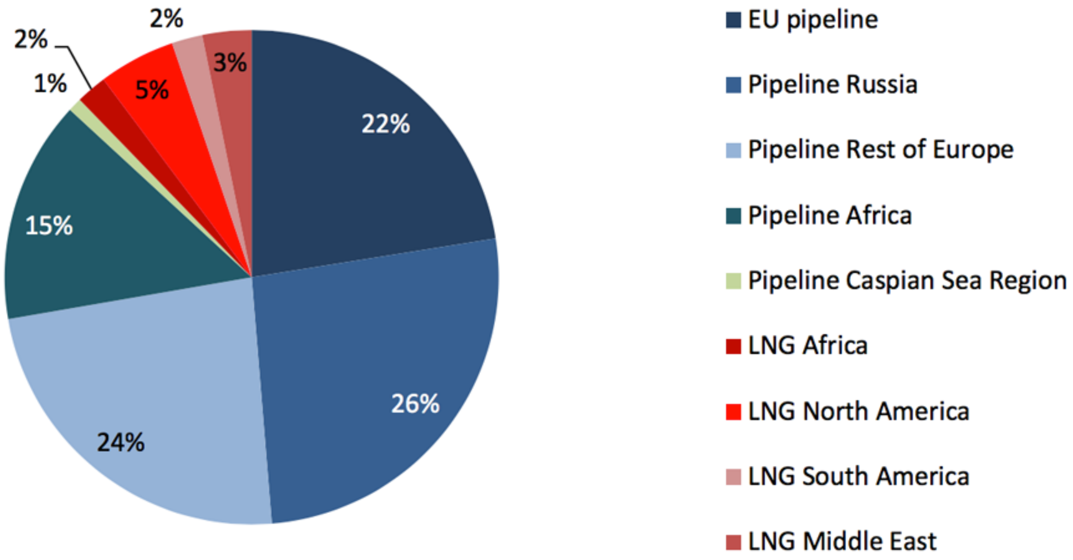


Figure 210: Natural gas supply to Europe by pipeline and as LNG.

Source: Holz & Kemfert, (2020).

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[640] Cf. Holz & Kemfert, (2020).

2.12.2.4 LNG terminals in Europe

Figure 211 shows the current locations of LNG terminals in Europe. Europe has 37 terminals, 26 of which are in the EU, with an annual capacity of 244 bn m^3 of gas (approx. 170 Mt of LNG).

13 EU countries imported 80 bn m^3 of gas as LNG in 2021 (about 20 % of total natural gas imports), including Spain 21 bn m^3, France 18 bn m^3 and Italy 9 bn m^3.

Accordingly, the European LNG terminals are heavily underutilised. Due to the unadjusted pipeline structure, the utilisation of the existing facilities will only gradually increase as a result of the Ukraine war. The planned EU-wide expansion corresponds to an annual capacity of 150 bn m^3 gas (approx. 110 Mt LNG).[641]

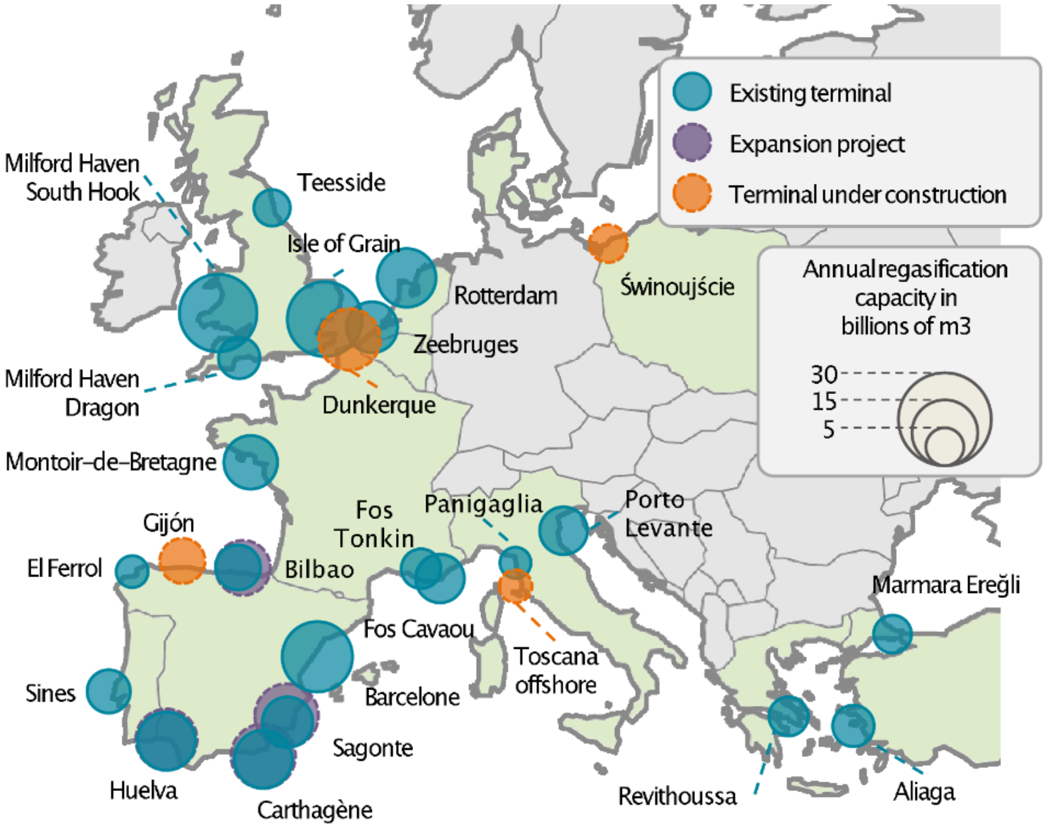

Figure 211: Existing and planned LNG terminals in Europe (before the Ukraine war).[641]

Germany is planning terminals at two locations with an annual capacity of 13.5 Mt LNG or 29 bn m^3 gas in Wilhelmshaven and Brunsbüttelkoog as well as mobile terminals in the Baltic Sea, among other places.

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[641] Cf. Clean Energy Wire (2022); PM BMWi, (2022).

2.12.2.5 LNG supply chain

Figure 212 and

Figure 213 show the basic sequence of the supply chain. The four LNG-specific steps generate additional methane emissions, especially through leakage during conversions and evaporation losses during storage and transport (boil-off gas).

After natural gas extraction, the natural gas must be conditioned for liquefaction in a first step, as otherwise some components would freeze out. These are in particular water, CO_2, higher hydrocarbons and sulphur compounds.

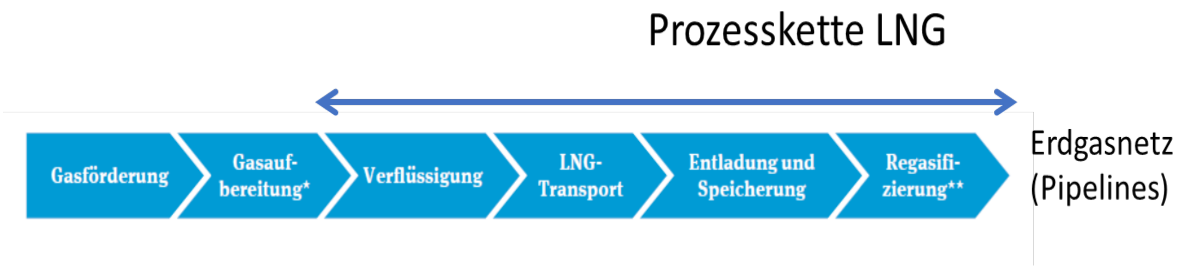

Figure 212LNG process chain

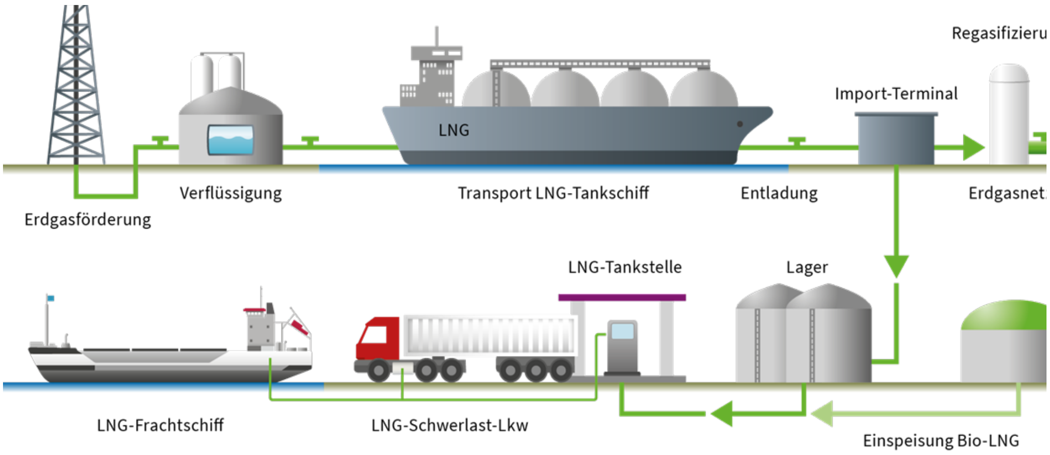

Figure 213: LNG supply chain.

Source: BGR, (2020).

2.12.2.6 Liquefaction and transport

Subsequently, the conditioned natural gas is cooled and liquefied to approx. –162 °C via several stages in exchange for a refrigerant (propane/methane/nitrogen) (see Illustration 214).[642]

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[642] Cf. Saunier, (2021).

In addition to fugitive emissions from leaks, methane is released primarily during purging operations, incomplete flaring of the "flash" gas" and through gas-powered compressors and generators.

Liquefaction, handling and boil-off emit approx. 0.3 kg CH_4/t LNG. Optimised new plants achieve up to less than 0.025 kg CH_4/t LNG.[643]

LNG liquefaction is energy-intensive, with the lower energy required for subsequent transport partially offsetting the energy requirements of pipeline transport.

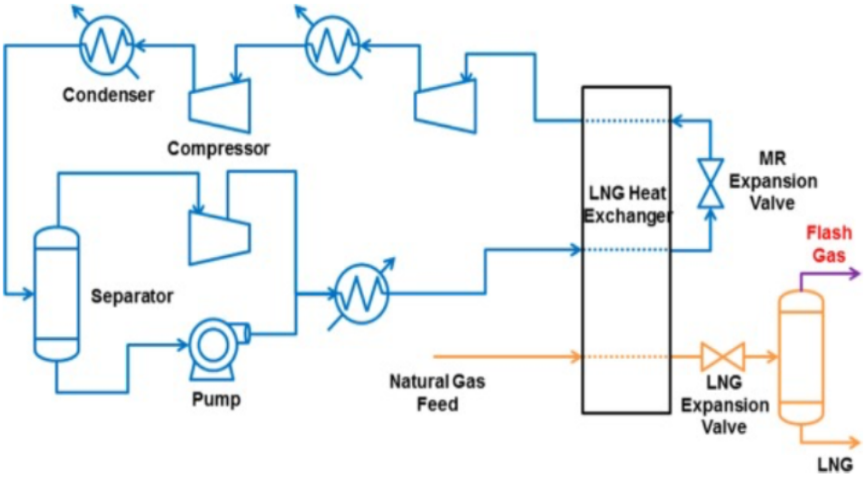

Illustration 214: Plant for the liquefaction of (conditioned) natural gas .

Source: Saunier, (2021).

There is currently no systematic analysis of methane emissions during transport. Rough estimates for a medium-sized LNG tanker are as follows

- 0.7 – 1.1 kg methane loss/t LNG and day due to boil-off and with
- 0.2 kg methane loss/t LNG and day for propulsion (emitted as CO_2)

in total, therefore, 0.9 – 1.3 kg methane/t LNG and day.[644]

2.12.2.7 Regasification and injection into the natural gas grid

Figure 215 schematically shows a plant for regasification of LNG and feeding it into the grid.[602]

Methane emissions also occur here due to diffuse leakage, purging and changing of connections, incomplete flaring of residual gas, and gas-powered generators, compressors and pumps for feeding into the pipeline network.

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[643] Cf. BGR , (2020).

[644] Notwithstanding the methane emissions from LNG propulsion, the overall emissions from ship transport are likely to be significantly lower than with heavy fuel oil propulsion.

Analyses at 20 European LNG terminals showed an average methane emission of 0.165 kg methane per tonne of LNG. Here, 83 % of the emissions were fugitive, 6 % from boil-off, 5 % from the flare and 6 % other emissions.

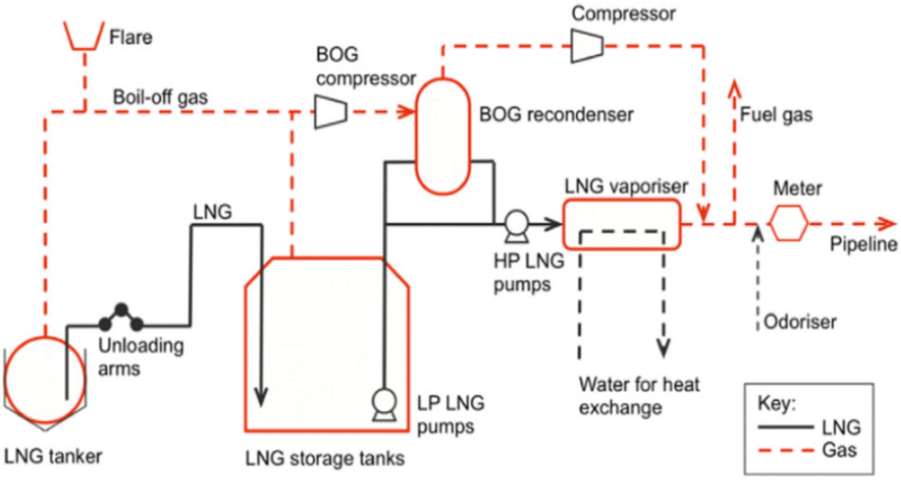

Figure 215: Plant for regasification of LNG for injection into the natural gas grid.

Source: Saunier, (2021).

2.12.2.8 Distribution as LNG (liquefied natural gas)

Illustration 216 shows the process chain of another LNG logistics with trucks, ships and further storage facilities. This type of LNG distribution generates the highest methane emissions along the supply chain – as a result of leakage, frequent flushing and changing of connections, and pumping.

Roughly estimated emissions are in the order of 1 kg methane/t LNG from boil-off and flushing losses, 1.3 kg methane/t LNG from truck supply to LNG refuelling stations and 2.2 kg methane/t LNG from vehicle refuelling.

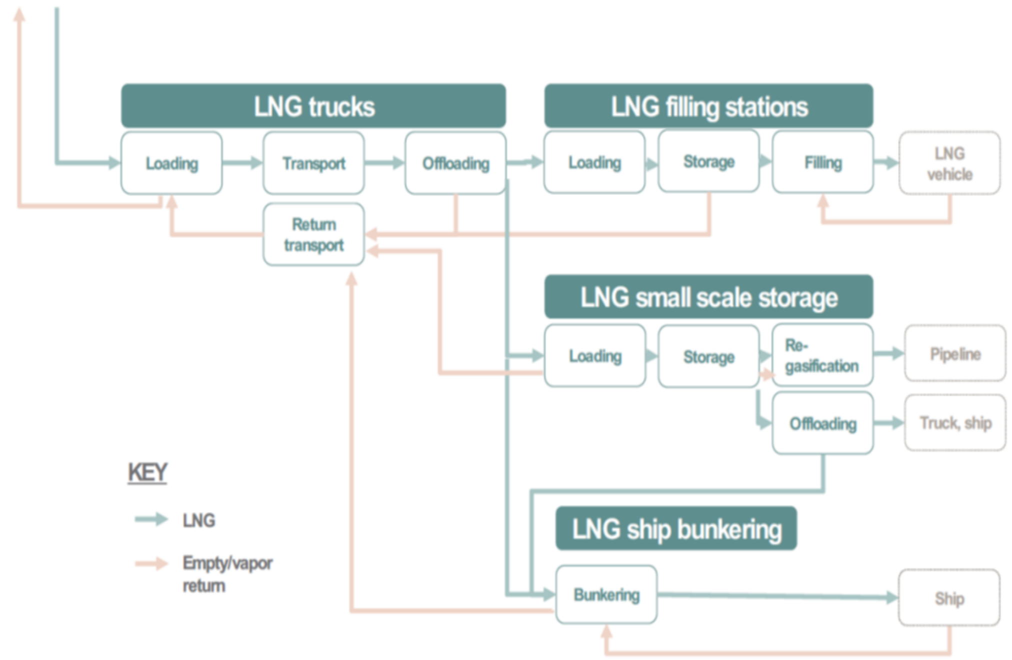

Illustration 216: Liquefied petroleum gas logistics (without feeding back into the natural gas grid).

Source: Saunier, (2021).

2.12.2.9 Estimation of upstream chain emissions and summary

Total pre-chain

Despite the dynamic development of international LNG trade and transport, the LNG supply chain has many variables and unknowns in terms of methane losses or emissions, partly due to a lack of systematic analysis.

The methane emissions of the process chain liquefaction – regasification – injection are in the order of 0.4 % (4 kg methane/t LNG) or 5.6 m^3 natural gas/t LNG. Depending on the assumed climate factor for methane, this corresponds to emissions of 100 – 350 kg CO_2 equivalents per t of LNG. To this must be added the transport by ship (0.9 – 1.3 kg methane/t LNG and day assuming LNG propulsion of the ship. Assuming ten days of transport, this corresponds to 9 – 13 kg methane per tonne LNG or 225 – 1130 kg CO_2 equivalents per tonne LNG.[645] The total methane emission of the entire supply chain for ten days of ship transport then amounts to 1.1 – 1.7 % or 13 – 17 kg methane/t LNG, or 325 – 1479 kg CO_2 equivalents per tonne LNG, depending on the climate factor. If one adds the energy input for liquefaction and vaporisation with LNG as the only energy source for processing, the losses increase by a further 0.3 – 0.75 % (3 – 7.5 kg methane/t LNG). [646]

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[645] 10 days at 15 kn, corresponding to a distance of approx. 6,500 km

[646] Cf. Timera Energy, (2021).

Comparison LNG / Pipeline

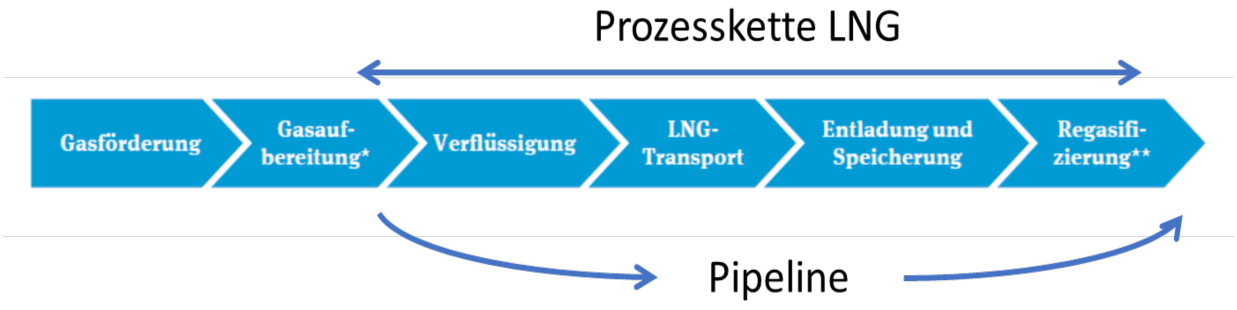

Figure 217: Process chains in comparison.

Comparing the loss rates of LNG logistics with those of pipeline supply, which skips the LNG-specific processing steps, the comparison (as far as it is at all comparable) results from Table 50.

Table 50Comparison of LNG and pipeline transport.

Mode of transport	**Losses during transport**
Methane emission LNG	1,4 – 2,5 %
Methane emission pipeline:[647] Netherlands to Germany:	0,03 %
Norway to Germany:	0,02 – 0,06 %
Russia to Germany:	0,5 – 1,5 %

The increasing use of LNG to secure energy supply is associated with significantly higher, additional upstream emissions of the climate gas methane and is increasingly viewed critically.[648]

Assuming an emission rate along the LNG process chain of 1.4 – 2.5 % and an LNG transshipment of 373 Mt (year 2021), this corresponds to additional annual emissions of 5.2 – 9.3 Mt methane. This corresponds to 130 – 233 Mt CO_2 equivalents (climate factor 25) or 452 – 809 Mt CO_2 equivalents (climate factor 87) or up to an additional 2.2 % of global CO_2 emissions in 2021 (36 Gt CO_2).

All the process engineering measures that are also required for natural gas production and transport by pipeline and are relatively easy to implement technically also apply in particular to the handling of LNG in order to reduce losses due to leakage, purging processes and boil-off through evaporation.[649]

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[647] Cf. Scientific Services, 2018; BGR, (2020).
[648] Cf. Angler, 2022; Tagesschau, 2022; Swanson, (2020).
[649] Cf. Stern, 2020; Reducing Methane Emissions, (2020).

With regard to the situation in Europe, a consistent expansion of the pipeline network – especially in a south-north direction – seems necessary in order to utilise existing LNG terminals as much as possible and thus minimise methane emissions at all transfer points.

2.12.2.10 Climate gas methane - Scope and control of LNG pre-chain emissions

Large quantities of methane-rich associated and residual gases are flared during the extraction of natural gas and crude oil. Recently published estimates put the number of flares worldwide at around 10,000 and the volume of flue gas at 144 bn m^3 in 2021, with a significant increase compared to previous years.[650] This corresponds to about $^1/_3$ of the EU's natural gas consumption or the emissions of 200 million vehicles.[651] Per m^3 of flare gas, approx. 2.8 kg CO_2 equivalent are produced, or total emissions of approx. 400 Mt CO_2 equivalent. This assumes 98 % combustion by the flare, which is rarely achieved. Figure 218 shows the country shares of gas volumes disposed of via flares for the year 2017.

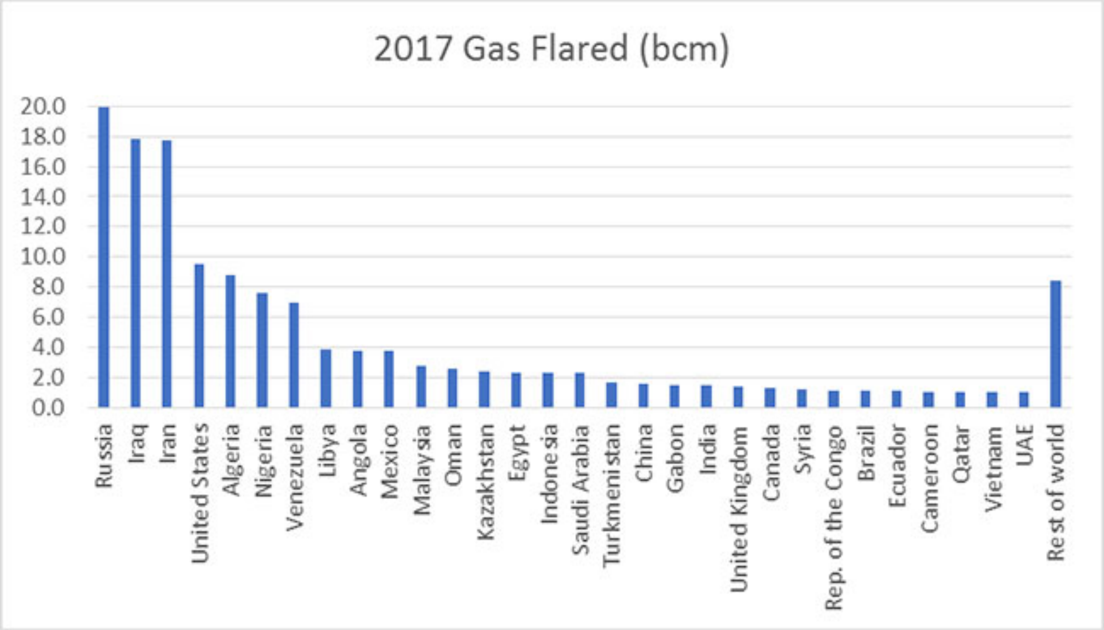

Figure 218: Gas volumes flared in 2017 (bcm)

Source: Tetratech, (2022).

By far the largest share is accounted for by Russia, Iran, Iraq, Algeria, Nigeria, Venezuela and the USA. They contribute 40 % of oil production, but 65 % of the amount of gas flared.[652]

Following the interruption of Russian gas supplies to Europe in 2022, the volumes of natural gas flared in Russia are currently expected to be significantly higher than those in Figure 214.

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[650] Cf. World Bank, (2022a).

[651] Cf. Aggreko, 2022; Duren & Gordon, (2022).

[652] Cf. World Bank, (2021).

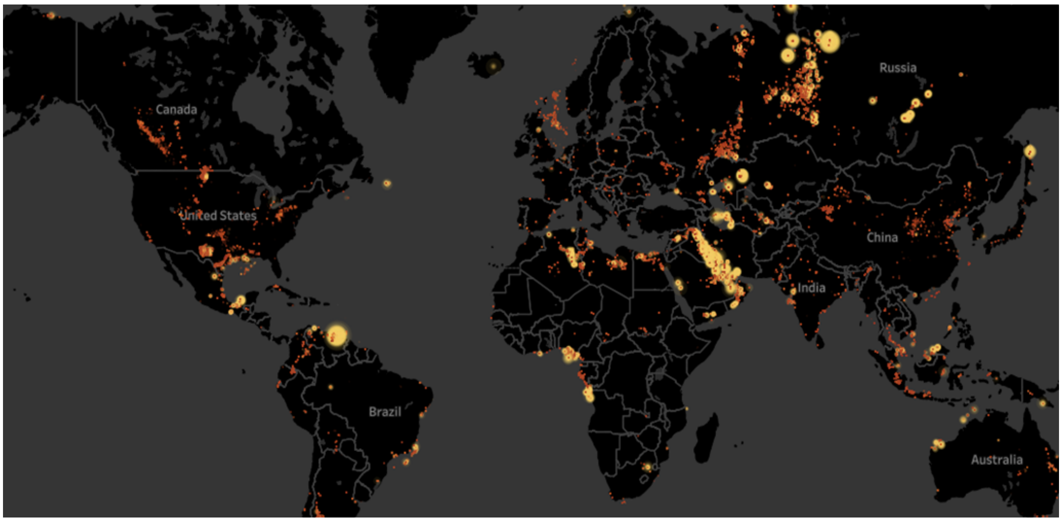

Figure 219: Global distribution of flares related to oil and gas production

Source: NOAA VIIRS Instrument, Skytruth.org

The global distribution of flares related to the production of natural gas and crude oil is shown in Figure 219.

The value of gas flared worldwide, based on the average gas price in 2018, is about 16 bn USD,[653] according to an IEA study for 2021 even 55 bn USD (at a gas price of 10 USD/MMBtU).[654]

2.12.3 Special case methane: residual gas flares

Since the climate impact of methane is 86 times or, in the long term, 28 times greater than that of CO_2 ("GWP_{20}" or "GWP_{100}"), the unburned portions of the flare gases and the many uncontrolled flares that are not in operation contribute significantly to climate gas emissions.

For decades it has been assumed, on the basis of a study by the American EPA in the 1980s, that 98 % of the hydrocarbons supplied are burnt in the flares.

Worldwide, it is estimated that of the approx. 400 Mt of total annual emissions (as CO_2 equivalent), at least 39 Mt are attributable to methane ("methane slip") with a correspondingly high climate impact.[594]

However, extensive analyses in 2020 and 2021 of three oil and gas fields in the USA showed average efficiencies of only about 95 % for flares in operation and, due to many flares being

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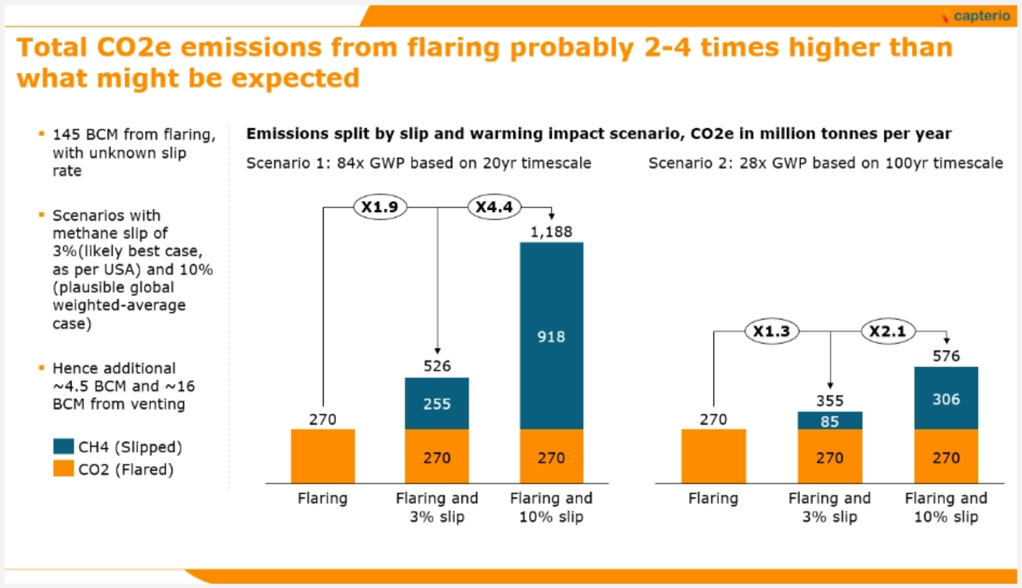
[653] Cf. Brainwave Energy, 2019
[654] Cf. Schulz et al., 2022

shut down, an overall efficiency of only 91 %, which means many times more methane emissions than assumed for an efficiency of 98 % (see Figure 220). [655]

The interruptions in the supply of Russian natural gas in connection with the Ukraine war suggest that at times large quantities of methane were flared uncontrollably and incompletely. Estimates based on satellite images assume more than 4 million m^3/day. [656]This corresponds to a daily emission of 2,900 t/methane and 250,000 t CO_2 equivalent ("GWP_{20}").


Total CO2e emissions from flaring probably 2-4 times higher than what might be expected

- 145 BCM from flaring, with unknown slip rate
- Scenarios with methane slip of 3%(likely best case, as per USA) and 10% (plausible global weighted-average case)
- Hence additional ~4.5 BCM and ~16 BCM from venting

Figure 220: Actual CO_2 emissions from flare gases as a function of methane slip.

Source: Flareintel, (2019).

Figure 221 shows satellite images of large flares at a Gazprom compressor station on the Nordstream 1 pipeline near the Finnish-Russian border, taken on 24.8.2022.

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[655] Cf. Plant et al., 2022

[656] Cf. Reuters report, August 26, 2022 www.zdf.de/nachrichten/wirtschaft/russland-fackelt-gas-ab-gazprom-ukraine-krieg,

Figure 221: Satellite image of natural gas flaring at Portovaya near St. Petersburg on 24.8.2022.

Source: EU, (2022).

2.12.3.1 Reduction of emissions from the residual gas flares

If international targets and agreements to reduce net emissions of greenhouse gases to zero in 2050 were implemented, hydrocarbon flaring, excluding nuisance flaring, would have to be reduced by 90 % by 2030.

The World Bank's zero-routine-flaring (ZRF) initiative, launched in 2015, is expected to make the largest contribution. The World Bank's Global Gas Flaring Reduction Partnership (GGFR) has been joined by countries and companies that, as things stand, account for around 60 % of the gases flared.[657]

Norway is the most advanced, with a flare efficiency of almost 99 % and a regulatory framework that has reduced flare emissions by 80 % since its introduction about 30 years ago.

In the USA, flaring of associated gases is now banned in some states, including Colorado, New Mexico and Alaska.

From the IEA's point of view, underutilised pipelines from North Africa could be used for Europe to take up to 15 bn m^3/a of associated gases from oil and gas fields that are currently flared. An additional potential of 10 bn m^3/a is seen in the LNG supply chain, totalling about 7 % of European natural gas consumption in 2021.

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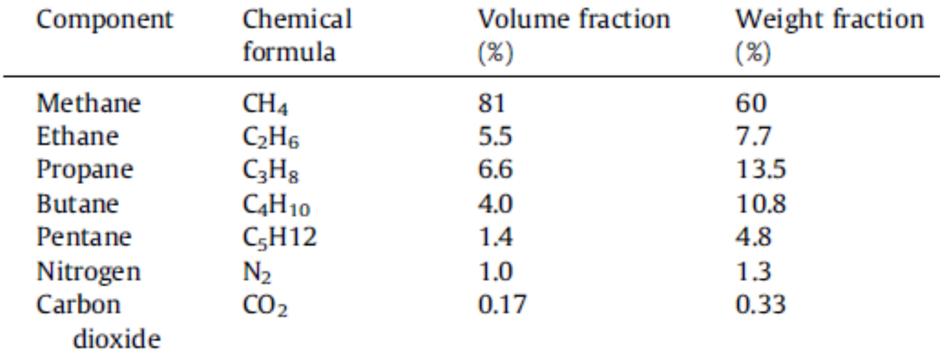
[657] Cf. World Bank, 2022b.

2.12.3.2 Construction of a flare gas collection system

Flare gases consist predominantly of methane, with smaller proportions of higher hydrocarbons and low contents of intergases (nitrogen, CO_2), a typical analysis is shown in Table 51.[658]

Table 51: Typical composition of a flare gas.



Component	Chemical formula	Volume fraction (%)	Weight fraction (%)
Methane	CH_4	81	60
Ethane	C_2H_6	5.5	7.7
Propane	C_3H_8	6.6	13.5
Butane	C_4H_{10}	4.0	10.8
Pentane	C_5H12	1.4	4.8
Nitrogen	N_2	1.0	1.3
Carbon dioxide	CO_2	0.17	0.33

Figure 222 shows the typical layout of a plant for the collection and flaring of associated and residual gases from an oil production facility.[659] The gas piped to the flare comes from the entire processing chain.[660]

The high methane content of flare gases, which can be over 95 %, argues for both material and energy use. The economic viability of an investment depends on any conditioning that may be required, the quantity of gas and also the possibility of collecting the gas regionally and processing it in larger units.

In any case, alternative use leads to a saving of raw materials for fossil-based products or a saving of energy as well as to lower emissions of the particularly effective greenhouse gas methane.

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[658] Cf. Ojijiagwo et al, (2016).
[659] Cf. Aregbe, (2017).
[660] Cf. DoE presentation, taken from Enverus, n.d.

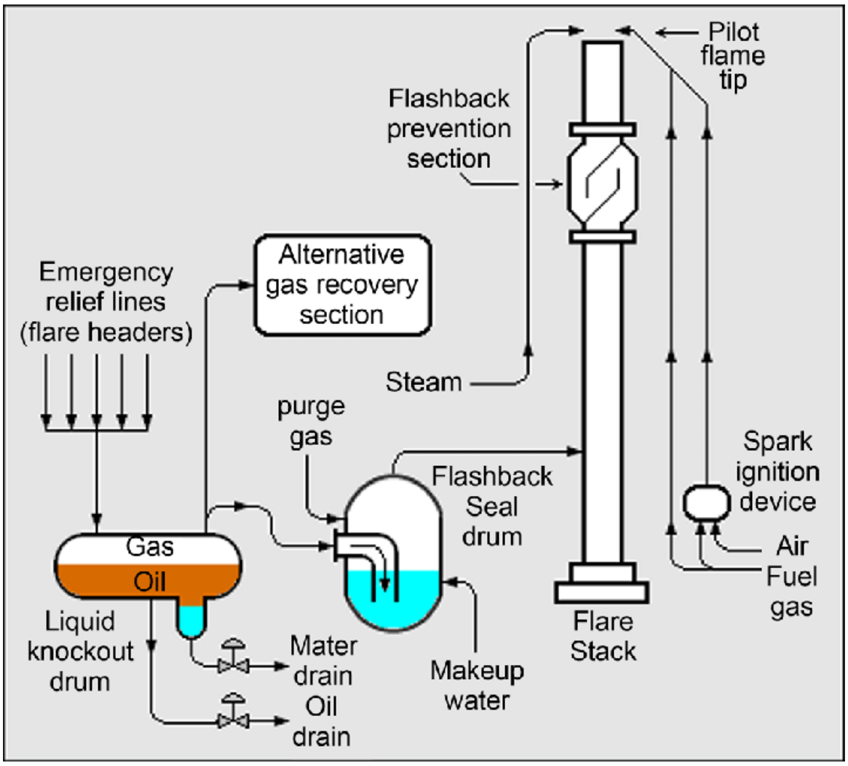
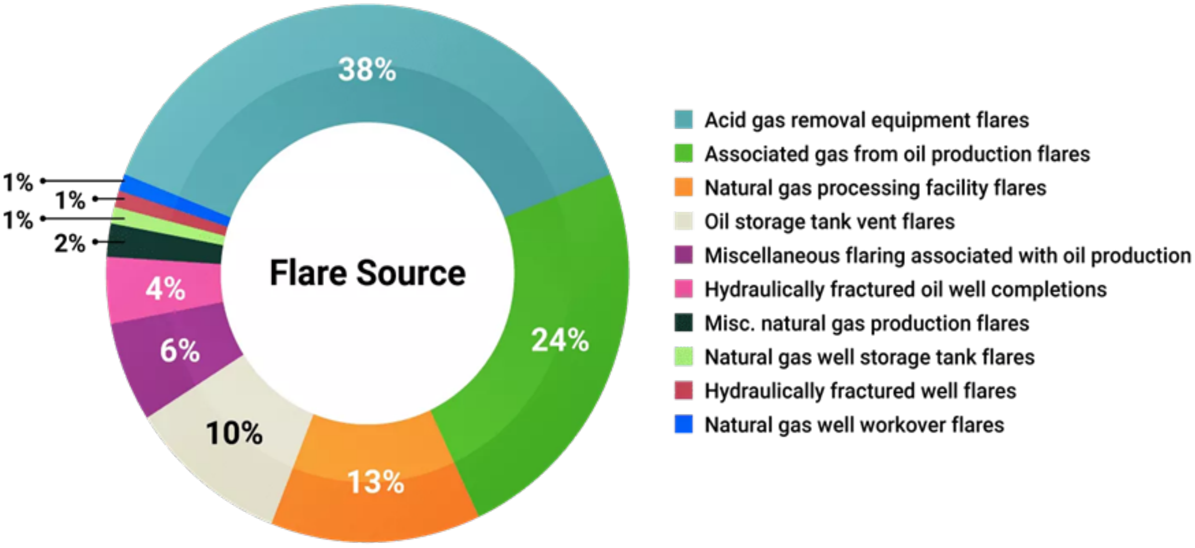


Figure 222: Structure of a flare system.

Source: Enverus (0.J.).



Source | US Department of Energy

Figure 223: Origin of the flare gases during the production of crude oil.

Source: Enverus, n.d.

2.12.3.3 Utilisation options and potential for flare gases from oil and gas processing

On-site use

The main objective is to avoid flaring in the sense of the World Bank's GGFR initiative by 2030. In addition to process optimisations of the production facilities and improving the efficiency of the flares, this is often done by on-site compression and returning the gases to the well. The aim here is to increase the production rate and ultimately to store the residual gases while avoiding major investments.

Energy use (on- or off-site)

Especially in the case of decentralised utilisation of the flare gas at the respective plant, the generation of electrical energy, e.g. with gas engines or turbines, is in the foreground. This type of utilisation is state of the art and is also widely used in biogas plants. Typical efficiencies are 34 – 55 % (thermal) and 28 – 47 % (electrical). Combined efficiencies in the range of 85 – 90 % are achieved in a combined heat and power plant.

The energy content of the flare gas is approx. 9 kWh/m^3 , which is divided accordingly into the thermal and electrical components.

Assuming that the 144 bn m^3 of flare gas produced worldwide in 2021 is completely converted into electricity, this results in a currently unused potential of 400 – 680 TWh of electrical energy (plus 490 – 790 TWh of waste heat).

A large proportion of the flares are located near natural gas pipelines (see Illustration 224),[661] which suggests feeding the methane-rich residual gases into the natural gas grid with manageable investments. Corresponding programmes are being launched, especially in the USA.

Another option is to use it as Compressed Natural Gas (CNG). Corresponding distribution networks are under construction, especially in the USA, with CNG being distributed via a "virtual pipeline system" (road transport).

Fuelling vehicles with CNG requires a corresponding infrastructure. For example, there are only 2,000 CNG filling stations in the USA and 800 in Germany, and the vehicle market is underdeveloped.

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[661] Cf. Flareintel, (2022).

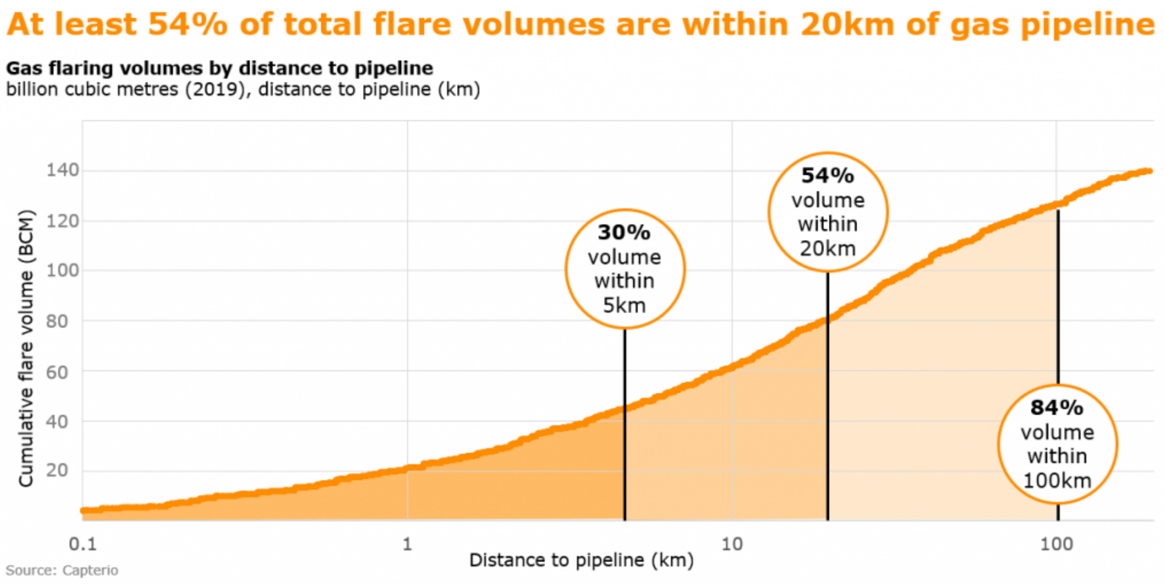

Illustration 224: Availability of natural gas pipelines for flare gas injection.

Source: H_2 -Industries, (2022)

Decentralised, partly container-based plants are under development that produce hydrogen and elemental carbon from flare gases via pyrolysis.[662] The addition of hydrogen produced in this way is to be tested for the first time at a 49 MW natural gas peak load power plant in England.

Other possible uses as an energy source include the energy-intensive production of cement and fertiliser.

2.12.3.4 Material use

Due to the composition of the flare gases, they can be used or mixed with all common conversion processes for which natural gas is also used. The key is appropriate logistics via pipelines or virtual pipelines for transport to plants with a corresponding economy-of-scale.

The products include hydrogen, ammonia and methanol via the intermediate synthesis gas stage.

For example, the annual 144 bn m^3 currently flared would be equivalent to 150 – 180 Mt of methanol annually (100 – 120 mega-methanol plants of 5,000 t/day each), i.e. more than the current global production capacity of 160 Mt (2021).[663]

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[662] Cf. PM HiiROC, (2022); H_2 -Industries, (n.d.).

[663] Cf. Statista (2022n)

2.12.4 Nitrogen oxides (laughing gas) as a greenhouse gas

Nitrogen oxides, especially nitrous oxide (N_2O), are the third most important (long-lived) greenhouse gas after CO_2 and methane (CH_4). Figure 225 shows the percentage distribution in the form of CO_2 equivalents.[664]

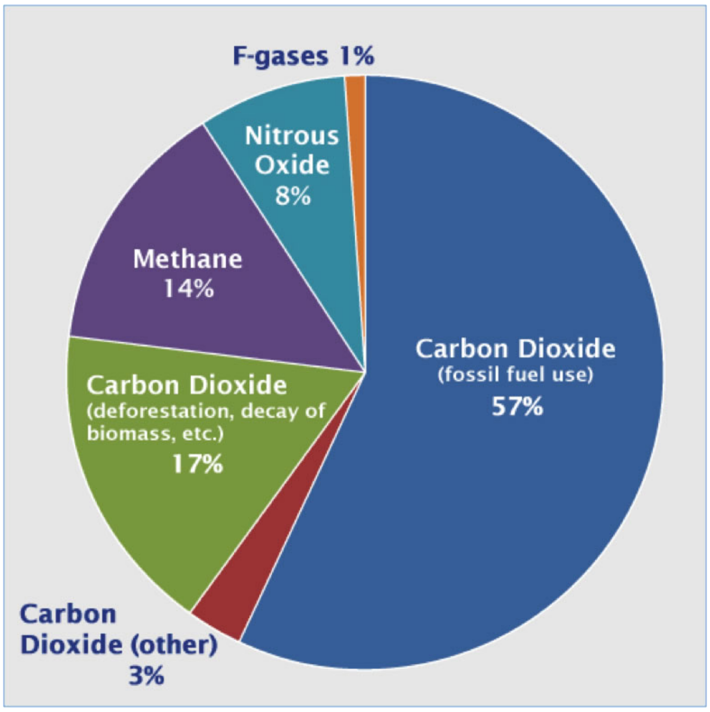

Figure 225: Percentage distribution of important climate gases.

Source: IPCC Report (2014).

Nitrous oxide has about 310 times the climate impact of CO_2, compared to methane, which has 21 times the climate impact.[665]

The residence time of nitrous oxide in the atmosphere is approx. 120 years (compared to CO_2: > 1,000 years, CH_4: approx. 10 years), so it accumulates in the atmosphere like CO_2. The nitrous oxide concentration in the atmosphere has increased exponentially compared to pre-industrial times to currently approx. 335 ppb (cf. Figure 226[666] and Figure 227[667]).

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[664] Cf. IPCC (2014)

[665] Related to GWP 100

[666] Cf. CSIRO (n.d.)

[667] Cf. Federal Environment Agency (n.d.)

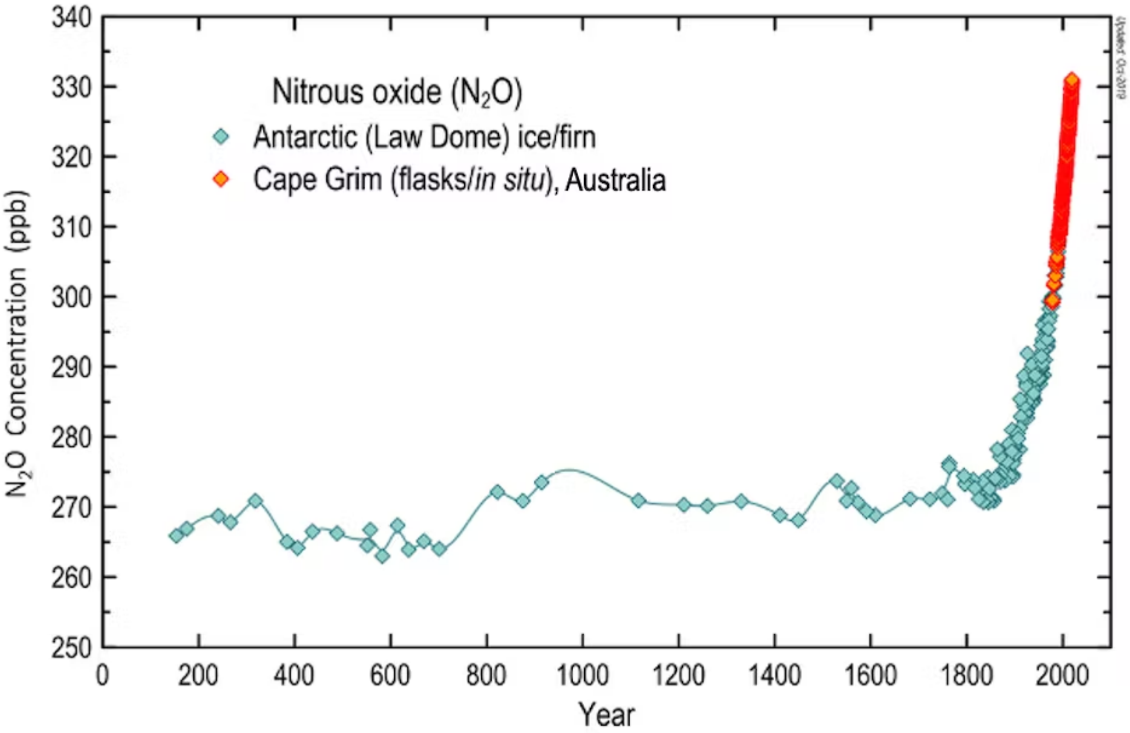

Figure 226: Long-term development of nitrous oxide concentration in the atmosphere in ppb.

Source: CSIRO (n.d.).

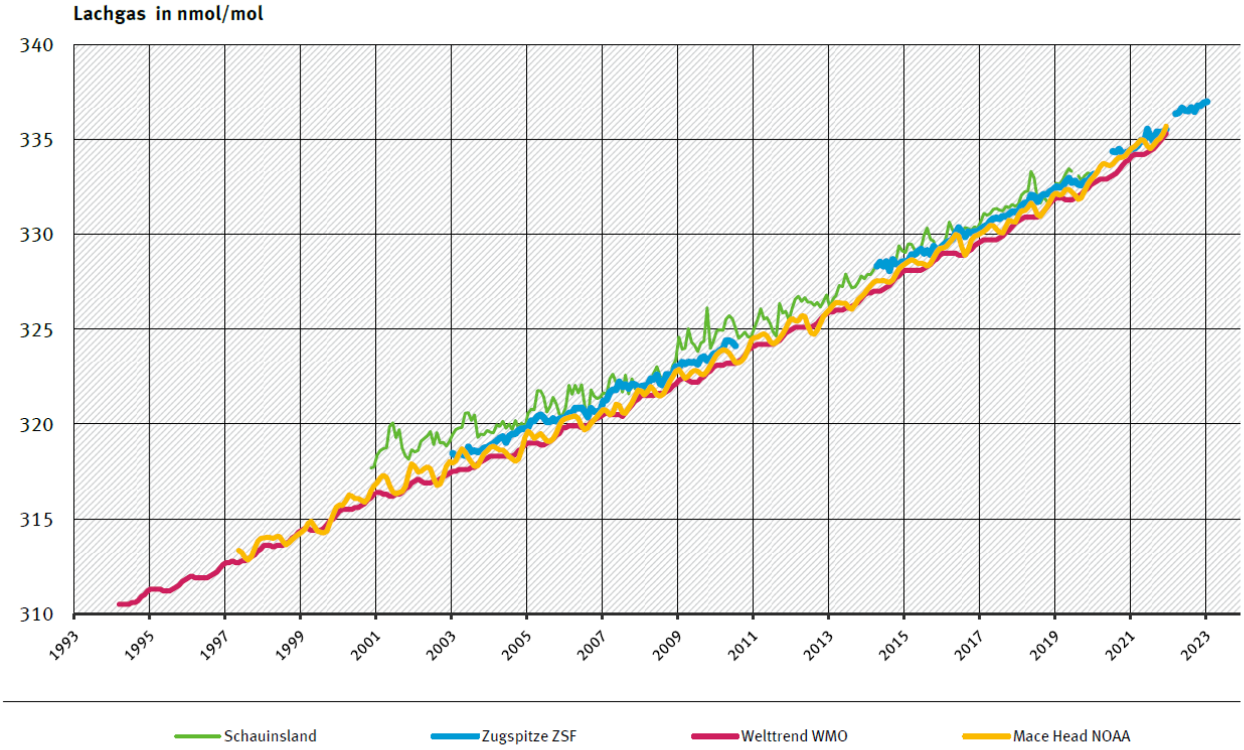

Figure 227: Development of nitrous oxide concentrations in the atmosphere (monthly mean values) from 1993 to 2023.

Source: Federal Environment Agency (n.d.).

Of the approx. 17 Mt of nitrous oxide emissions worldwide each year, approx. 7.3 Mt (approx. 43 %) are anthropogenic in nature, the majority of which come from agriculture through the increasing use of inorganic and organic nitrogen fertiliser.

Geographically, in the period from 1980 to 2016, anthropogenic nitrous oxide emissions occurred mainly in East and Southeast Asia and Africa (see Figure 228) – a sign of the intensification and expansion of agriculture associated with increasing fertiliser use.

Only in Europe are nitrous oxide emissions decreasing, due to stricter exhaust gas limits in both industry and agriculture.

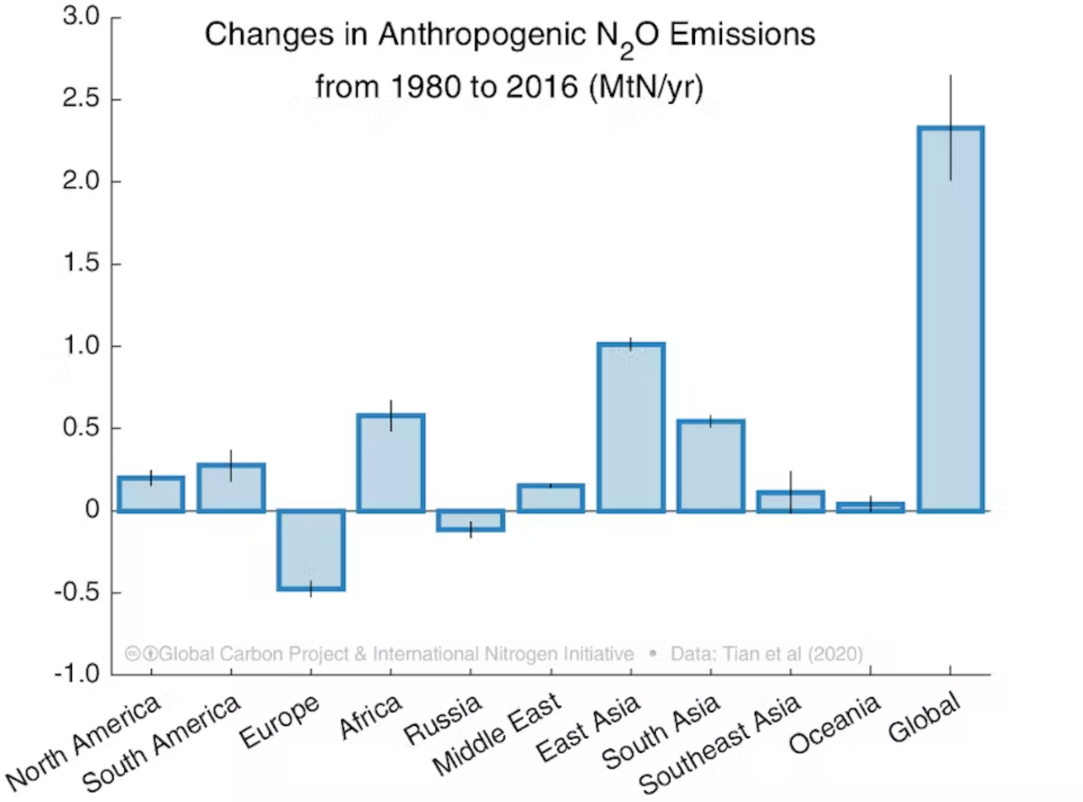

Figure 228: Regional changes in anthropogenic nitrous oxide emissions 1980-2016.

Source: Tian (2020.) [668]

The example of the USA is shown in Figure 229, the percentage distribution of nitrogen oxide emissions in 2019, with agricultural emissions dominating at 75 %, compared to other (anthropogenic) sources such as wastewater and manure treatment, transport, chemicals and stationary power generation.[669]

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[668] Cf. Tian (2020)
[669] Cf. EPA (2021)

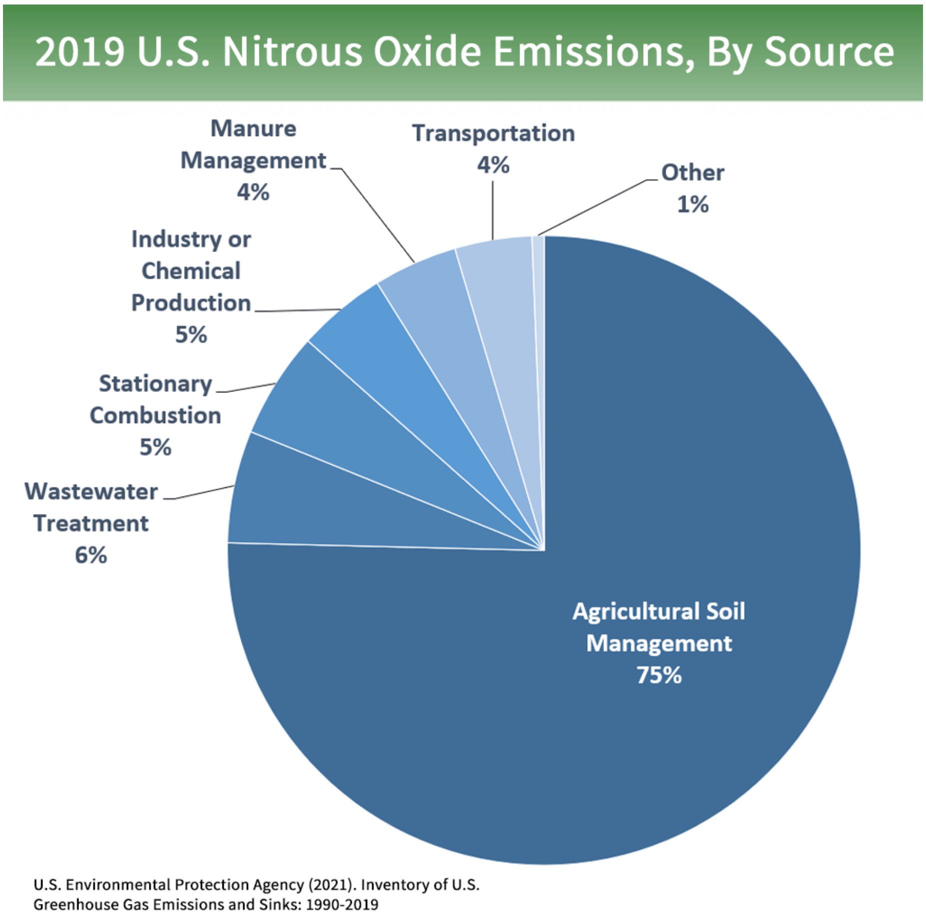

Figure 229: Percentage distribution of nitrous oxide emissions in the USA.

Source: EPA (2021).

As part of the Global Carbon Project, a balance sheet for nitrous oxide from anthropogenic and natural sources was drawn up for the period 2007 – 2016, and the sinks in the atmosphere were shown (see Figure 230). The concentration of nitrous oxide is shown in the form of nitrogen (N). According to this, the atmosphere accumulates 4.3 Mt N annually as a result of the long residence time of nitrous oxide. This compares with the concentration shown in Figure 228 This also indicates a certain accumulation of nitrogen oxides and nitrous oxide in the atmosphere as a result of the long residence times.

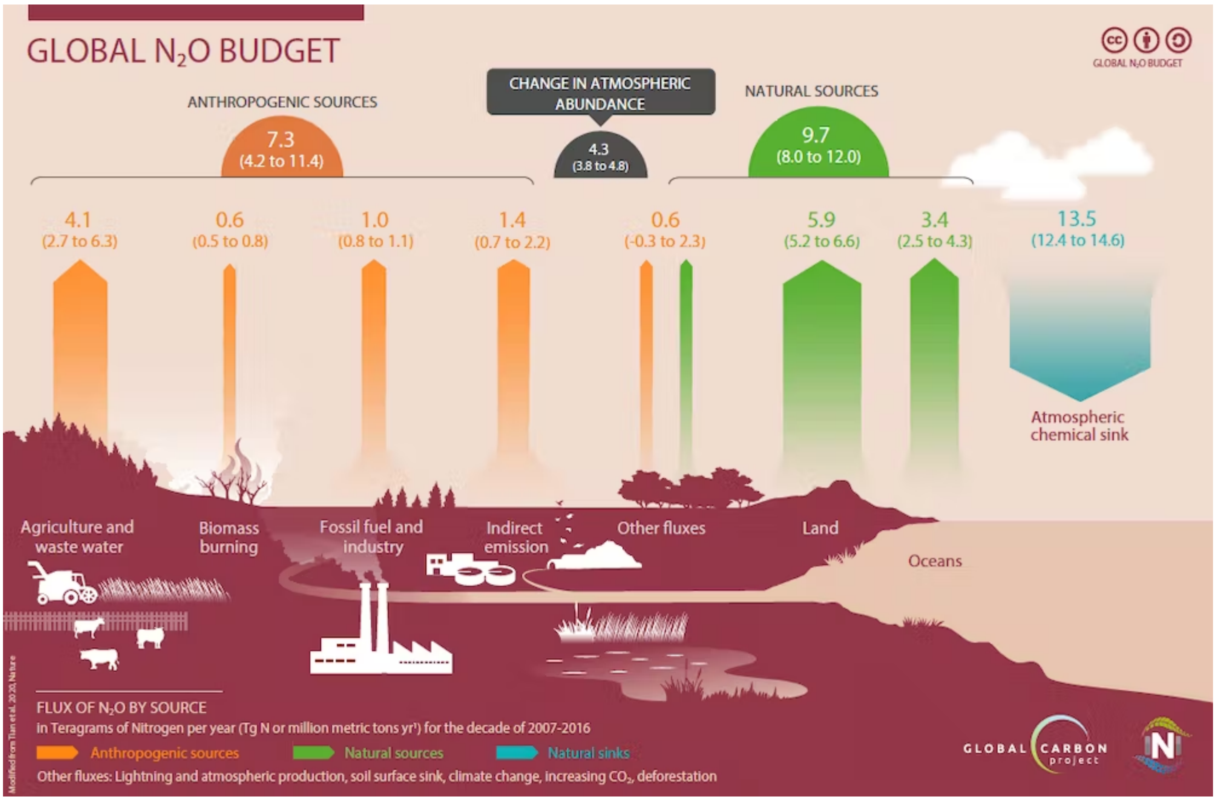

Figure 230: Nitrous oxide balance in the period 2007 – 2016.

Source: Tian (2020).

2.12.4.1 Options for reducing nitrogen oxide emissions

Agriculture

Agriculture is by far the dominant source of nitrogen oxide emissions and the most difficult to limit. Nitrous oxide is produced by the use of inorganic (artificial) fertiliser and organic manure (including slurry) through a nitrification/denitrification cycle, as shown in Figure 231 and Figure 232 schematically. Thus, a maize plant takes up approx. 50 % of the nitrogen introduced, microbes in the soil another 25 %, while 25 % lead to nitrogen oxide emissions via leaching processes and denitrification or nitrification reactions in addition to nitrate accumulation in the soil.

Important countermeasures are the more targeted and at the same time more economical use of artificial fertilisers as well as organic fertilisers and slurry, and increased cultivation of nitrogen-fixing plants such as clover, field beans and lupins, also in alternating crop rotation with other plants.

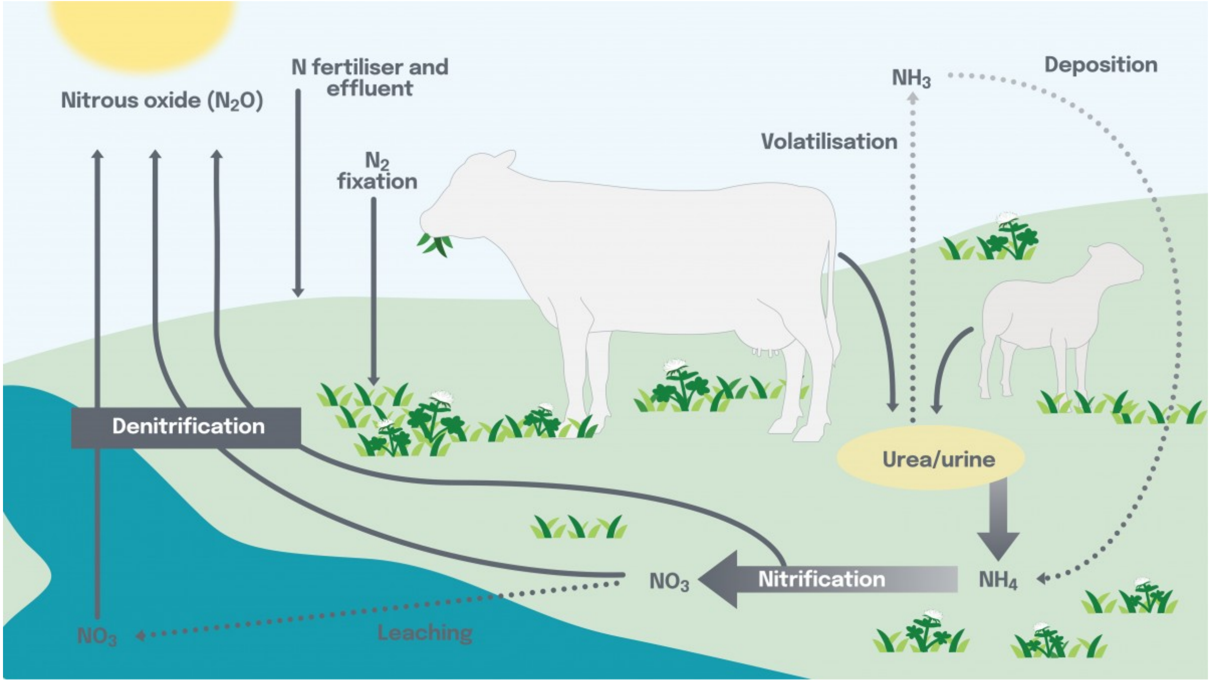

Figure 231: Nitrous oxide formation via nitrification/denitrification in soil.

Source: NZ (2021).

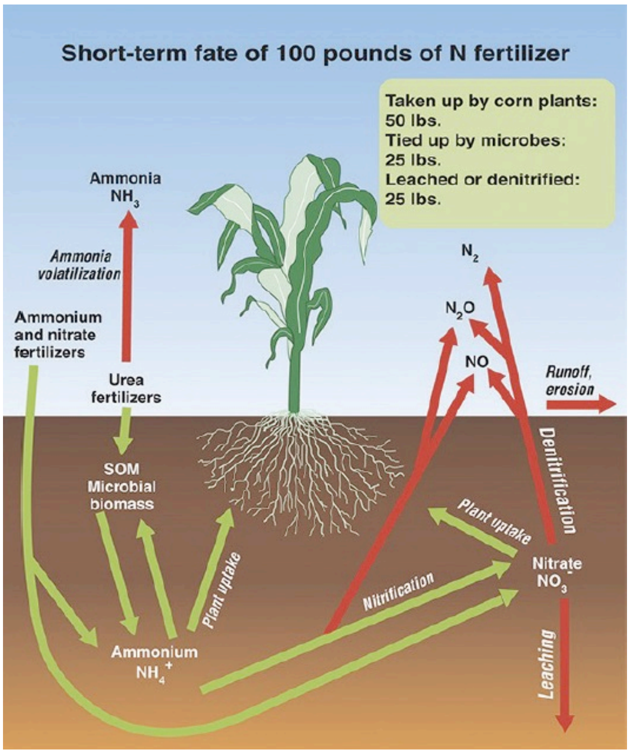

Figure 232: Nitrogen utilisation using maize as an example.

Source: Millar (2014).

Combustion processes

The source of nitrogen oxide emissions are combustion plants of all types and engines. In addition to efficiency measures such as primary combustion technology measures, secondary measures in the exhaust gas flow are primarily used to achieve exhaust gas limits. In selective catalytic nitrogen oxide reduction (SCR), the nitrogen oxides react with metered ammonia or urea to form elemental nitrogen N_2. This is largely state of the art, although it is constantly being further developed to achieve stricter limit values.

Ammonia as an energy source

In the context of the increased use of ammonia as a carbon-free energy source, e.g. in turbines and ship propulsion systems, the control of nitrogen oxide emissions is taking on a new, strong significance. Here, too, mainly catalytic SCR processes[670] are used, which clean the exhaust gas by converting the nitrogen oxides with added ammonia.

Industry

A historically large source of nitrogen oxide emissions was the production of nitric acid and adipic acid, among others. The latter is a precursor for nylon and is also used, among other things, in the food industry as an acidifier and in flue gas scrubbing to increase the efficiency of sulphur separation. The aforementioned catalytic flue gas cleaning processes are also used here. In Germany, for example, adipic acid production was responsible for almost one-third of nitrous oxide emissions until 1997, but only about 3 % in 2017.[671]

Conclusion

Nitrogen oxides, here mainly nitrous oxide, is the third most important long-lived climate gas after CO_2 and methane. The anthropogenic share of total global nitrogen oxide emissions is over 40 %.

The main source of anthropogenic emissions is the use of inorganic and organic fertilisers in an agriculture that is growing and becoming increasingly intensive to ensure food security. Geographically, emissions are increasing especially in the countries with the highest population growth in Asia and Africa.

A limitation is possible if the methods for the targeted use of fertiliser, including the recycling and control of manure and other wastewater, which have been successful in the example of

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[670] SCR: Selective Catalytic Reduction

[671] Cf. Federal Environment Agency (n.d. a)

European countries, are also introduced in other regions. The cultivation of nitrogen-fixing plants as part of a fertiliser-saving crop rotation can make an additional contribution.

Other emission sources can be controlled by technical measures such as selective catalytic reduction with ammonia (SCR).

SCR processes will become increasingly important with the predicted widespread use of ammonia as an energy source in combustion processes.

2.12.5 Hydrogen as a greenhouse gas

In the context of the development of large global production capacities for hydrogen with corresponding logistics and new fields of application, the question of the potential impact of hydrogen as a climate gas arises.

Since hydrogen does not absorb infrared radiation, its effect on the climate is only indirect through interaction with other components of the upper atmosphere.

Hydrogen is a particularly volatile and permeable gas that rises quickly into the upper layers of the air and influences sensitive balances there by forming water or reacting with other gases. Thus, hydrogen emissions have a particular impact on other climate gases such as carbon dioxide and methane.

Already in 2003 and 2005, the risk was pointed out that larger hydrogen emissions could cause ozone depletion, but also a cooling of the stratosphere as a result of the water formed in the form of cloud formation.[672, 673, 674]

The global shift to a hydrogen economy will therefore place higher demands on minimising emissions in the future, especially those caused by leakage. "Best practice" standards for technical measures are needed to limit losses throughout the supply chain.

2.12.5.1 Hydrogen in the upper atmosphere

Atmospheric depletion of hydrogen occurs through reaction with hydroxyl radicals as the basic reaction for the indirect climate effect with several subsequent reactions. Figure 233 shows this schematically.[675]

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[672] Cf. Löfken, (2003)
[673] Cf. Tromp, (2003)
[674] Cf. Jacobson (20 05)
[675] Cf. Ocko, (2022)

Methane degradation in the troposphere through reaction with hydroxyl radicals to ultimately water and CO_2 is slowed by the competing reaction of methane with hydrogen, thus increasing the climate impact of methane emissions.

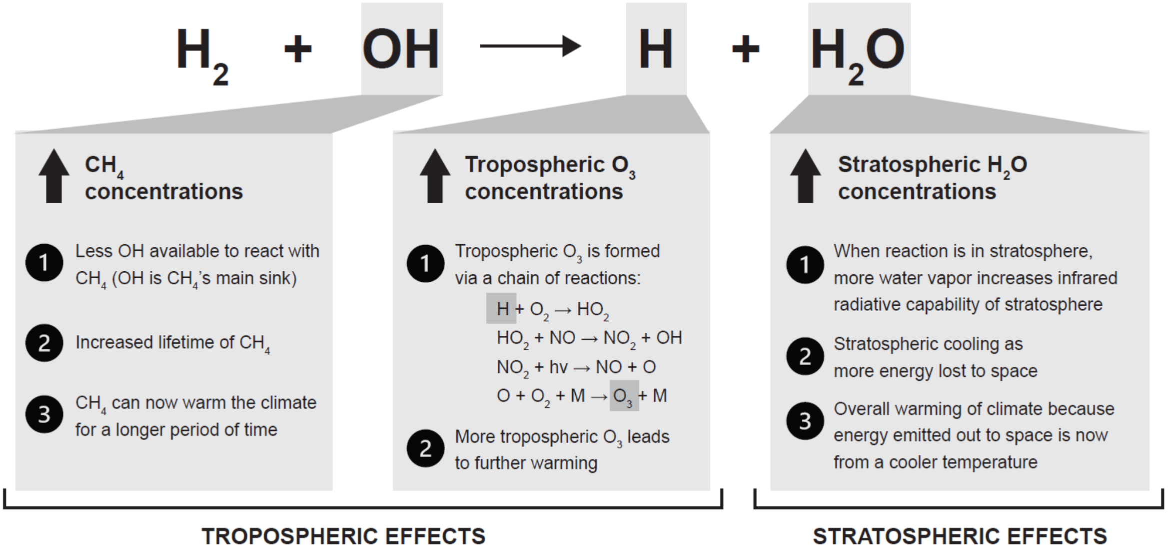

Figure 233: Reactions of hydrogen in the upper atmosphere.

Source: Ocko (2022).

Hydrogen radicals, which are formed from hydrogen by reaction with hydroxyl radicals, promote the formation of ozone in a reaction chain with nitrogen oxides and thus additional heating and delayed reduction of the ozone hole.

The increase in water vapour concentration in the stratosphere leads to cooling effects, increased cloud formation and reduced radiation as well as an increase in ozone formation.

2.12.5.2 Climate impact of hydrogen compared to CO_2

Extensive research by the Federal Environment Agency (UBA) on the greenhouse gas effect of hydrogen yields the figures shown in Table 52 in comparison with CO_2.[676]

Recent studies by Warwick et al.[677] and Ocko et al.[675] agree that the global warming potential of hydrogen is about twice as high as previously assumed and that over a period of 100 years, one tonne of hydrogen in the atmosphere warms the Earth about eleven times more than one tonne of CO_2.

Table 52: Greenhouse gas potential of hydrogen.

Source: Riemer (2022)

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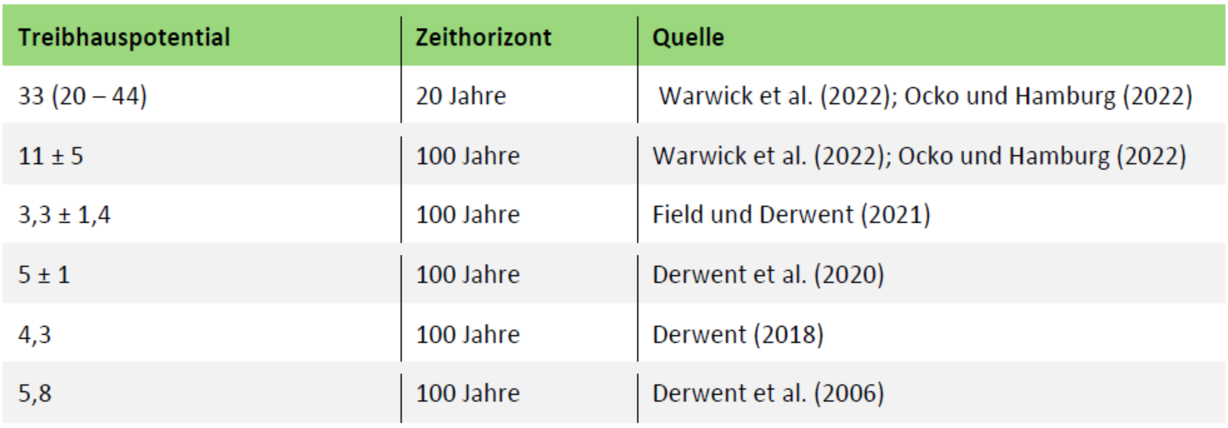
[676] Cf. Riemer, (2022)
[677] Cf. Warwick (2022)



Treibhauspotential	Zeithorizont	Quelle
33 (20 – 44)	20 Jahre	Warwick et al. (2022); Ocko und Hamburg (2022)
11 ± 5	100 Jahre	Warwick et al. (2022); Ocko und Hamburg (2022)
3,3 ± 1,4	100 Jahre	Field und Derwent (2021)
5 ± 1	100 Jahre	Derwent et al. (2020)
4,3	100 Jahre	Derwent (2018)
5,8	100 Jahre	Derwent et al. (2006)

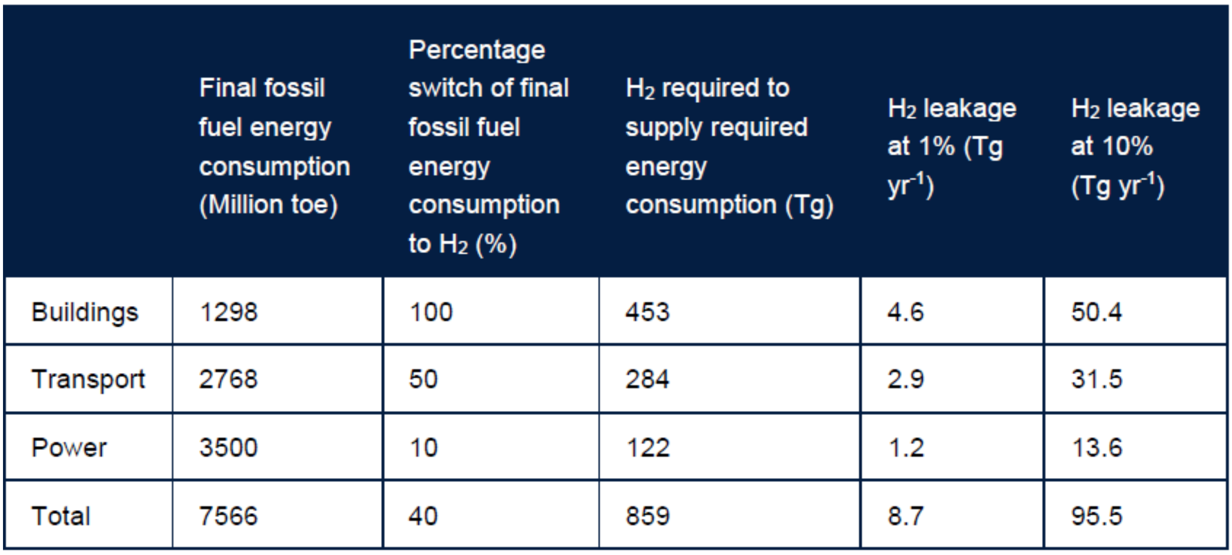
2.12.5.3 Scenarios for hydrogen emissions

The magnitude of hydrogen emissions, their development over time and the measures to limit emissions through technical measures can currently only be roughly estimated and outlined through assumptions.

Warwick et al.[677] base their estimate on a global energy demand of about 7,566 Mt oil equivalent (based on 2018) in the building, transport and power generation sectors. This comprises about 75 % of the total global energy demand.

Depending on the use sector, an energy carrier is switched in the model to an assumed hydrogen share, see Table 53.

Table 53: Hydrogen emissions per sector at 1 % and 10 % assumed leakage (Warwick model (2022)).



	Final fossil fuel energy consumption (Million toe)	Percentage switch of final fossil fuel energy consumption to H_2 (%)	H_2 required to supply required energy consumption (Tg)	H_2 leakage at 1% (Tg yr^{-1})	H_2 leakage at 10% (Tg yr^{-1})
Buildings	1298	100	453	4.6	50.4
Transport	2768	50	284	2.9	31.5
Power	3500	10	122	1.2	13.6
Total	7566	40	859	8.7	95.5

This results in a hydrogen demand of 859 Mt H_2. Assuming 1 % and 10 % leakage, this corresponds to annual hydrogen emissions of 8.7 Mt and 95.5 Mt, respectively.

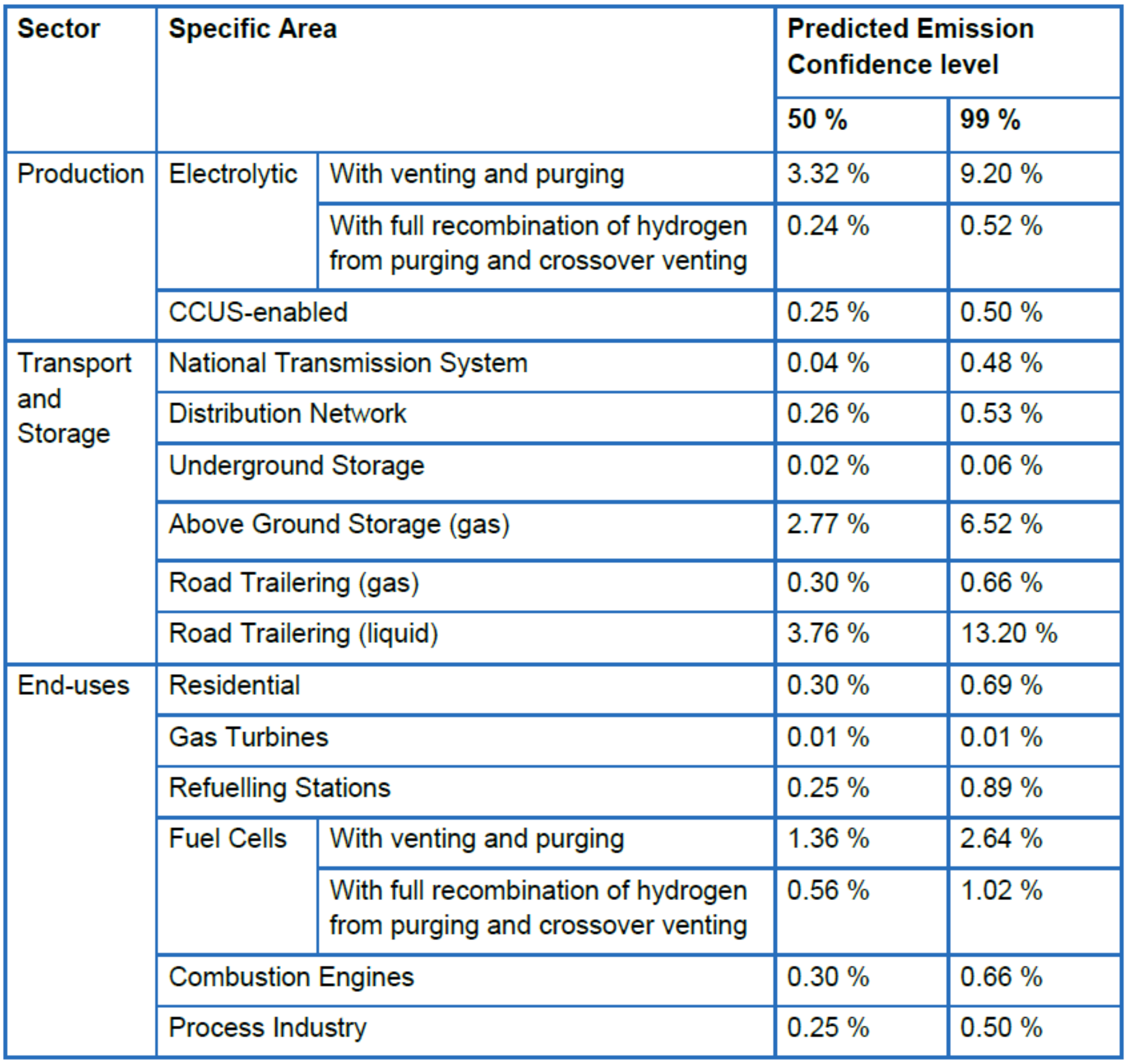
For comparison: today's amount of hydrogen in the atmosphere is approx. 89 Mt.[678]

2.12.5.4 Leakage

In a study prepared in and for the UK[679] leakage rates for the entire chain of hydrogen production (electrolysis or grey with CCS) via transport and distribution to consumers were investigated, which at the same time also show the potential for measures to limit losses, see Table 54.

Table 54: Estimation of hydrogen leakage along the utilisation chain.

Source: Frazer Nash Consultancy, (2022).



Sector	**Specific Area**		**Predicted Emission Confidence level**	
			50 %	**99 %**
Production	Electrolytic	With venting and purging	3.32 %	9.20 %
		With full recombination of hydrogen from purging and crossover venting	0.24 %	0.52 %
	CCUS-enabled		0.25 %	0.50 %
Transport and Storage	National Transmission System		0.04 %	0.48 %
	Distribution Network		0.26 %	0.53 %
	Underground Storage		0.02 %	0.06 %
	Above Ground Storage (gas)		2.77 %	6.52 %
	Road Trailering (gas)		0.30 %	0.66 %
	Road Trailering (liquid)		3.76 %	13.20 %
End-uses	Residential		0.30 %	0.69 %
	Gas Turbines		0.01 %	0.01 %
	Refuelling Stations		0.25 %	0.89 %
	Fuel Cells	With venting and purging	1.36 %	2.64 %
		With full recombination of hydrogen from purging and crossover venting	0.56 %	1.02 %
	Combustion Engines		0.30 %	0.66 %
	Process Industry		0.25 %	0.50 %

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[678] Cf. Pieterse (2013)

[679] Cf. Frazer Nash Consultancy, (2022)

The high losses during hydrogen production by electrolysis, due to start-up and shut-down, switching and rinsing processes, as well as the losses during liquid transport are conspicuous here.

Estimates suggest that hydrogen emissions from leakage could have a climate effect (which can certainly be described as a "worst case") of up to 0.15 – 0.35 °C based on 3,000 teragrams = 3 Gt of hydrogen and 10 % leakage rates, see Figure 234.

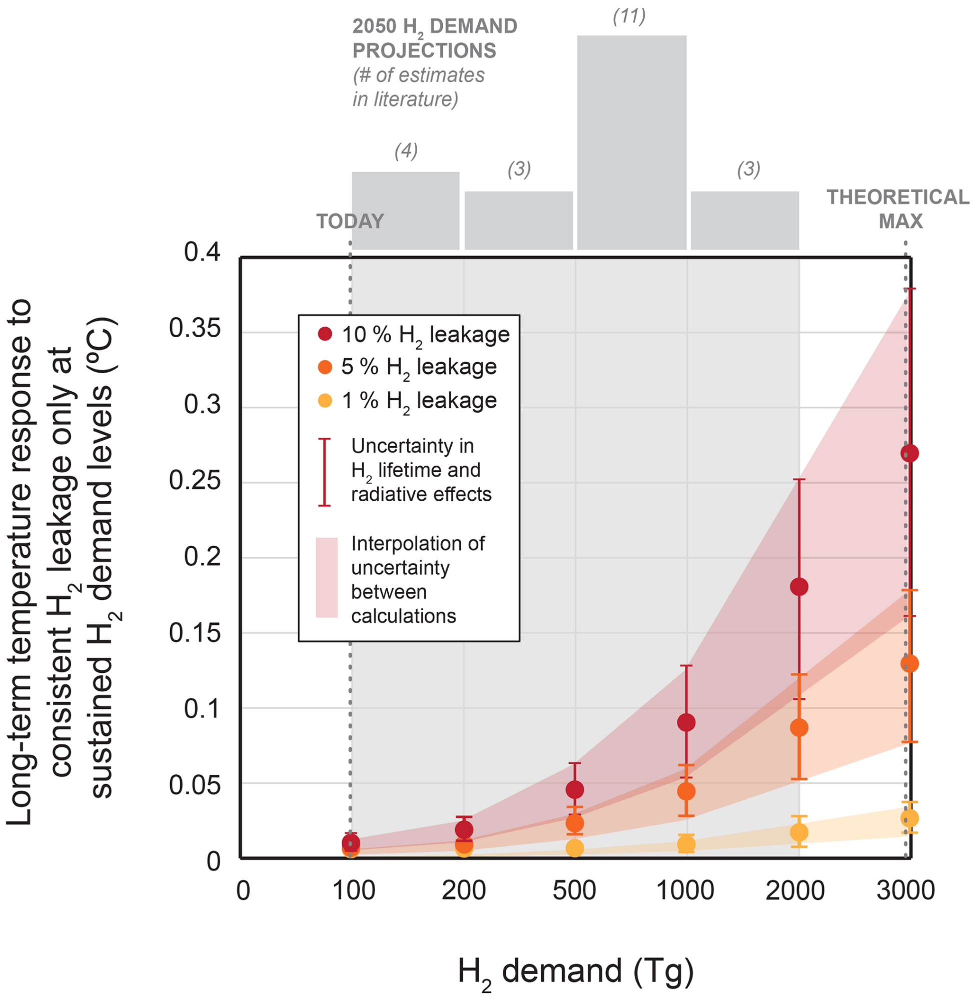

Figure 234: Estimated climate effect of hydrogen emissions depending on production volume and leakage rate. Source: S&P (2023).

2.12.5.5 Conclusion: Relevance of hydrogen emissions

Knowledge about the climate impact of hydrogen is extremely limited so far, but could become relevant as hydrogen production and the associated supply and handling chains expand.

It is certain that hydrogen has an 11-fold (based on 100 years) and probably approx. 30-fold (based on 20 years) greenhouse gas potential compared to CO_2.

Hydrogen is an indirect climate gas. It reacts in the upper atmosphere to form water vapour (with a corresponding shielding effect) and promotes ozone depletion. It also reacts with the molecule that is largely responsible for the decomposition of methane, so that methane molecules remain in the atmosphere for a longer time and have a higher warming effect.

All previous models show a hydrogen concentration in the atmosphere of a few ppm. The influence of the indirect climate effect of hydrogen on global warming cannot be determined at present.

Generally accepted "best practices" or standards for reducing emissions, especially from the main sources of electrolysis and liquid H_2 transport, do not currently exist.

The technically induced and controllable hydrogen losses are estimated to be in the single-digit percentage range and up to 10 % for electrolysis.

However, the general idea that the production and use of hydrogen, especially electrolysis hydrogen, is climate-neutral is wrong.

Overall, it can be assumed that additional climate effects from hydrogen are comparatively small and that the positive effects from the increased use of hydrogen and the associated reduction in emissions of other greenhouse gases such as CO_2 and methane outweigh the negative effects.

In this context, it is astonishing that hydrogen is not included in the list of climate gases of the Paris Climate Agreement and is therefore not included in the individual climate balances.