Background informal technical document on techniques to reduce methane emissions in Europe from landfill gases, the natural gas supply system and biogas facilities

TFTEI background informal technical document

December 2020

Prepared by KIT DFIU - TFTEI Technical Secretariat

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List of Abbreviations / Acronyms

BAT	Best Available Technique
BREF	Best Available Technique Reference Document
CHP	Combined Heat and Power
DOC	Dissolved Organic Carbon
FID	Flame Ionization Detection
FOD	First-Order Decay
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
LFG	Landfill Gas
LRTAP	Long-range Transboundary Air Pollution
LDAR	Leak Detection and Repair
LCA	Life-Cycle-Assessment
LNG	Liquified Natural Gas
MSW	Municipal Solid Waste
OECD	Organisation for Economic Co-operation and Development
PM	Particulate Matter
TFTEI	Task Force on Techno-Economic Issues
TFRN	Task Force on Reactive Nitrogen
UNFCCC	United Nations Framework Convention on Climate Change
OECD	Organisation for Economic Co-operation and Development

Executive Summary

This document was prepared by the TFTEI Technical Secretariat as a first overview of relevant methane emissions in Europe and related mitigation and abatement techniques. Starting with a general description of methane emissions and the importance of methane as a greenhouse gas and an air pollutant, the document provides information on the most important non-agricultural sources of methane emissions and techniques applied to reduce these emissions. This includes information on landfill gas emissions and techno-economic analyses of landfill gas collection and utilization system. Furthermore, a brief overview of the European natural gas grid and associated emissions along the entire value chain is provided. Beside technical aspects of emission reduction through e.g. the application zero emitting pneumatic and compressor systems, more management related measures such as the reduction of maintenance emissions and inspection programs to early identify fugitive emissions, also referred to as leak detection and repair (LDAR) are of key importance to reduce methane emissions form the natural gas supply system. Subsequently, this report provides an outlook on methane emissions from biogas plants which is also considered as an important source of methane emissions from technical applications.

1 Introduction

According to the Decision 2018/7[1] of the Executive Body (EB) of the Convention on Long-range Transboundary Air Pollution (LRTAP) (38th session, Geneva, 10–14 December 2018)[2], in the revised mandate of the Task Force on Techno-economic Issues (TFTEI), the Task Force "..will continue to examine, assess, validate and provide information on emission abatement technologies for stationary and mobile sources". Among the new tasks assigned to TFTEI, described in the revised mandate, the Task Force has to initiate work to assess information on emissions abatement technologies and measures for the reduction of the methane emissions from key sources. This first document on methane emissions aims to provide systematic information on emissions from landfill gases, the natural gas grid as well as from biogas facilities in Europe. The synthesis gives a rapid understanding about the main issues of global warming potential and air pollution through methane emissions and what measures have been applied or can be taken to reduce these emissions. It is based on the latest information available from different scientific and industry sources as well as from public institutions such as environmental agencies.

TFTEI experts were informed about this work during the 2019 TFTEI meeting in Ottawa and the preliminary results have been presented during the TFTEI meeting in Warsaw (online) in October 2020. The first draft of the methane report has been circulated among TFTEI experts to receive comments and to agree on a first informal report by December 2020. Additionally, next steps regarding the assessment of methane emissions and related abatement technologies will we discussed. As sources of emissions are diverse which leads to a broad range of potential abatement measures, this report can also be seen as a first step to address methane emissions and further work will have to follow in future TFTEI activities in 2021.

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[1] http://www.unece.org/fileadmin/DAM/env/documents/2002/eb/air/EB%20Decisions/Decision_2018_7.pdf
[2] http://www.unece.org/index.php?id=45532

In its current form, this document focuses on European emissions (EU28) and gives brief information about current emission sources and levels, state-of-the-art in abatement technologies and economic aspects of emission abatement as far as information was available. This work is limited to a review of existing literature and technological information, mainly from North America and Europe and does not include own empirical research. Due to the complexity and diversity of methane emissions, further TFTEI activities in the context of methane emissions also in preparation of the review of the Gothenburg Protocoll will be necessary in the coming year. This could for example include an assessment of upstream emissions of the natural gas supply chain in Europe or a more detailed analysis of technologies that can be applied for early leakage detection.

2 Methane emissions in Europe

After CO_2, which is the most important Greenhouse Gas (GHG), methane (CH_4) is considered the second largest source of GHG emissions. Methane is responsible for about 18% of the global overall GHG emissions (Olivier et al. 2019). This is not due to the single emission levels, but mainly due to the significantly higher global warming potential of CH_4 compared to CO_2. Methane is the second largest contributor to total anthropogenic radiative forcing and is equivalent to 58% of the radiative forcing of CO_2 (Saunois et al. 2016).The global warming potential (GWP) of CH_4 is around 28 times higher than that of CO_2 on a 100-year timescale (Peng et al. 2016). While methane has a very high radiative forcing, it has a comparatively low atmospheric lifetime of about 12 years, meaning that current methane emissions will affect the climate for just over a decade. In the short run (coming 20 years) the GWP of methane is more than 80 times higher than that of CO_2. The ability to lower the near-term rate of global warming through reducing methane emissions provides society with a valuable mitigation option for climate risk management even though CO_2 emission reduction definitely remains the most important strategy for long-term climate change mitigation (Gas Naturally 2018). EU member states report their methane emissions to the United Nations Framework Convention on Climate Change (UNFCCC) and to the European Commission (EC), under the GHG monitoring mechanism. Table 1 summarizes the development of European GHG emissions transferred into CO_2 equivalents to demonstrate their GWP since 1990. As illustrated in Table 1, methane emissions currently contribute to overall GHG emissions with around 11 % in terms of GWP in the EU.

Table 1 GHG emissions (Mt CO_2 equivalents) in the EU 28 (EEA 2019), LULUCF: Land Use, Land-Use Change and Forestry

GHG Emissions Mt CO_2 eq.	1990	1995	2000	2005	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
CO_2 emissions (without LULUCF)	4478	4225	4189	4315	4171	3833	3949	3804	3746	3658	3489	3522	3505	3523
CH_4	740	679	618	557	523	511	501	491	487	476	469	469	465	466
N_2O	401	360	323	303	283	267	257	253	250	250	254	250	254	256
HFCs	29	44	55	77	97	98	104	106	109	111	114	110	107	105
PFCs	26	17	12	7	5	3	4	4	4	4	3	4	4	3
Total (without CO2 from LULUCF)	5691	5346	5210	5268	5087	4721	4822	4665	4603	4507	4335	4361	4343	4363

Beside the importance of CH_4 emission abatement for climate change mitigation, methane is a precursor of ground-level ozone formation (EEA 2019). Hence, also from an air pollution and human health perspective, CH_4 emissions are an important issue. This makes CH_4 both a greenhouse gas and an air pollutant.

According to basic estimates, about 40% of global methane emissions come from biogenic (natural) sources, such as wetlands, while the other 60% are anthropogenic, or man-made (IEA 2017a). The atmospheric CH_4 concentration has tripled since the beginning of industrialization in 1750 (Peng et al. 2016). CH_4 emission growth is highly related to increasing emissions from human activities, such as agriculture, fossil fuel production, solid waste and waste water treatment, while the largest source of global anthropogenic methane emissions is agriculture. This is also the case within Europe, where emissions from framing and enteric fermentation contribute to around 50% of overall CH_4 emissions (cf. Figure 1).

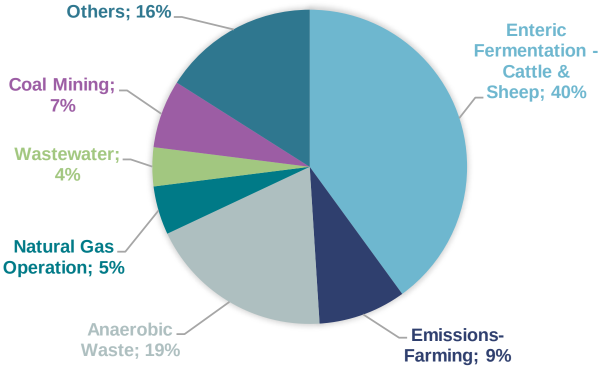

Figure 1 Methane emissions in Europe (EU 28) by source (EEA 2019)

There have been actions to reduce methane emissions in Europe since 1990, which in combination with structural changes have led to a decrease of CH_4 emissions within the EU by around 37% (see Figure 2 left side). However, this decrease is mainly driven by a reduction of landfilled waste and a reduction of coal mining (Figure 2 right side), which directly affected CH_4 emission levels in Europe. There are further potentials for emission reduction, of which several options from the field of landfill emissions and natural gas operations are discussed in the following sections. Subsequently this report shortly assesses the upcoming issue of methane emissions from biogas facilities, which is also considered as technology related emissions and therefore is seen as a part in the mandate of TFTEI. Agricultural emissions, even though most relevant, are not considered in this report because these sources of methane emissions are within the mandate of the Task Force on Reactive Nitrogen (TFRN).

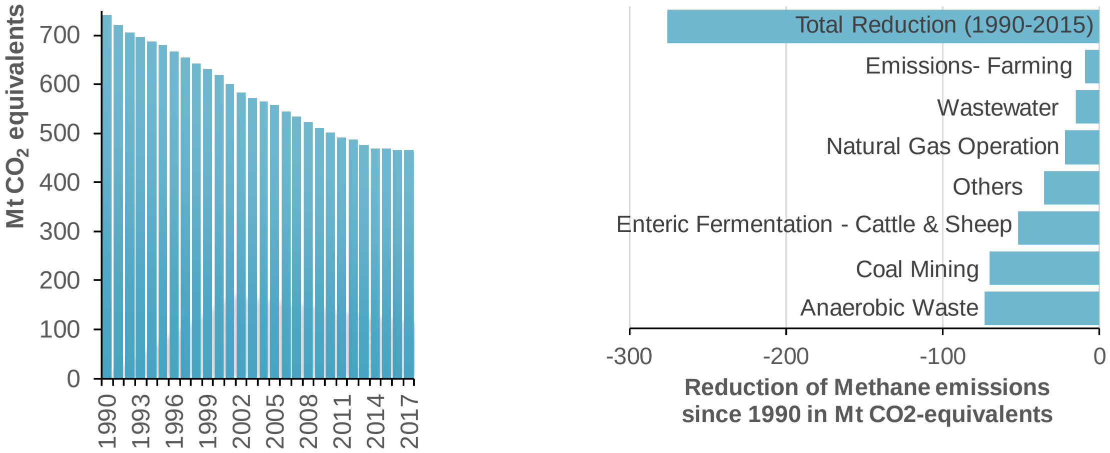

Figure 2 Development of methane emissions in Europe (EU 28) from 1990 to the present measured in CO2 equivalents (EEA 2019)

3 Emissions from Landfill Gases

As illustrated in Figure 1, methane emissions from anaerobic decomposition of landfilled municipal solid waste (MSW) is the most important non-agricultural source of anthropogenic methane emissions. Gas collection systems and combustion for heat and power generation in combination with decreasing shares of landfilled waste has led to a reduction of annual emissions since 1990 (cf. Figure 2, left), however, there is further potential for emission reduction particularly through a systematic implementation and application of gas collection and combustion systems for heat and power generation.

In the following section, we will give a brief overview of landfill gas formation and related methane emissions as well as technical solutions for gas collection and combustion systems. Subsequently some techno-economic literature-based figures on investment and operation costs are provided.

3.1 Methane emissions from landfills

3.1.1 Mechanism of landfill gas formation

Municipal solid waste contains significant portions of organic materials that produce a variety of gaseous products when deposited, compacted, and covered in landfills. Anaerobic bacteria thrive in the oxygen-free environment, resulting in the decomposition of the organic materials and the production of primarily carbon dioxide and methane. (Buendia et al.)

Landfill gas generation occurs under a four-phase process, as shown in Figure 3. First, CO_2 is produced under aerobic conditions. After oxygen (O_2) is depleted, CO_2 and hydrogen (H_2) are produced under anaerobic conditions. Then CO_2 production depletes in proportion to the CH_4 that is produced. Finally, CH_4, CO_2 and nitrogen (N_2) production stabilize. (US EPA 2011)

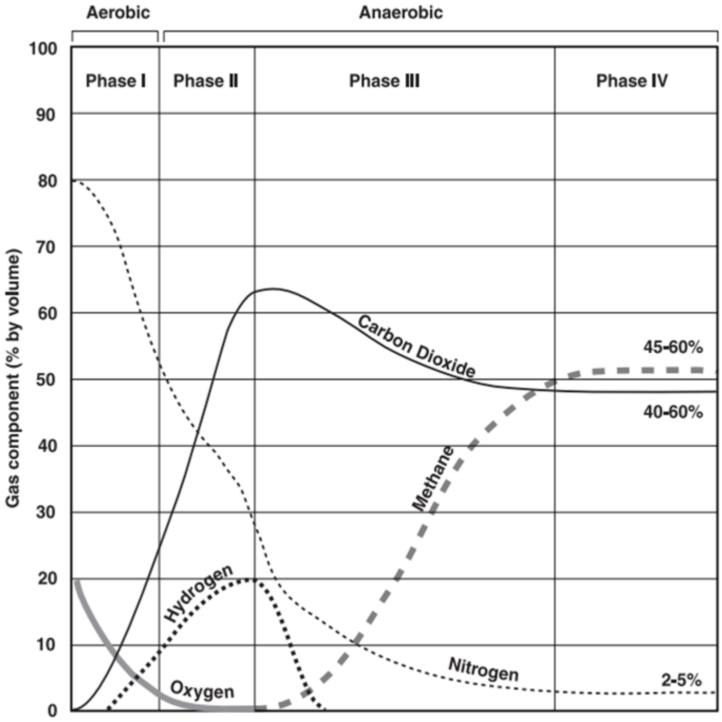

Figure 3: Production phases of landfill gas (US EPA 2011)

Methane produced by anaerobic methanogenic microorganisms in landfills can take different paths which are shown in Figure 4:

1. Emission into the atmosphere
2. Recovery via gas wells
3. Oxidation by aerobic methanotrophic microorganisms in cover soils

Not shown in are two longer-term CH_4 pathways: lateral CH_4 mitigation and internal changes in CH_4 storage (Spokas et al. 2006).

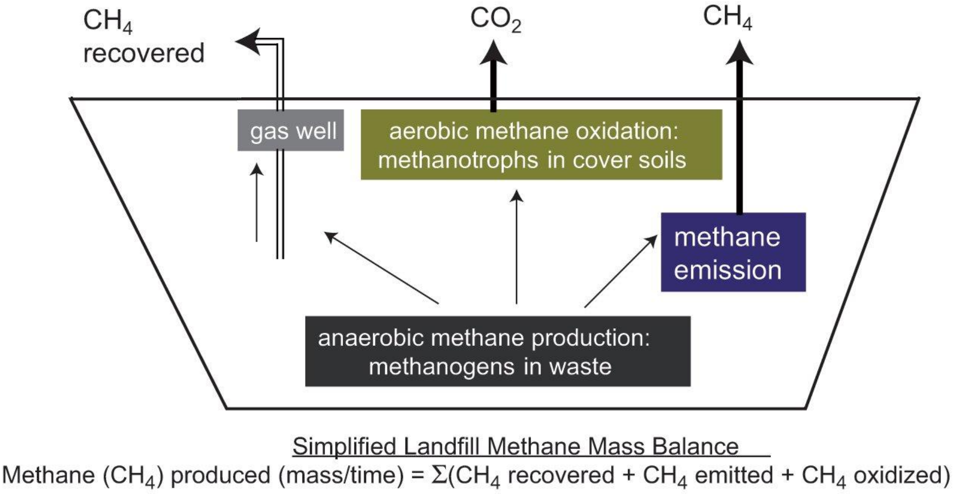

Figure 4: CH_4 pathways in a landfill (Metz 2007)

The CH_4 emissions from landfills are not the same as the quantity of CH_4 generated since about 10% of CH_4 generated is oxidized and does not result in CH_4 emissions. Additionally, CH_4 generated can be reduced by installing technologies for heat and power production, flaring, and producing biomethane via recovering of CH_4. (Duscha et al. 2019b)

There are two life stages in a landfill, its operating stage, where municipal solid waste (MSW) is being disposed of, and its closed stage, where storage capacity is reached. Operating landfills emit more CH_4 than closed landfills as most of the degradation occurs in the first few years following disposal. (Lou and Nair 2009)

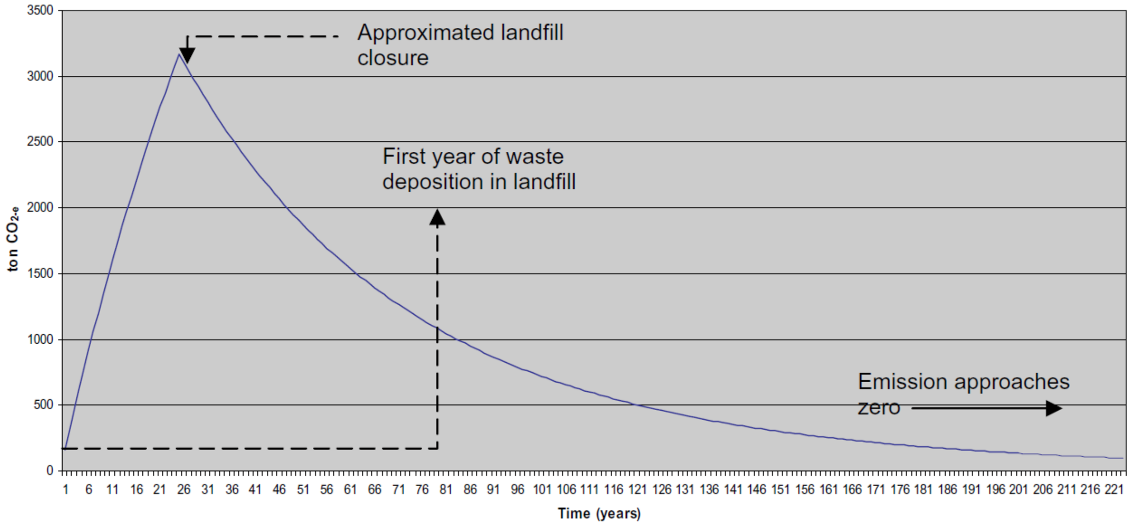

Figure 5: General trend of CH_4 emission from landfills in their operating post closure years (calculated using the IPCC 1st order decay model) (Lou and Nair 2009)

3.1.2 Estimating and modelling methane emissions from landfills

As landfills account for a significant share of global methane emissions, there has been a growing interest in understanding landfill emissions as well as mitigation measures. A bibliometric analysis by (Zhang et al. 2019) indicated an increasing trend in the scientific literature on landfill emissions, with most articles focusing on methane quantification or life cycle assessments.

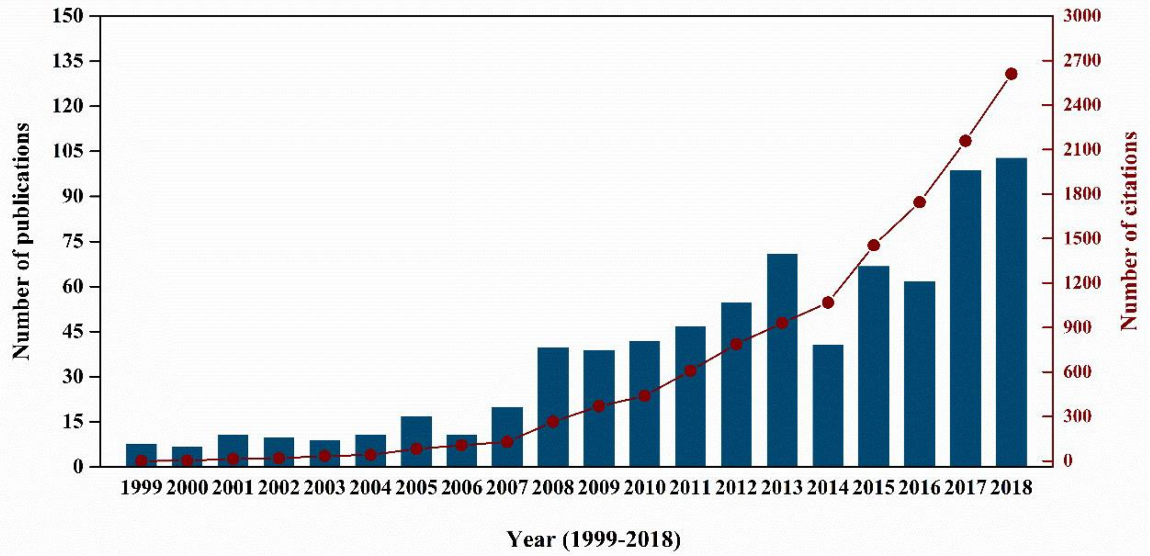

Figure 6: Trends in the quantity of articles and citations related to GHG emissions from landfills (Zhang et al. 2019)

It is not always possible to measure all methane emissions directly, for instance due to imperfect gas collection or a lack of sensor equipment. Therefore, methane emissions are often estimated using models representing the decay of organic substance in the landfill.

A significant share of such estimations follow the IPCC guidelines for GHG inventories. The Intergovernmental Panel on Climate Change (IPCC) protocol for predicting national methane emission inventories from landfills was published 22 years ago in the 1996 Revised Guidelines. The IPCC has refined its approach over the previous two decades but the landfill methane parameters exist as they were published in the 1996 Revised Guidelines. (Krause 2018; Penman et al. 2000)

The 1996 Revised Guidelines provided two approaches to calculate landfill methane emissions: a mass-balance approach or a first-order decay equation (Penman et al. 2000). The mass-balance method was based on the assumption that all potential methane is generated in the year the waste was placed (Akintayo and Olonisakin 2014; Browne et al. 2009; Castrejón-Godínez et al. 2015; Tsai 2007). This simple approach frequently overestimated methane emissions for a given year (Kim and Yi 2009). In contrast, the first-order decay (FOD) method considers the in-place mass of decomposable dissolved organic carbon (DOC) and a methane generation rate constant (Eggleston et al. 2006).

In the 2006 guidelines, the mass-balance approach was removed in favor of first-order decay methods and a third tier was added. The third tier is based on high-quality, country- or region-specific data and models validated for those sites (Eggleston et al. 2006). The removal of the mass-balance approach was significant because it indicated the engineering and scientific community's acceptance of the first-order decay model above all others, including more complex models (Govindan and Agamuthu 2014; Krause 2018).

The IPCC protocol has been used to estimate national methane inventories (Kumar 2004; Santalla et al. 2013) as well as to estimate landfill gas generation from a single site (Abualqumboz et al. 2016; Penteado et al. 2012). The IPCC Waste Model also provides for 19 regions the average weight fraction dissolved organic carbon (DOC) under aerobic conditions as input parameter for the First Order Decay model. (Crippa et al. 2018)

In 2019, the IPCC officially adopted a refinement to the 2006 guidelines which primarily improved the given parameter values. For instance, the default values for the fraction of degradable organic carbon for different waste components and their uncertainties were updated. (Buendia et al.)

While the first-order decay method is generally unchallenged in use and application, specific parameters and their values are still examined and discussed (Manfredi et al. 2009). Both the CH_4 and N_2O from the waste sector are microbially produced and consumed with rates controlled by temperature, moisture, pH, available substrates, microbial competition and many other factors (IPCC 2000). As a result, CH_4 and N_2O generation, microbial consumption, and net emission rates routinely exhibit temporal and spatial variability over many orders of magnitude, exacerbating the problem of developing credible national estimates (Metz 2007).

For instance, an experimental evaluation in Brazil showed that waste decomposes 4–5 times faster in a tropical wet climate than predicted by traditional first-order models using default parameters (Maciel and Jucá 2011).

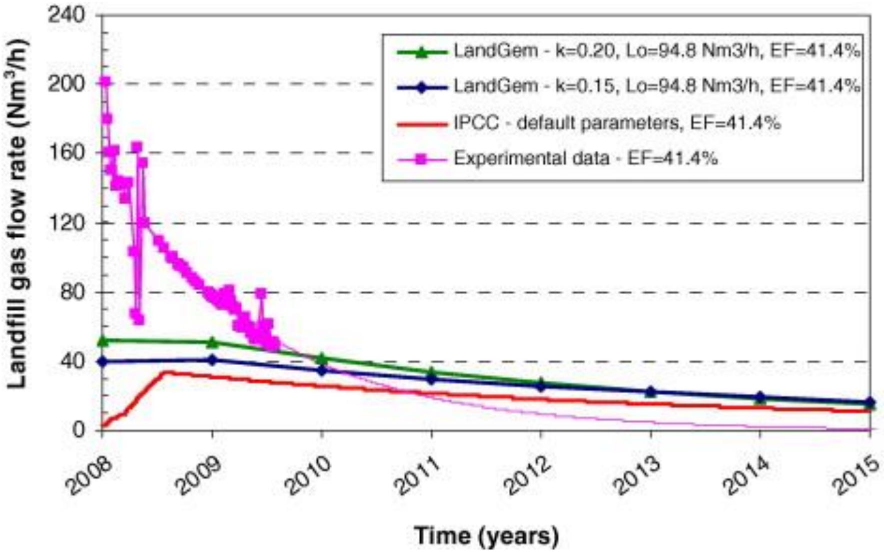

Figure 7: Experimental landfill gas flow rate in Brazil in comparison with IPCC and LandGEM (Maciel and Jucá 2011)

Another model that produces time-dependent generation profile is the Landfill Gas Emissions Model (LandGEM) developed by U.S. EPA (Alexander et al. 2005). Like the IPCC guidelines FOD method, it requires a large amount of data on current as well as historic waste deposition, composition and management practices and delivers relatively accurate results (Zhao et al. 2019).

3.2 Landfill gas emission levels and sources of emissions

3.2.1 Global landfill GHG emissions

Global CH_4 emissions from landfills are estimated to be 500–800 $MtCO_2$-eq/yr (US EPA 2006a; Monni et al. 2006; Bogner and Matthews 2003). Direct emissions from the waste sector almost doubled during the period from 1970 to 2010. Globally, approximately only 20 % of municipal solid waste (MSW) is recycled and approximately 13.5 % is treated with energy recovery while the rest is deposited in open dumpsites or landfills (Edenhofer 2014).

It has been estimated that annually about 50 Mt of methane is generated in global landfills, 6 Mt of which are captured at sanitary landfills (Themelis and Ulloa 2007). Facility CH_4 recovery (also referred to as capture efficiency) varies by landfill type and range from 10% for open dumps to 75% for basic landfills and 85% for engineered landfills (US EPA 2019a). However, significantly higher collection efficiencies have been demonstrated at certain well designed and operated landfills with final covers of up to 95 % (Themelis and Bourtsalas 2013).

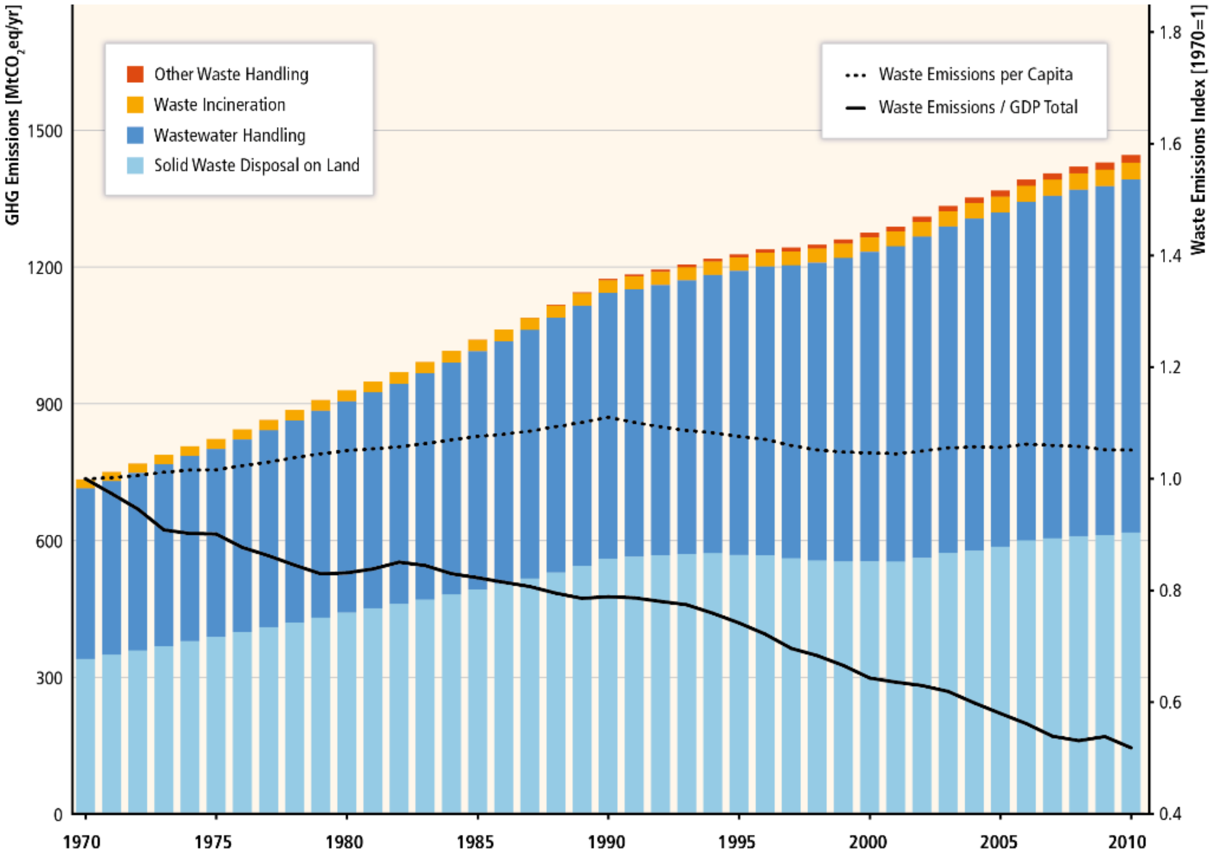

Figure 8: Global waste emissions (Edenhofer 2014)

The drop in CH_4 emissions from solid waste disposal sites starting around 1990 is most likely related to the decrease in such emissions in Europe and the United States. Several reasons may explain these trends: GHG emissions from waste in EU, mainly from solid waste disposal on land and wastewater handling decreased by 19.4 % in the decade 2000 – 2009; the decline is notable when compared to total EU27 emissions over the same period, which decreased by 9.3

%25. Energy production from waste in the EU in 2009 was more than double that generated in 2000, while biogas has experienced a 270 % increase in the same period. (Edenhofer 2014)

3.2.2 Landfill GHG emissions in the European Union

According to the definition of the IPCC 2006 Guidelines, GHG emissions from the waste sector are reported in the GHG inventory under category 5 of the common reporting format (CRF) (eurostat 2013). This category includes CH_4 emissions from solid waste disposal on landfills, CH_4 and N_2O emissions from biological treatment of waste (composting and anaerobic digestion), CO_2, CH_4 and N_2O emissions from waste incineration (without energy recovery) and CH_4 and N_2O emissions from domestic and industrial wastewater handling. (Duscha et al. 2019b). The emissions from landfill sites reported by Eurostat are not measured but modelled, following the IPCC guidelines on waste (eurostat 2013).

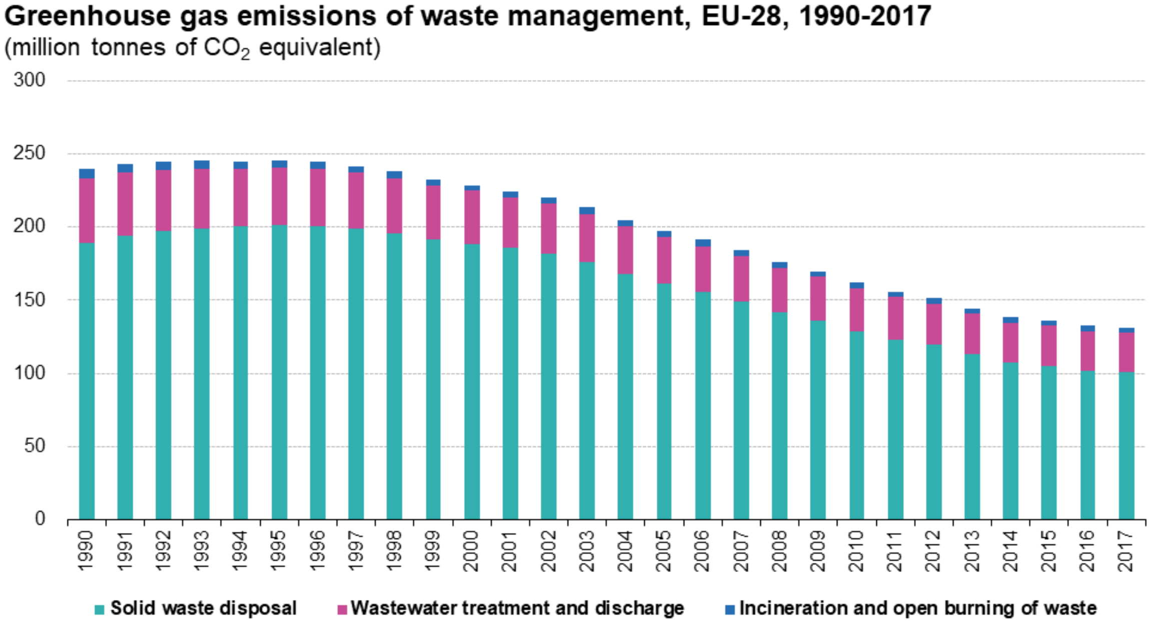

Figure 9: Greenhouse gas emissions from waste (eurostat 2020a)

In the EU-28, CH_4 emissions from solid waste disposal are dominated by seven member states. Italy, France, the United Kingdom, Spain, Germany, Poland and Portugal reported the highest emissions from landfills in 2015 (Figure 10). These seven member states accounted for 69% of total emissions from managed and unmanaged landfills in 2015 in the EU. CH_4 emissions from unmanaged landfills are of minor importance in the European Union. Since 2015 waste disposal on unmanaged landfills was only practiced in seven member states and make up only 2% of total waste disposed. (Duscha et al. 2019b)

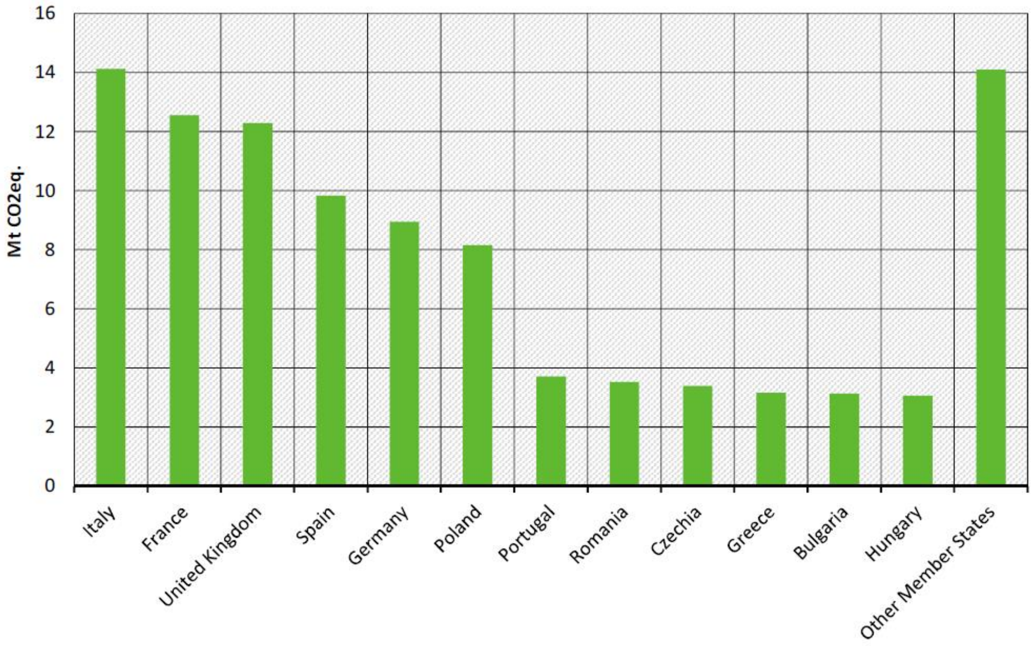

Figure 10: CH_4 emissions from solid waste disposal 2015 (Duscha et al. 2019b)

GHG emissions from the waste sector contributed with 3% to EU total emissions in 2015. Since 1990, total emissions from the waste sector decreased by 42% from 240 Mt in 1990 to 138 Mt in 2015. In 2015, 53% of waste related emissions are CH_4 emissions from waste disposal on landfills, while waste incineration contributes 29% to total emissions from waste treatment (Duscha et al. 2019a; EU COM 2019).

In the study by (Duscha et al. 2019a), the EU member states are clustered into representative groups. The grouping is based on the share of landfilled waste, waste composition, CH4 recovery rates and amount of landfilled organic waste per capita as wells as climate conditions.

Table 2: Representative groups (Duscha et al. 2019b)

	Country 1	Country 2	Country 3	Country 4	Characterization
1.Group	Germany	United Kingdom			Very low emissions from waste disposal due to ban of organic waste disposal (Germany) and high amount of CH_4 recovery (UK)
2. Group	France	Italy			Similar share of landfilled waste and organic waste disposal per capita
3.Group	Poland	Portugal	Hungary	Bulgaria	Similar share of solid waste disposal, low CH_4 recovery rates
4.Group	Spain	Greece	Romania	Czechia	High landfill rates per capita, dry climate* (except Czechia)

The waste treatment routes in the representative groups are shown in Figure 11. There are large differences in the treatment routes and reaching recycling goals of 55% in 2025, 60% in 2030 and 65% in 2035 requires very fast and focused action in many member states, especially in those of Group 3 and Group 4 (Duscha et al. 2019b).

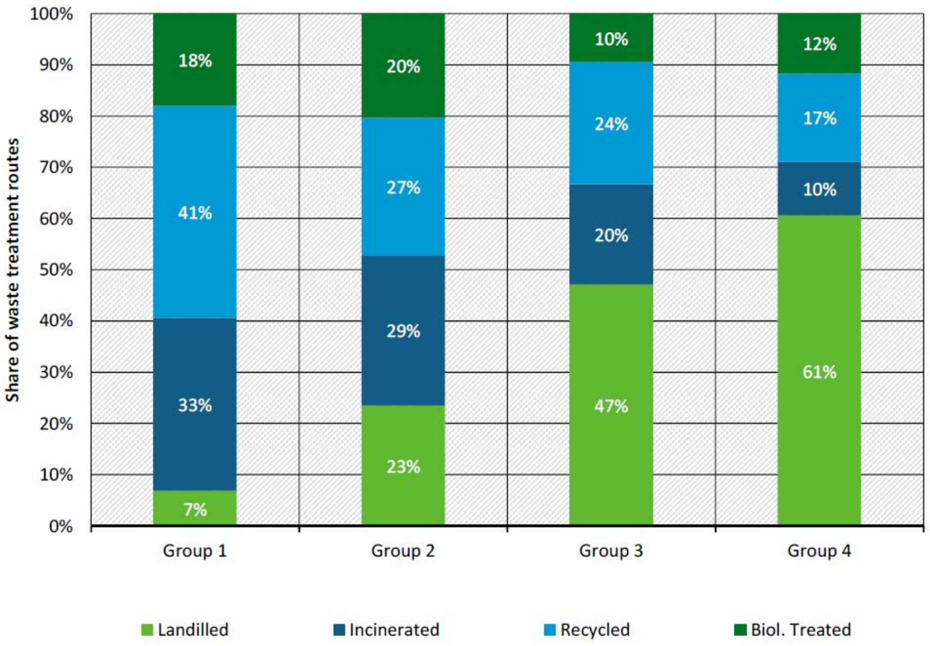

Figure 11: Share of solid waste treatment routes in 2017 (Duscha et al. 2019b)

Both the OECD and Eurostat only provide data on total landfilling. For more precise differentiation between landfills with and without gas collection, data from National Inventory Reports (NIR) or other studies were evaluated by (Vogt et al. 2015). The relatively low gas collection efficiency of the EU-OECD countries of 34.6% is primarily explained by the fact that the countries with high effective gas collection efficiencies[3] now landfill only very small untreated quantities or none at all. For example, Germany and Belgium with effective gas collection efficiencies of 45% and 50% respectively send virtually no untreated waste to landfill, while Spain and Poland with effective gas collection efficiencies of 20% and 17% respectively landfill larger amounts. (Vogt et al. 2015)

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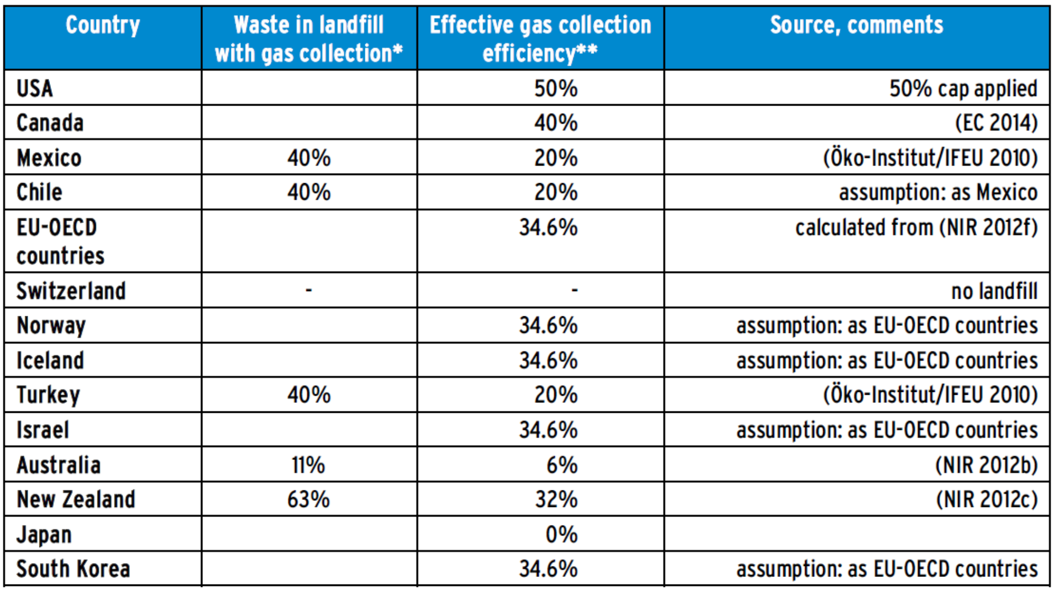
[3] A country's effective gas collection efficiency is the product of the proportion of landfills that have gas collection systems installed and the average gas collection efficiency of these systems over the entire duration of the deposits (Vogt et al. 2015.)

Table 3: Landfill gas collection rates (Vogt et al. 2015)



Country	Waste in landfill with gas collection*	Effective gas collection efficiency**	Source, comments
USA		50%	50% cap applied
Canada		40%	(EC 2014)
Mexico	40%	20%	(Öko-Institut/IFEU 2010)
Chile	40%	20%	assumption: as Mexico
EU-OECD countries		34.6%	calculated from (NIR 2012f)
Switzerland	-	-	no landfill
Norway		34.6%	assumption: as EU-OECD countries
Iceland		34.6%	assumption: as EU-OECD countries
Turkey	40%	20%	(Öko-Institut/IFEU 2010)
Israel		34.6%	assumption: as EU-OECD countries
Australia	11%	6%	(NIR 2012b)
New Zealand	63%	32%	(NIR 2012c)
Japan		0%	
South Korea		34.6%	assumption: as EU-OECD countries

3.2.3 Scenarios for the development of landfill GHG emissions

As landfills account for a significant share of the global methane emissions, the future development of the waste sector is critical for national and international emission pathways and climate targets. The remaining section briefly summarizes four studies presenting scenarios for the development of landfill gas emissions until 2030 and 2050.

1) Global climate change mitigation scenarios for solid waste management (Monni et al. 2006)

In this study by the Finnish VTT, country- or region-specific first-order decay (FOD) models based on the 2006 IPCC Guidelines are used to estimate emissions from municipal solid waste disposal in landfills. Five global scenarios are compiled from 1990 to 2050. These scenarios take into account political decision making and changes in the waste management system.

Global emissions from landfills are projected to increase from 340 Tg CO_2 eq in 1990 to 1500 Tg CO_2 eq by 2030 and 2900 Tg CO_2 eq by 2050 in the Baseline scenario. The emission reduction scenarios give emissions reductions from 5% (9%) to 21% (27%) compared to the Baseline in 2030 (2050). As each scenario considered one mitigation option, the results are largely additive, and the total mitigation potential can be assumed to be up to 30% in 2030 and 50% in 2050. According to the calculations of economic potentials, one third of global CH_4 emissions from landfills could be reduced at zero to negative costs in 2030. Below 10–20 USD/t CO_2 eq, more than half of the emissions could be reduced.

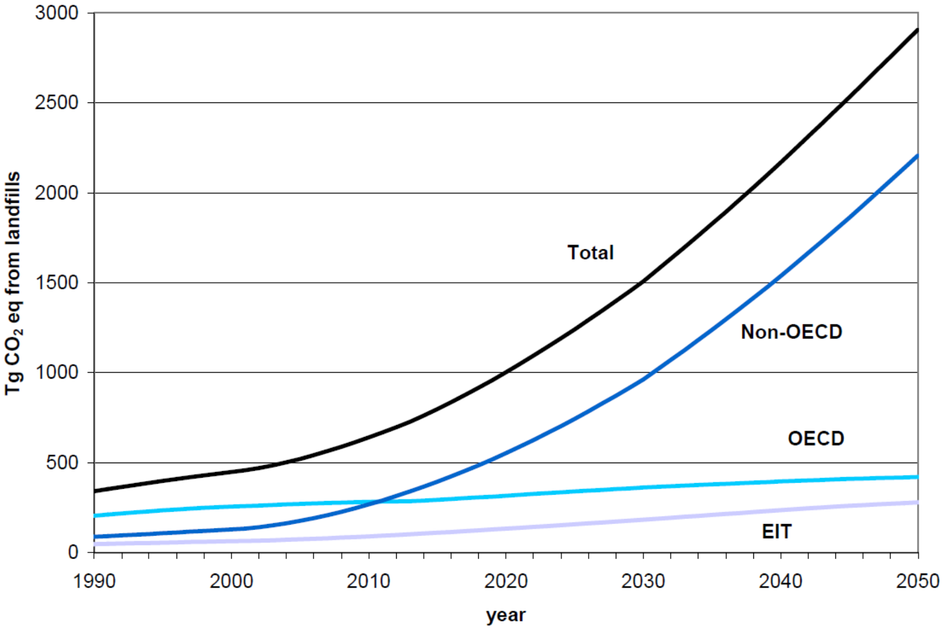


Figure 12: CH$_4$ emissions (Tg CO2 eq) from landfills in different regions in the Baseline scenario (Monni et al. 2006)

2) Fourth Assessment Report, IPCC Working Group III, Chapter 10: Waste (Metz 2007)

In the Fourth Assessment Report of the IPCC, different scenarios from the literature were reviewed and compared (including (Monni et al. 2006; Delhotal et al. 2006)). The mitigation scenarios show that reductions by individual measures in 2030 range from 5–20% of total emissions and increase proportionally with time. In 2050, the corresponding range is approximately 10–30%. As the measures in the scenarios are largely additive, total mitigation potentials of approximately 30% in 2030 and 50% in 2050 are projected relative to the baseline. Nevertheless, the estimated abatement potential is not capable of mitigating the growth in emissions.

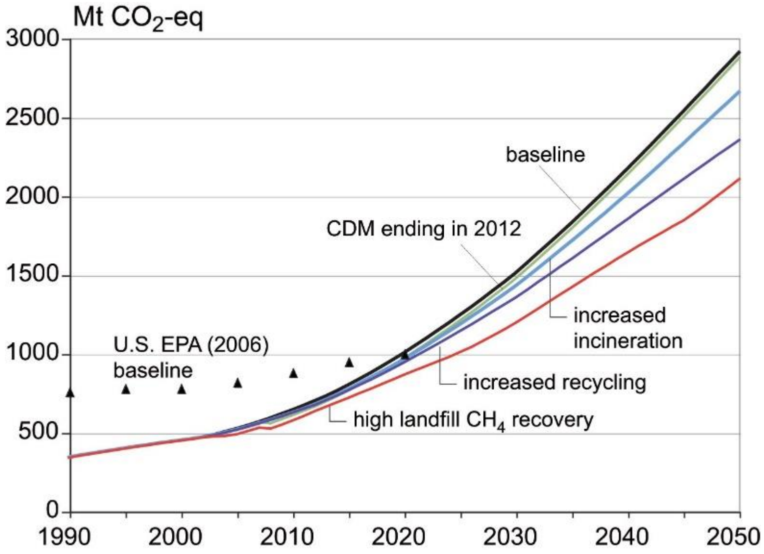


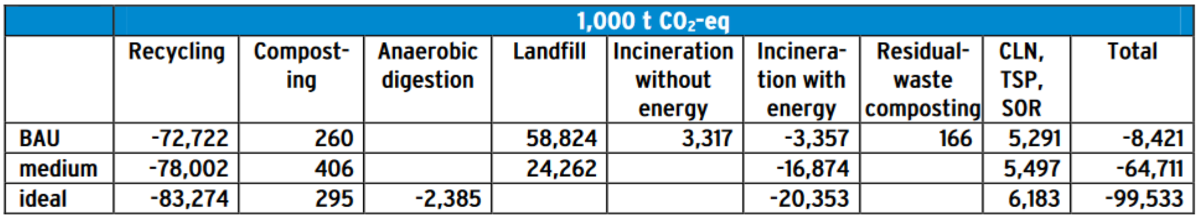
Figure 13: Scenario pathways to 2050 (Metz 2007)

3) The Climate Change Mitigation Potential of the Waste Sector (Vogt et al. 2015)

This study evaluates the greenhouse gas (GHG) mitigation potential of municipal solid waste (MSW) management in OECD countries as well as India and Egypt. Three detailed GHG balances for the USA, India, Egypt and one balance for the OECD countries are elaborated applying the life cycle assessment (LCA) method according to ISO 14040/14044 for waste management. For each balance the respective status quo is determined and compared with two scenarios to 2030.

Table 4 shows the net contributions of the three future scenarios to 2030 – "business as usual" (BAU), "medium scenario" (medium) and "ideal scenario" (ideal) – by disposal methods. In the medium scenario the total net credit of around -8 Mt CO_2-eq per year increases to around -65 Mt CO_2-eq per year. The total GHG reduction is around 57 Mt CO_2-eq per year. In terms of the overall result the ideal scenario improves on the medium one by a further 34 Mt CO_2-eq. By comparison with BAU the ideal scenario achieves a GHG reduction of around 91 Mt CO_2-eq.

Table 4: Net contributions of three future scenarios to 2030 (Vogt et al. 2015)



	1,000 t CO_2-eq								
	Recycling	Composting	Anaerobic digestion	Landfill	Incineration without energy	Incineration with energy	Residual-waste composting	CLN, TSP, SOR	Total
BAU	-72,722	260		58,824	3,317	-3,357	166	5,291	-8,421
medium	-78,002	406		24,262		-16,874		5,497	-64,711
ideal	-83,274	295	-2,385			-20,353		6,183	-99,533

4) "GHG-neutral EU2050 – a scenario of an EU with net-zero greenhouse gas emissions and its implications" (Duscha et al. 2019a)

The aim of this study was to design a scenario called "GHG-neutral EU2050" as one way to realize a European Union with net-zero greenhouse gas emissions under further sustainability criteria. The scenario shows that a GHG-neutral EU is feasible even without the use of carbon capture and storage and with limited amounts of bioenergy.

In comparison to the year 1990, large mitigation potential exists in the category of solid waste disposal and for waste water treatment. For both categories emissions can be reduced by ca. 90% until 2050. Biological treatment of waste becomes more relevant in 2050, but emissions can be reduced by applying appropriate technologies for anaerobic digestion and composting. Even in 2050, a small amount of waste that cannot be completely sorted will still be incinerated. (Duscha et al. 2019b)

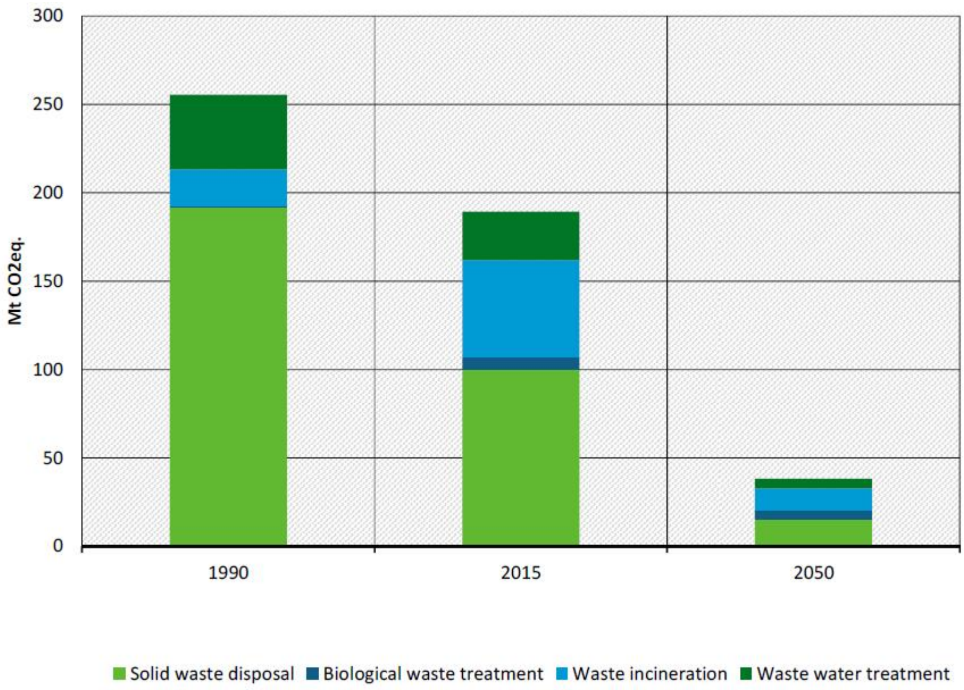


Figure 14: Emissions from the waste sector in 2050 (Duscha et al. 2019b)

3.3 Techno-economic issues of reducing landfill emissions

In this section, techno-economic issues of reducing GHG landfill emissions are discussed. First, the most important legislation in the EU with regard to landfill emissions is summarized. Second, available technologies for the mitigation of CH_4 from landfills are described. Finally, current literature estimates for the costs of the identified technologies is presented.

3.3.1 Relevant legislation (EU)

According to EU "Roadmap for moving to a competitive low carbon economy in 2050" non-CO_2 emissions, which also refer to the waste sector, shall be reduced by 70-78% until 2050 (Duscha et al. 2019b). The main legislation regulating landfill emissions in the EU has been the landfill directive from 1999, which was amended in 2018.

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

With the introduction of the Landfill Directive 1999/31/EC, the EU has established a powerful tool to reduce the amount of biodegradable municipal waste disposed in landfills (Blodgett and Parker, 2010). The landfill directive provides instructions to the members states to include specific aspects in the landfill permit. With respect to the control and treatment of landfill gas, Annex I of the Landfill Directive contains the following specifications (EUR-Lex 1999):

4 Gas control

4.1 Appropriate measures shall be taken in order to control the accumulation and migration of landfill gas (Annex III).

4.2 Landfill gas shall be collected from all landfills receiving biodegradable waste and the landfill gas must be treated and used. If the gas collected cannot be used to produce energy, it must be flared.

4.3 *The collection, treatment and use of landfill gas under paragraph 4.2 shall be carried on in a manner which minimises damage to or deterioration of the environment and risk to human health.*

The directive is not directly binding for landfill operators. It is an instruction to member states and competent authorities to include specific aspects in a landfill permit. As the specifications of the Landfill Directive were perceived as vague by the member states, an additional guidance document on landfill gas control (EU COM 2013) was developed and adopted (Scharff 2019).

Article 5 of the Landfill Directive also sets targets for reduction of the amount of biodegradable municipal waste sent to landfill. On the basis of the amount of biodegradable municipal waste generated in 1995 the amount of biodegradable waste allowed to be send to landfill is limited to 75 % in 2006, to 50 % in 2009, and to 35 % in 2016. (eurostat 2013)

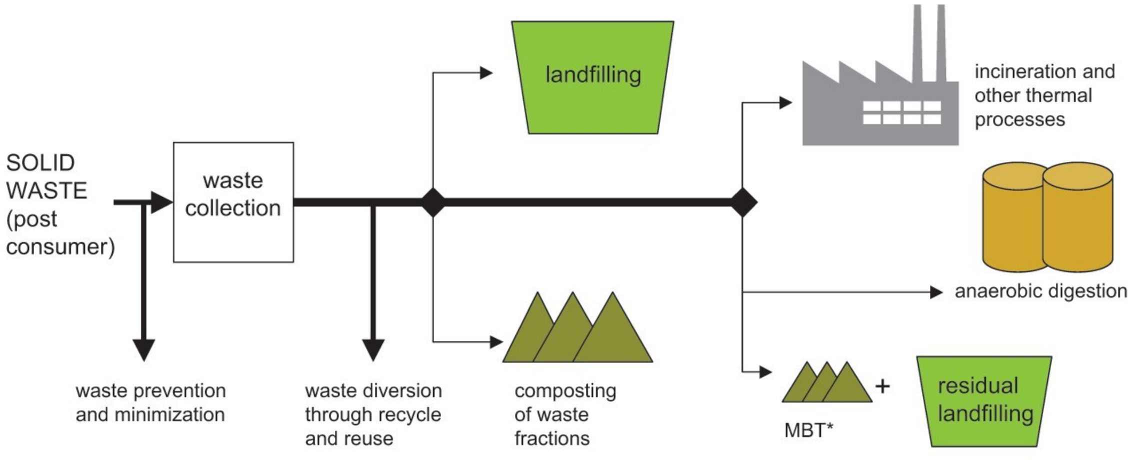
Directive (EU) 2018/850

In 2018, the landfill directive (1999/31/EC) was amended by Directive (EU) 2018/850 of the European Parliament and of the Council. Some of the key components of the new directive include limitations on the landfilling of waste collected separately, and an aspirational target for 2030 that any waste suitable for recycling and recovery should not be disposed of in landfills. By 2035, the amount of municipal waste landfilled is to be reduced to 10 % or less of the total amount of municipal waste generated. (EU COM 2019)

Thus, the new targets of the landfill directive will have a significant impact on the development of CH_4 emissions from landfills until 2050. However, the landfill directive sets no specific target for the amount of organic waste landfilled until 2035. The introduction of a separate collection system for bio-waste and textiles is mandatory from 2024 and 2025 onwards. As it is not allowed to landfill separately collected waste fractions, this will lead to reduced amounts of organic waste landfilled. (Duscha et al. 2019b)

3.3.2 Overview of abatement technologies

A wide range of technologies is available for the treatment and disposal of solid waste and the mitigation of GHG emissions (Figure 15). Solid waste can be recycled, landfilled, incinerated and biological treated (Yusuf et al. 2012). Landfilling is reduced through recycling, waste minimization, and waste diversion to alternative treatment and disposal methods, such as composting and incineration (Karakurt et al. 2012). Therefore, the mitigation of GHG emissions from waste relies on the combination of multiple technologies whose application depends on local, regional and national drivers for both waste management and GHG mitigation (Metz 2007).



Technology:	Low to Intermediate	Low to Intermediate	High
Unit Cost: (per t waste)	Low to Intermediate	Low to Intermediate	High
Energy Balance	Negative to positive	Negative to positive *Composting: negative to zero* *Landfill CH_4 utilization: positive*	Negative to positive *MBT (aerobic): negative* *MBT (anaerobic): positive* *Anaerobic digestion: positive* *Incineration: positive (highest)*

Figure 15: Technology gradient for waste management: major low- to high-technology options (Metz 2007)

It must also be taken into account that the different technologies are complementary over the lifetime of a landfill. Generally, collection and energetic use of landfill gas is the favorable option that should be maximized. However, at the beginning of the life of the landfill there will be a period where the gas quality and quantity will not be adequate for gas utilisation. During this period, the operator should maximise the quantity of methane collected and oxidised prior to the introduction of gas utilisation. When the lifetime of the landfill comes to an end and gas generation declines, the operator should consider using different methane oxidation techniques to maximise the quantity of methane collected and oxidised. (EU COM 2013)

In the remaining section, four main technologies for mitigating GHG emissions from landfills will be shortly described:

- Oxidation (biocovers / biofiltration)
- Landfill aeration
- Gas collection and utilization
    - Flaring
    - Electricity generation
    - Direct gas use for heat generation
    - Other uses (gas grid injection, fuel cells)

3.3.2.1 Oxidation (biocovers and biofiltration)

CH_4 oxidation is a process which naturally takes place through different layers of cover soil due to the profusion of methanotrophic organisms (Majdinasab and Yuan 2017). The idea of using biofiltration for CH_4 elimination derives from the fact that some bacterial species are able to degrade CH_4 while generating oxidation by-products such as water (H_2O), CO_2, salts and biomass, all products much less harmful for the environment than the initial substrate (Nikiema et al. 2007).

CH_4 oxidation rates at landfills can vary over several orders of magnitude and range from negligible to 100% of the CH_4 flux to the cover. Under circumstances of high oxidation potential and low flux of landfill CH_4 from the landfill, it has been demonstrated that atmospheric CH_4 may be oxidized at the landfill surface. In such cases, the landfill cover soils function as a sink rather than a source of atmospheric CH_4 (Metz 2007). A secondary benefit of CH_4 oxidation in cover soils is the co-oxidation of many non-CH_4 organic compounds, especially aromatic and lower chlorinated compounds, thereby reducing their emissions to the atmosphere (Schuetz et al. 2003).

The technologies to increase the CH_4 oxidation rate include biocovers and biofiltration beds (US EPA 2011). A biocover is an additional final cover that functions as a CH_4 oxidation enhancer to convert CH_4 into CO_2 prior to venting to the atmosphere. A biocover is composed of two substrate layers: a gas dispersion layer and a CH_4 oxidation layer. The gas dispersion layer is an additional permeable layer of gravel, broken glass, or sand beneath the porous media of the CH_4 metabolizing layer. This layer is added to evenly distribute the uncaptured landfill gas to the CH_4 oxidation media and to remove excess moisture from the gas. The CH_4 oxidation media can be made of soil, compost, or other porous media. This media is usually seeded with methanotrophic bacteria from the waste decomposition. (US EPA 2011)

Similar to biocovers, biofiltration beds aim to further oxidize CH_4 from passively collected LFG. The collected LFG is passed through a vessel containing CH_4-oxidizing media prior to venting to the atmosphere or to a control system. This control technology is only feasible for small landfills or landfills with passive gas collection systems due to the size of the biofiltration bed required to treat an air/gas mixture. (US EPA 2011)

3.3.2.2 Landfill Aeration

In situ aeration is a technology that introduces ambient air into MSW landfills to enhance biological processes and to inhibit methane production (Chai et al. 2013). Ambient air is introduced in the landfill via a system of gas wells, which results in accelerated aerobic stabilization of deposited waste. The resulting gas is collected and treated (Heyer et al. 2005; Prantl et al. 2006). Biological stabilization of the waste using in-situ aeration provides the possibility to reduce both the actual emissions and the emission potential of the waste material (Prantl et al. 2006). Landfill aeration, which is not widely applied yet, is a promising technology for treating the residual methane from landfills utilizing landfill gas for energy when energy recovery becomes economically unattractive (Ritzkowski et al. 2006; Rich et al. 2008). In the absence of mandatory environmental regulations that require the collection and flaring of landfill gas, landfill aeration might be applied to closed landfills or landfill cells without prior gas collection and disposal or utilization. (Edenhofer 2014) For an in situ aerated landfill in northern Germany, for example, landfill aeration achieved a reduction in methane emissions by 83 % to 95 % under strictly controlled conditions (Ritzkowski and Stegmann 2010).

Depending on the landfill site, aeration of the landfill may be feasible at different stages of landfill operation. Early aeration means that energy generation is forfeited, but may be suitable for landfills where waste-to-energy is unfeasible. Late aeration is more common as it allows for energy recovery and continues to mitigate CH_4 emissions when the production of CH_4 has plateau and is no longer cost-effective to continue operation. (Lou and Nair 2009)

3.3.2.3 Gas Extraction and Utilisation

A) Gas collection

According to the EU Landfill Directive, energy must be recovered from the collected landfill gas. If a landfill operator considers that landfill gas cannot be used at the landfill then they must demonstrate to the competent authority that, at that individual landfill, there are site-specific reasons why utilisation is not feasible. (EU COM 2013)

The implementation of an active landfill gas extraction system using vertical wells or horizontal collectors is the single most important mitigation measure to reduce emissions. Intensive field studies of the CH_4 mass balance at cells with a variety of design and management practices have shown that over 90% recovery can be achieved at cells with final cover and an efficient gas extraction system (Spokas et al. 2006). Some sites may have less efficient or only partial gas extraction systems and there are fugitive emissions from landfilled waste prior to and after the implementation of active gas extraction; thus estimates of lifetime recovery efficiencies may be as low as 20% (Oonk and Boom 1995). For closed landfills, reported efficiencies range from 10–90%. For landfills in operation, efficiencies are 10 to 80% (Oonk 2012). For active gas collection systems, the collection efficiency depends primarily upon the design and maintenance of the collection system and the type of materials used to cover the landfill (Table 5).

Table 5: LFG Collection Efficiencies for Various Cover Materials (US EPA 2011)

Type of Landfill Cover Material	Gas Collection Efficiency
Operating cell (no final cover)	35%
Temporary cover	65%
Clay final cover	85%
Geomembrane final cover	90%

Gas collection, by vertical wells and horizontal trenches, typically begins after a portion of a landfill, called a cell, is closed. Vertical wells are most commonly used for gas collection, while trenches are sometimes used in deeper landfills, and may be used in areas of active filling. The collected gas is routed through lateral piping to a main collection header. Ideally, the collection system should be designed so that an operator can monitor and adjust the gas flow if necessary. Once the landfill methane is collected, it can be used in a number of ways, including electricity generation, direct gas use, biomethane production, powering fuel cells, or compression to liquid fuel. (Karakurt et al. 2012)

Extraction wells are typically composed of slotted plastic pipe, surrounded by stone or other aggregate material, that are installed in borings in the waste mass below the surface of the SWD site. Above the surface of the waste mass, the extraction well typically has a wellhead to allow for vacuum adjustment and sampling of the LFG. The orientation of these wells can either be vertical or horizontal, and the decision to use vertical and/or horizontal wells will depend on site-specific factors. (GMI 2012)

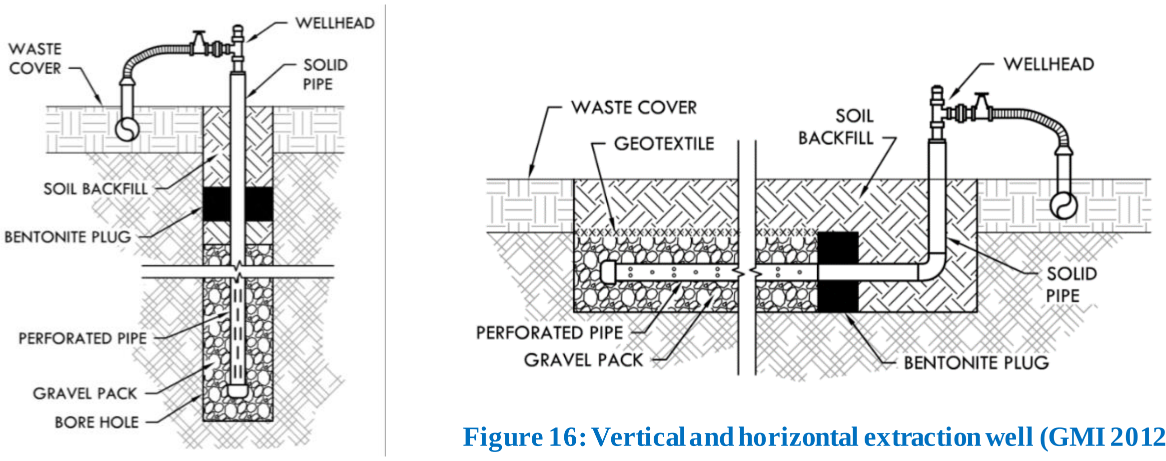


Figure 16: Vertical and horizontal extraction well (GMI 2012)

Vertical wells are usually installed in areas where the site has stopped receiving waste or where waste filling will not occur for a year or more. However, they can be installed and operated in areas with continued waste placement, but placement will result in increased operation and maintenance requirements.

Horizontal extraction wells can be installed while a waste disposal site is still receiving waste and may be used if landfill gas collection is desired in an area before closure. Horizontal extraction wells are placed in a trench within the refuse. The trench is backfilled with gravel (or other aggregate such as tire chips or broken glass), and the perforated pipe is installed in the center of the trench. (GMI 2012)

Table 6: Advantages and disadvantages of vertical and horizontal LFG collection wells (GMI 2012)

Vertical Wells		Horizontal Wells	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
Minimal disruption of landfill operations if placed in closed area of landfill Most common design Reliable and accessible for inspection and pumping	Increased operation and maintenance required if installed in active area of landfill Availability of appropriate equipment Delayed gas collection if installed after site or cell closes	Facilitates earlier collection of LFG Reduced need for specialized construction equipment Allows extraction of gas from beneath an active tipping area on a deeper site	Increased likelihood of air intrusion until sufficiently covered with waste More prone to failure because of flooding or landfill settlement

B) Gas utilisation

B1) Flaring

Collecting and flaring the landfill gas is part of the normal operation of the landfill, independent of additional systems for heat or power generation. The landfill gas generation rate will decline over time producing lower volumes of gas with a low methane content. According to the EU guidance on landfill gas control, operators should follow a hierarchy of treatment techniques over the life of the landfill to ensure that the maximum amount of landfill gas is oxidised over the whole lifecycle of the landfill. (EU COM 2013):

- High temperature flaring
- Low calorific flaring
- Other techniques for oxidation of methane

There are generally two types of flares:

(1) open flares (candle-stick flares)
(2) enclosed flares (ground flares)

Enclosed flares that are properly engineered and operated may achieve destruction efficiencies of 99 percent or greater. Higher combustion temperatures and residence times destroy unwanted constituents such as un-burnt hydrocarbons. One significant drawback to this type of flare system is that it is more expensive to install and operate than an open flare. (GMI 2012)

Figure 17: Open flare (left) and enclosed flare (right) (GMI 2012)

B2) Electricity generation

Landfill gas collected at the waste disposal site can be used for electricity generation. After pumping out, the gas usually must undergo pretreatment to remove liquids, sulphur, and siloxanes. If the cleaned landfill gas will be upgraded to biomethane, CO_2 also must be removed. Reciprocating engines for cogeneration of electricity and heat can operate even when the landfill gas contains up to 40% of CO_2 by volume. Energy production also requires temporary gas storage or a flare station to burn the excessive methane production (Karakurt et al. 2012).

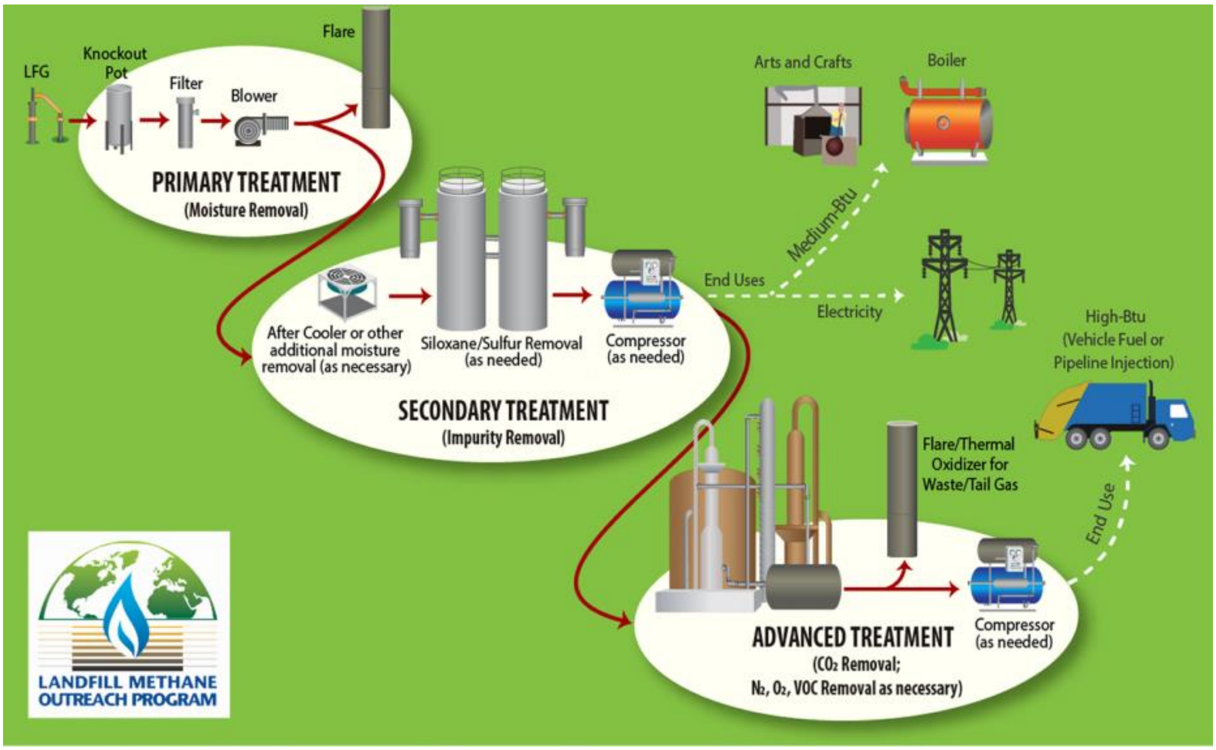


Figure 18: Landfill gas capture and utilization pathways (LMOP 2020)

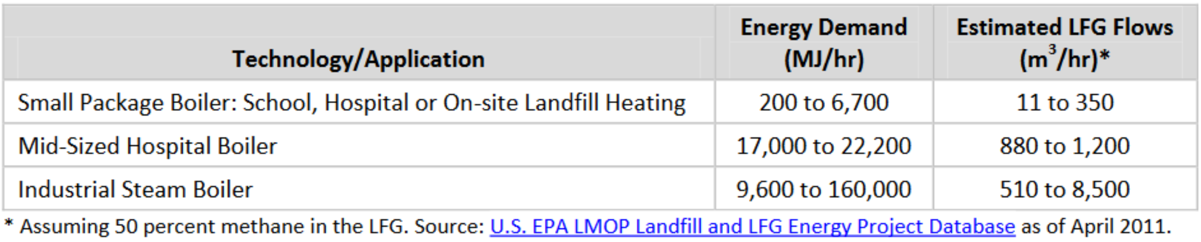
Typical technologies for electricity generation from landfill gas (LFG) are (US EPA 2011):

- **Reciprocating internal combustion engines** are the most widely used technology for the conversion of LFG to electricity. Advantages of this technology include: low capital cost, high efficiency, flexibility with respect to methane content, and adaptability to variations in the gas output of landfills.
- **Gas turbines** using LFG require a dependable gas supply for effective operation, and are generally suitable for landfills when gas production can generate at least 3 MW. However, such small gas turbines are very sensitive to contamination in the fuel gas and require more specialized and expensive maintenance than reciprocating engines.
- **Micro-turbines** generally work best for small scale recovery projects that supply electricity to the landfill or to a site that is in close proximity to the landfill. Single micro-turbine units have capacities ranging between 30 and 250 kW, and are most suitable for applications below 1 MW. Sufficient LFG treatment is generally required for micro-turbines and involves the removal of moisture and other contaminants

B3) Direct gas use

Landfill gas can also be used as a fuel for boilers or industrial processes, such as drying operations, kiln operations, and cement and asphalt production. In these projects, the cleaned and dries gas is piped directly to a nearby customer where it is used as a replacement or supplementary fuel (Karakurt et al. 2012).

Table 7: Typical LFG boiler sizes (GMI 2012)



Technology/Application	Energy Demand (MJ/hr)	Estimated LFG Flows (m^3/hr)*
Small Package Boiler: School, Hospital or On-site Landfill Heating	200 to 6,700	11 to 350
Mid-Sized Hospital Boiler	17,000 to 22,200	880 to 1,200
Industrial Steam Boiler	9,600 to 160,000	510 to 8,500

* Assuming 50 percent methane in the LFG. Source: U.S. EPA LMOP Landfill and LFG Energy Project Database as of April 2011.

B4) Other options

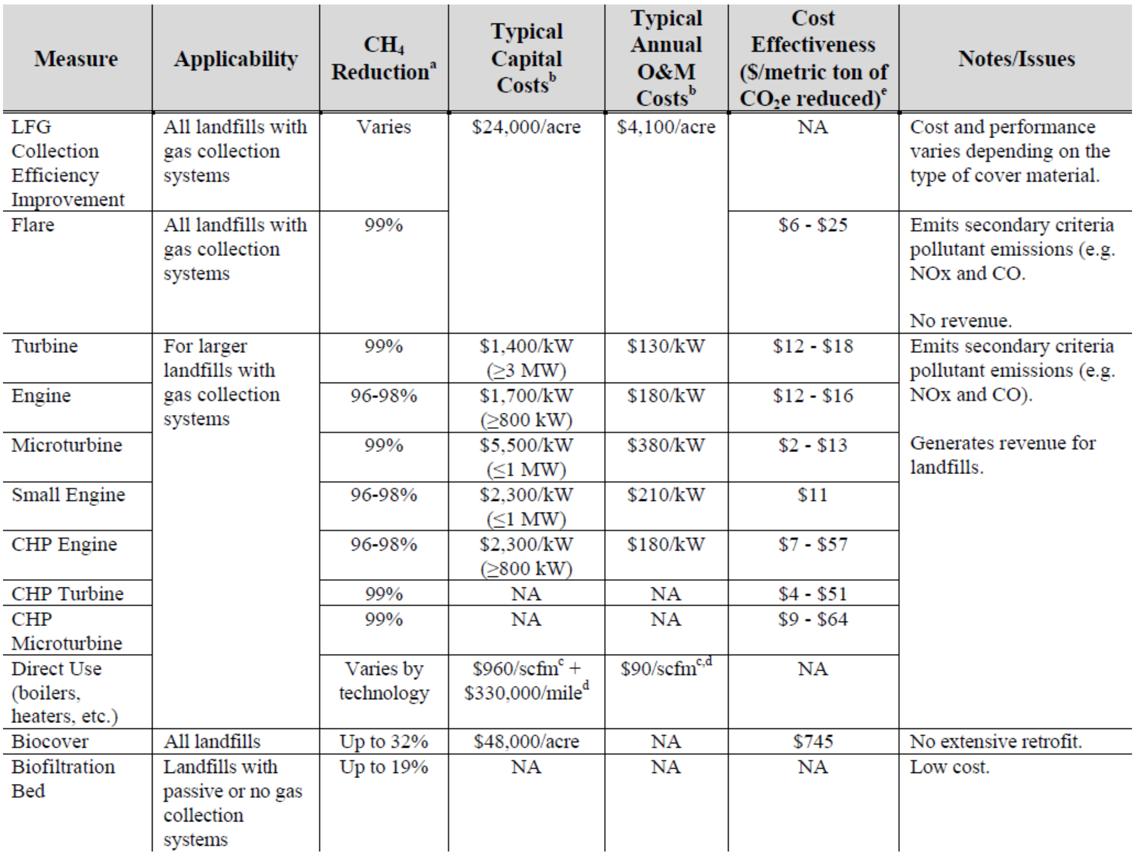
Landfill gas can be sold to the natural gas pipeline system once it has met certain process and treatment standards. This option is appropriate in limited cases, such as when very large quantities of gas are available. Additionally, landfill gas is processed into liquid vehicle fuel for use in trucks hauling refuse to a landfill. (Karakurt et al. 2012)

Fuel cells are another technology for energy generation from landfill gas. Fuel cells have an advantage over combustion technologies in that the energy efficiency is typically higher without generating combustion by-products such as NO_X, CO, and sulfur oxides. If fuel cells are used to generate electricity from landfill CH_4, then a very effective gas cleanup system is required to ensure that the catalyst within the fuel cell is not contaminated by trace constituents that are present in the gas. To date, the high sensitivity of fuel cells to contamination represents a significant barrier for this utilization of landfill gas. (US EPA 2011)

3.3.3 Cost estimates for abatement technologies

The costs of measures to control landfill emissions were analyzed by the U.S. Environmental Protection Agency (EPA) in 2011 (Table 8). The study also estimated the global abatement potential in the solid waste landfill sector by 2030 to be approximately at 61% of the baseline emissions, of which 12% at relatively low or zero costs, and 49% at increasingly higher costs. (US EPA 2011)

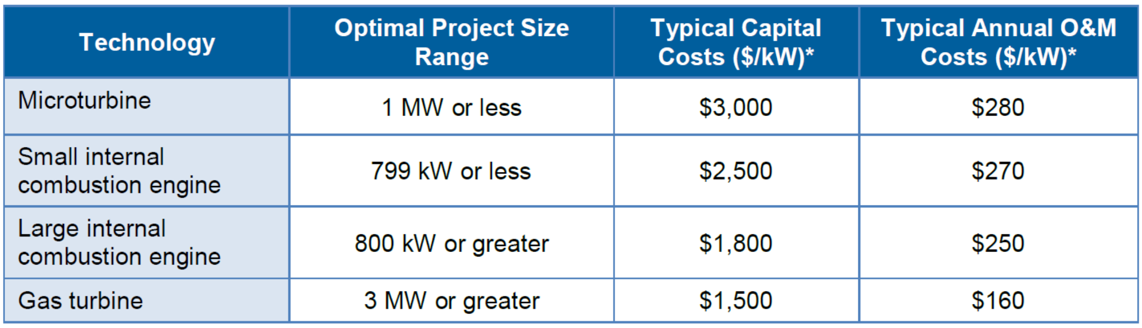
Table 8: Summary of GHG control measures for MSW landfills (US EPA 2011)



Measure	Applicability	CH_4 Reduction^{a}	Typical Capital Costs^{b}	Typical Annual O&M Costs^{b}	Cost Effectiveness ($/metric ton of CO_2e reduced)^{e}	Notes/Issues
LFG Collection Efficiency Improvement	All landfills with gas collection systems	Varies	$24,000/acre	$4,100/acre	NA	Cost and performance varies depending on the type of cover material.
Flare	All landfills with gas collection systems	99%			$6 - $25	Emits secondary criteria pollutant emissions (e.g. NOx and CO. No revenue.
Turbine	For larger landfills with gas collection systems	99%	$1,400/kW (≥3 MW)	$130/kW	$12 - $18	Emits secondary criteria pollutant emissions (e.g. NOx and CO). Generates revenue for landfills.
Engine		96-98%	$1,700/kW (≥800 kW)	$180/kW	$12 - $16	
Microturbine		99%	$5,500/kW (≤1 MW)	$380/kW	$2 - $13	
Small Engine		96-98%	$2,300/kW (≤1 MW)	$210/kW	$11	
CHP Engine		96-98%	$2,300/kW (≥800 kW)	$180/kW	$7 - $57	
CHP Turbine		99%	NA	NA	$4 - $51	
CHP Microturbine		99%	NA	NA	$9 - $64	
Direct Use (boilers, heaters, etc.)		Varies by technology	$960/scfm^{c} + $330,000/mile^{d}	$90/scfm^{c,d}	NA	
Biocover	All landfills	Up to 32%	$48,000/acre	NA	$745	No extensive retrofit.
Biofiltration Bed	Landfills with passive or no gas collection systems	Up to 19%	NA	NA	NA	Low cost.

The US EPA also provides estimates for typical costs of LFG energy technologies (Table 9) in the recently updated LFG Energy Project Development Handbook (US EPA 2020a).

Table 9: Typical costs of LFG energy projects (US EPA 2020a)



Technology	Optimal Project Size Range	Typical Capital Costs ($/kW)*	Typical Annual O&M Costs ($/kW)*
Microturbine	1 MW or less	$3,000	$280
Small internal combustion engine	799 kW or less	$2,500	$270
Large internal combustion engine	800 kW or greater	$1,800	$250
Gas turbine	3 MW or greater	$1,500	$160

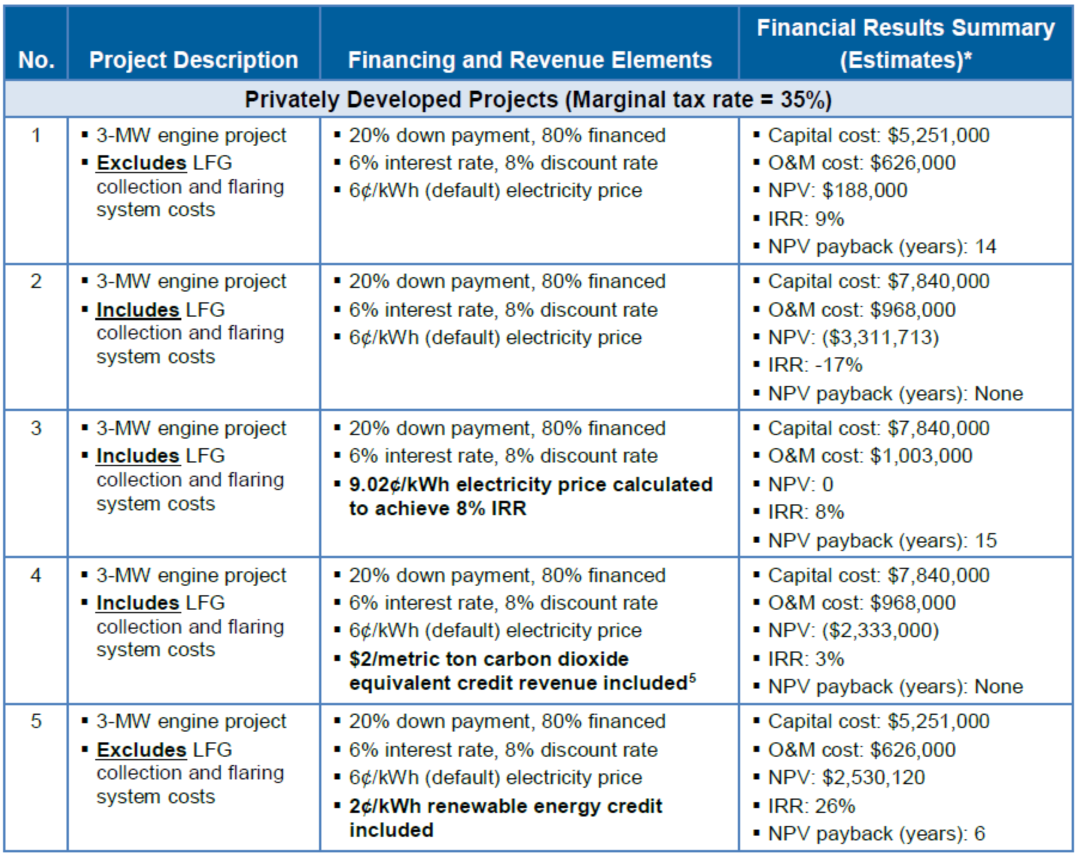
$/kW: dollars per kilowatt   kW: kilowatt   MW: megawatt
*2013 dollars for typical project sizes

However, these tables only show typical costs for installation and operation of LFG energy technologies, but do not allow any conclusion about the economic viability of LFG energy in general or about specific projects. The economic viability of a project will not only depend on the costs for the technology, but also on potential revenue sources and especially the local prices for electricity and process heat. Thus, the best configuration for a particular landfill will depend on a number of factors, including the existence of an available energy market, project costs and financing, potential revenue sources and other technical considerations.

The Landfill Methane Outreach Program (LMOP) of the US EPA provides the LFG cost web tool which accounts for these factors and helps with the preliminary economic evaluation of 12 types of LFG energy projects (US EPA 2020b). Table 10 shows exemplary assessment results for an LFG electricity project which can be found in the LFG Energy Project Development Handbook (US EPA 2020a). It can be seen that the profitability depends on various factory beyond the technology itself, such as financing, electricity price and carbon credits.

The Global Methane (GMI) Initiative published a guideline document in 2012 which uses the cost model developed by the U.S. EPA. It is pointed out that the uncertainty of these costs estimates is +/ 30 to 50 percent and that costs may vary by country as a result of import fees, taxes, labor, materials, permitting requirements and regulations. (GMI 2012)

Table 10: Example results for an electricity project (US EPA 2020a)



No.	Project Description	Financing and Revenue Elements	Financial Results Summary (Estimates)*
Privately Developed Projects (Marginal tax rate = 35%)			
1	▪ 3-MW engine project ▪ **Excludes** LFG collection and flaring system costs	▪ 20% down payment, 80% financed ▪ 6% interest rate, 8% discount rate ▪ 6¢/kWh (default) electricity price	▪ Capital cost: $5,251,000 ▪ O&M cost: $626,000 ▪ NPV: $188,000 ▪ IRR: 9% ▪ NPV payback (years): 14
2	▪ 3-MW engine project ▪ **Includes** LFG collection and flaring system costs	▪ 20% down payment, 80% financed ▪ 6% interest rate, 8% discount rate ▪ 6¢/kWh (default) electricity price	▪ Capital cost: $7,840,000 ▪ O&M cost: $968,000 ▪ NPV: ($3,311,713) ▪ IRR: -17% ▪ NPV payback (years): None
3	▪ 3-MW engine project ▪ **Includes** LFG collection and flaring system costs	▪ 20% down payment, 80% financed ▪ 6% interest rate, 8% discount rate ▪ **9.02¢/kWh electricity price calculated to achieve 8% IRR**	▪ Capital cost: $7,840,000 ▪ O&M cost: $1,003,000 ▪ NPV: 0 ▪ IRR: 8% ▪ NPV payback (years): 15
4	▪ 3-MW engine project ▪ **Includes** LFG collection and flaring system costs	▪ 20% down payment, 80% financed ▪ 6% interest rate, 8% discount rate ▪ 6¢/kWh (default) electricity price ▪ **$2/metric ton carbon dioxide equivalent credit revenue included**[5]	▪ Capital cost: $7,840,000 ▪ O&M cost: $968,000 ▪ NPV: ($2,333,000) ▪ IRR: 3% ▪ NPV payback (years): None
5	▪ 3-MW engine project ▪ **Excludes** LFG collection and flaring system costs	▪ 20% down payment, 80% financed ▪ 6% interest rate, 8% discount rate ▪ 6¢/kWh (default) electricity price ▪ **2¢/kWh renewable energy credit included**	▪ Capital cost: $5,251,000 ▪ O&M cost: $626,000 ▪ NPV: $2,530,120 ▪ IRR: 26% ▪ NPV payback (years): 6

A third techno-economic comparison of landfill gas abatement options can be found in the Fourth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC). The chapter on waste management compares emission reduction and typical costs and provides aggregated estimates (Table 11) (Edenhofer 2014). In this context, anaerobic digestion refers to the biological treatment of MSW before landfilling which requires source separation and is mostly applied to small quantities of food waste. and do not indicate which percentage of projects are ultimately profitable. It should be pointed out that these estimates show a range between minimum and maximum costs with negative minimum values representing a profit for heat and power generation.

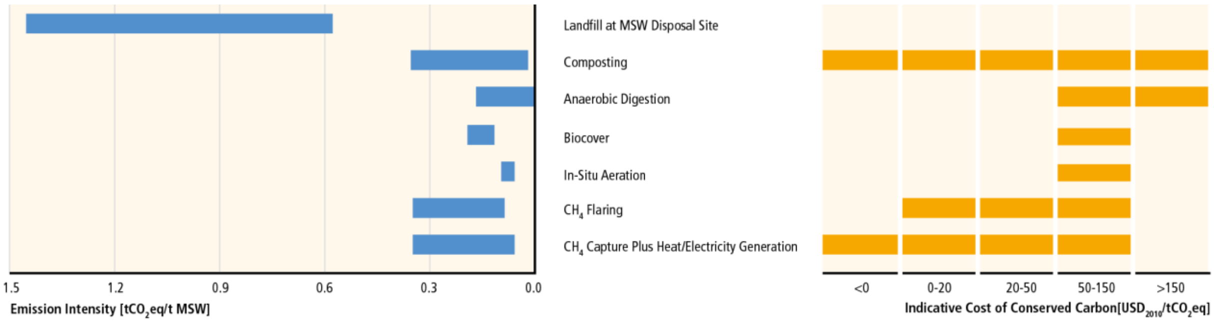


Figure 19: Indicative CO_2eq emission intensities and levelized cost (Edenhofer 2014)

Table 11: Technical parameters and cost estimates (Schlömer et al. 2014)

		Biocover	**In-situ aeration**	**Flaring**	**CH_4 capture for power generation**	**CH_4 capture for heat generation**
Oxidation factor (fraction)	min / max	0.8	0.9	–	–	–
Fraction of recovered CH_4		–	–	0.6 / 0.85	0.6 / 0.9	0.6 / 0.9
CH_4 emission intensity of MSW (gCH_4 / kg MSW)		8.5 / 21	4.2 / 11	6.4 / 43	4.2 / 43	4.2 / 43
CO_2eq emission intensity of MSW (tCO_2eq / t MSW)		0.12 / 0.19	0.058 / 0.10	0.087 / 0.35	0.058 / 0.35	0.058 / 0.35
Levelized cost of conserved carbon at 10 % WACC (USD/tCO_2eq)		99 / 100	99 / 130	5.0 / 58	-37 / 66	-70 / 89

With regard to the economic prospects of LFG energy, it is also important how landfill gas compares to natural gas and to other sources of biogas such as manure or energy crops. In a recent study by the International Energy Agency (IEA), the techno-economic potential of biogas and biomethane from different sources was analyzed (IEA 2020).

The results show that capturing and cleaning landfill gas generally is the least expensive option to produce biogas (Figure 20). The study also found that most biomethane produced today is more expensive than the prevailing natural gas price, with the exception of landfill gas. Upgrading biogas captured from landfill sites was identified as the cheapest option to produce cost-competitive biomethane. (IEA 2020)

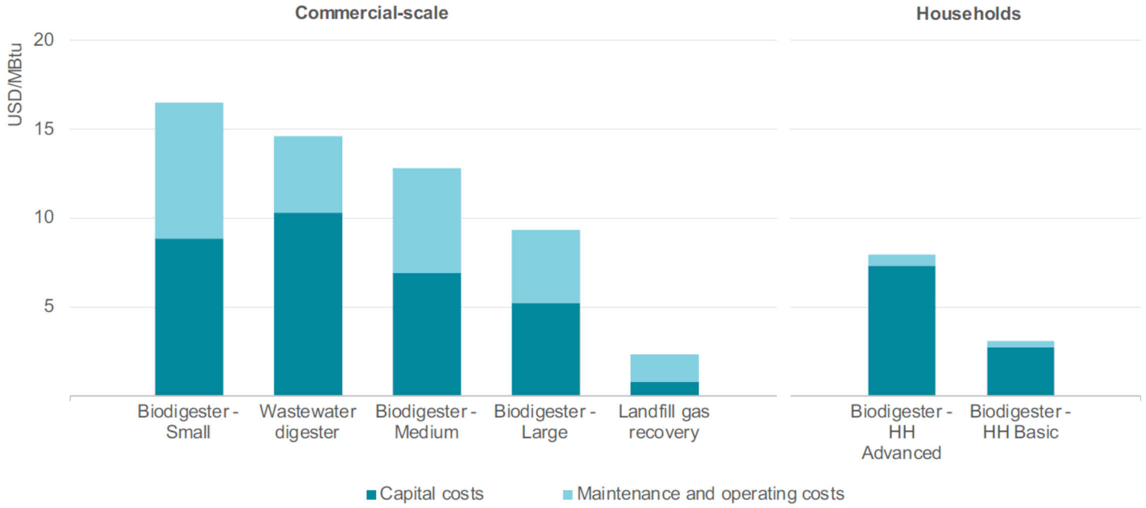


Figure 20: Average costs of biogas production technologies per unit of energy produced in 2018 (IEA 2020)

The study also predicts that the biogas potential in 2040 will be more than 50% larger than today, based on increased availability of the various feedstocks in a larger global economy. The projected costs of production also fall modestly over time. With regard to landfill gas, the report finds that MSW will provide a smaller fraction of the total potential in 2040 than today. However, landfill gas will remain the lowest-cost source of supply (Figure 21)

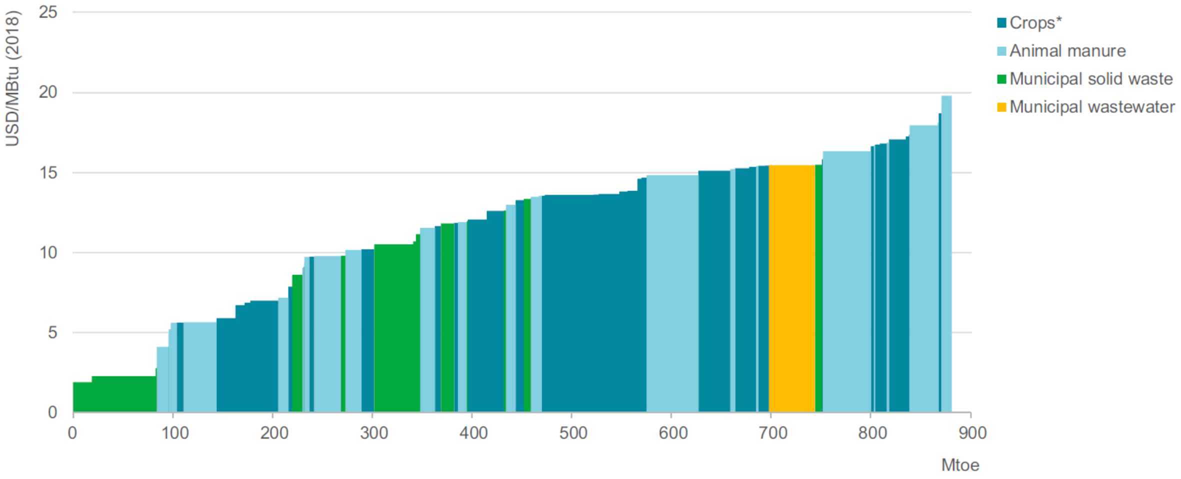


Figure 21: Cost curve of potential global biogas supply by feedstock in 2040 (IEA 2020)

The potential for landfill emission reductions with regard to costs and technologies was also investigated in a recent analysis by the US EPA on global non-CO2 emissions (US EPA 2019b). The study considered 12 abatement options to control landfill emissions, which are grouped into three categories: (1) collection and flaring, (2) landfill gas (LFG) utilization systems (LFG capture for energy use), and (3) enhanced waste diversion practices (e.g., recycling and reuse programs). The results indicate that abatement measures with costs below $0/ tCO2e can achieve a 19% reduction in landfill baseline emissions (Figure 22).

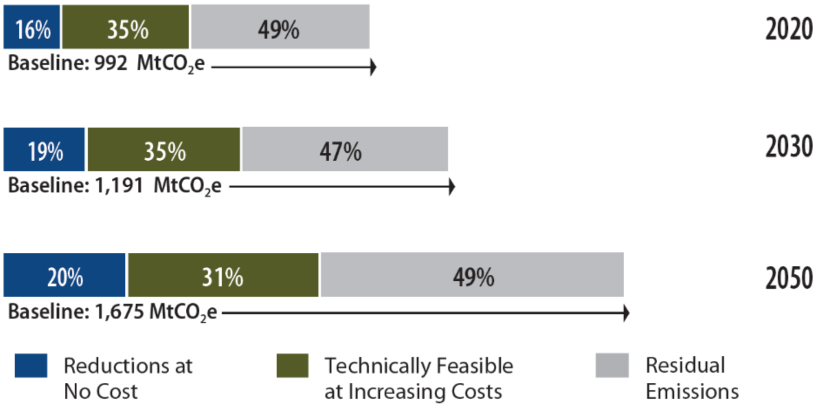


Figure 22: Total reduction potential (US EPA 2019b)

The study also differentiated between abatement technologies (Figure 23). In 2030, landfill gas recovery for direct use is the leading emission abatement measure at $0/tCO$_2$e; flaring offers the highest abatement potential at higher prices. Electricity generation with a reciprocating engine is the leading abatement measure, accounting for 12% of potential. Overall, electricity generation measures comprise the largest share of potential abatement with 78 MtCO$_2$e.

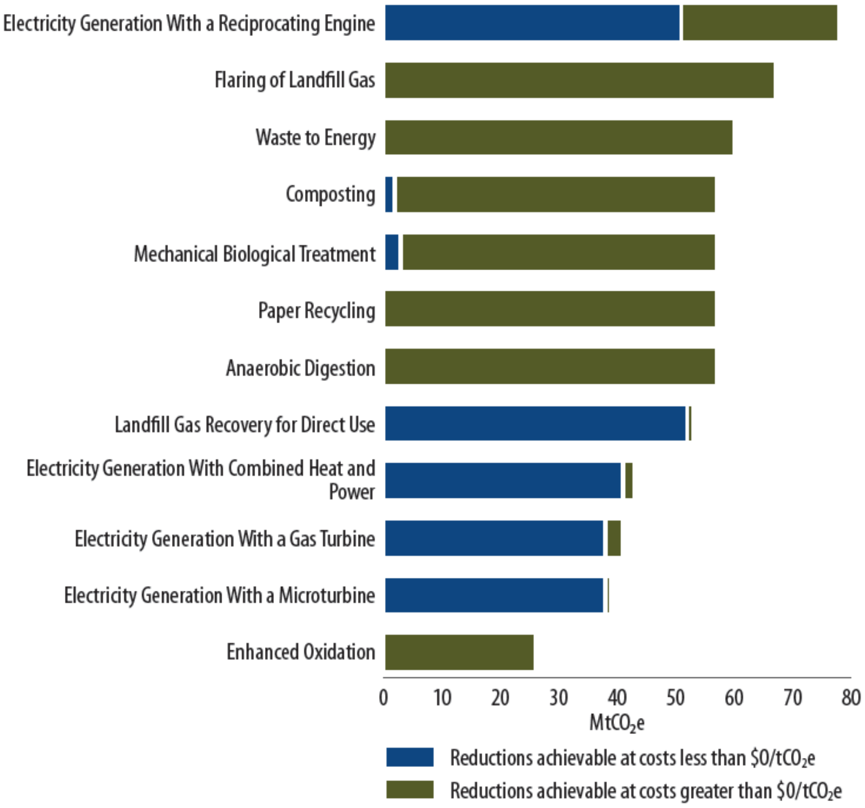


Figure 23: Reduction potential by technology (US EPA 2019b)

4 Emissions from the natural gas grid

With only 5% of overall methane emissions within the EU (see Figure 1), the natural gas system shows a comparatively moderate contribution to the overall European emission level. In terms of mass this results in slightly below 1 Mt of methane emissions according to figures from the European Environment Agency (EEA 2019). Hence, natural gas emissions are responsible for around 0.6% of total GHG emissions in Europe. However, it has to be taken into account that the major share of European natural gas supply is imported mainly from Russia, Norway and Northern Africa and major emissions occur during gas extraction, processing and transmission. As this report mainly focusses on emissions from the natural gas grid within the EU, these emissions are not addressed in a detailed manner. However, reference figures from several studies indicate high indirect emissions of European gas supply in the upstream value chain (Exergia 2015; DBI 2016; Köppel et al. 2018). Hence, based on the figures discussed in this section, it seems reasonable that future TFTEI work will consider these emissions particularly against the backdrop of Russia as the main source of European natural gas supply (ca. Figure 24, right side). In this context, it shall also be mentioned that the situation regarding European natural gas supply might change in nearby future concerning e.g. US and Canadian LNG shipped to the EU or the future of Nord Stream 2 pipeline and additional Russian gas coming to Germany and the EU.

4.1 European natural gas grid structure

As illustrated in Figure 24 (left side) the European gas grid is a complex and dense network with major supply from outside the EU. Russia is the most important European gas supplier followed by offshore gas from Norway. From Northern Africa (mainly Algeria) both pipelines and shipped Liquified Natural Gas (LNG) supply particularly Southern Europe. The Netherlands are the most important natural gas producer within the EU.

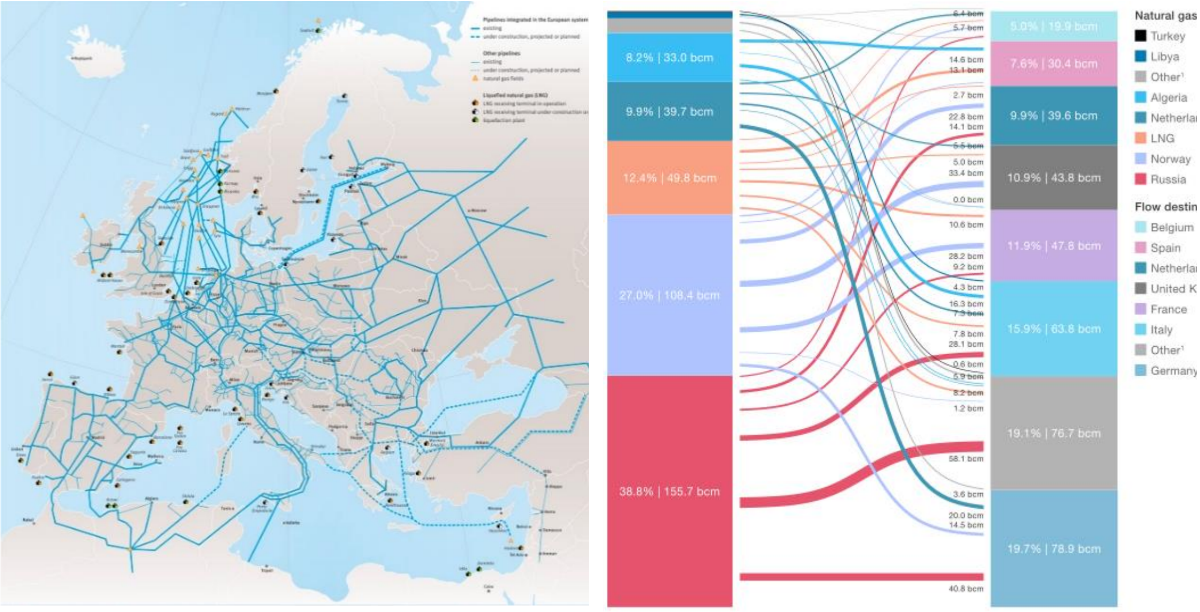


Figure 24 Natural gas pipeline network in the EU28 and sources of natural gas for EU supply in billion cubic meters (bcm) (Isabella Ruble 2017; McKinsey & Company 2019)).

4.2 Major components of a natural gas supply system and general sources of CH_4 emissions

Before focusing on specific methane emissions in the European gas grid, we provide a general overview of natural gas processing and supply systems. This seems necessary for the sake of completeness, because the majority of production, processing and compression steps as well as gas transmission in high pressure pipelines is conducted outside of Europe. This leads to comparatively low emissions within the EU, while the upstream emissions are much higher. These upstream emissions should be part of further investigation. However, as indicated before, in this report we focus on European emissions.

As illustrated in Figure 25, the natural gas supply network consists of the basic production facility, where raw natural gas is collected from various well sites. The raw gas containing water, sulphur additional hydrocarbons and further impurities is then transferred to the processing plant where the raw gas is refined and prepared for transmission. As natural gas is usually transported via transmission pipelines over very long distances (cf. Figure 24) high pressures are required which is achieved in compressor stations that are installed along the transmission lines. Large consumers such as electrical power plants are sometimes directly connected to the transmission lines. However, the majority of natural gas from transmission lines is transferred to the “city gate”. The city gate is where a transmission system feeds into a lower pressure distribution system that brings natural gas directly to consumers (homes and businesses). At the city gate, the pressure of the gas is reduced, and this is normally the location where odorant (typically mercaptan) is added to the gas, giving it the characteristic smell so leaks can be detected. In some countries such as France and Spain, odorant is already added in the transmission line. While transmission pipelines may operate at pressures over 70 bar (1000 psi), distribution systems operate at much lower pressures (1,5-10 bar).

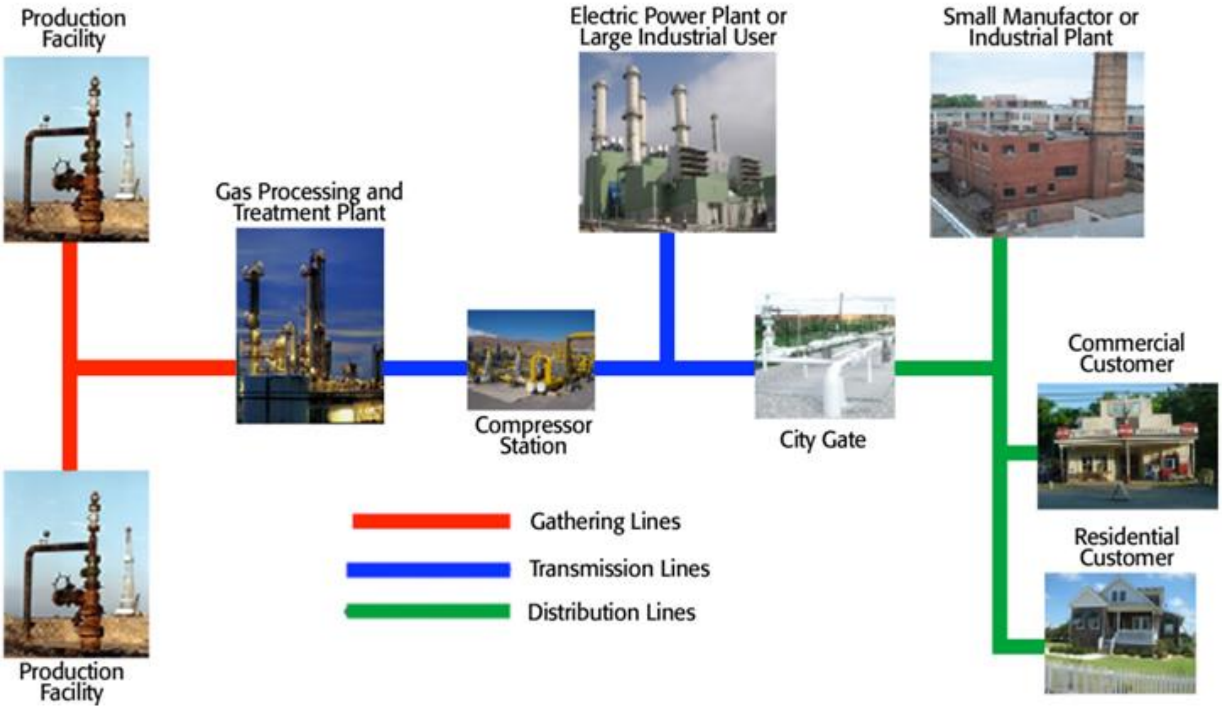


Figure 25 General structure of the natural gas supply network (Pipeline Safety Trust 2015).

There are many sources of methane emissions across the entire gas supply chain. These emissions are characterized as either fugitive emissions or vented emissions:

- Fugitive emissions occur when methane “leaks” unintentionally from equipment such as from flanges or valves that do not operate correctly. Also leakages in the pipeline or from tanks are generally accounted to fugitive emissions.
- Vented emissions occur when methane is released due to equipment design or operational procedures, such as from pneumatic device bleeds, blowdowns, incomplete combustion, or equipment venting. Venting emissions may be both routine of non routine.

Figure 26 provides an overview of the general characterization of methane emissions according to Directive 60 of the Alberta Energy Regulator (AER 2018). This is a reasonable and useful characterization, which seems to be standardized in North America. However, even though the determinations in Europa are comparable, there does not seem to be such a strict distinction and characterization in most literature sources.

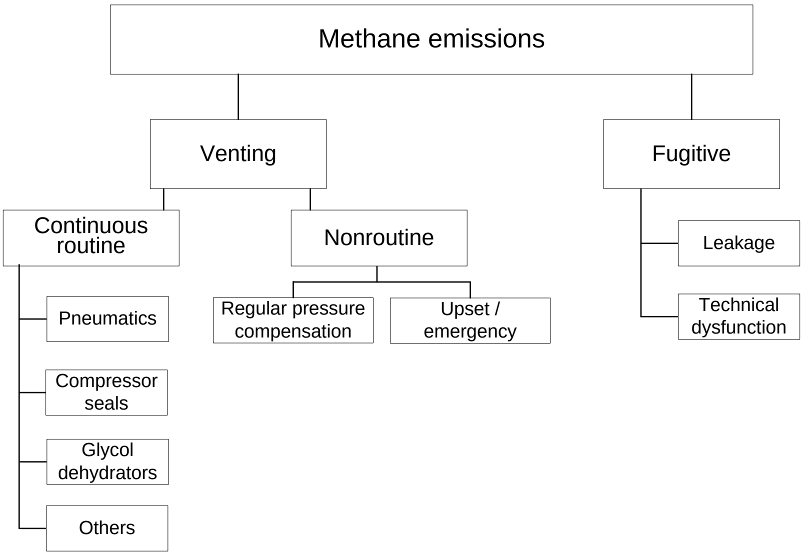


Figure 26 Characterization of general methane emissions from the natural gas supply system.

In the following, general sources of emissions and related processes along the entire supply network (cf. Figure 25), as described by (ICF International 2014) are listed an briefly explained.

Production

Raw gas (including methane) is vented at various points during the production process. Gas can be vented when the well is “completed” at the initial phase of production. As gas wells are often in remote locations without electricity, the gas pressure is used to control and power a variety of control devices and on-site equipment, such as pumps. These pneumatic devices typically release or “bleed” small amounts of gas during their operation. Water and hydrocarbon liquids are separated from the product stream at the wellhead. The liquids release gas, which may be vented from tanks unless it is captured. Water is removed from gas stream by glycol dehydrators, which deposit the removed moisture and vent some gas to the atmosphere. In some cases, the gas released by these processes and equipment may be flared rather than vented, to maintain safety and to relieve over-pressuring within different parts of the gas extraction and delivery system. Flaring produces CO_2, a significant but less potent GHG than methane, but no flare is 100% efficient, and some methane is emitted during flaring. In addition to the various sources of vented emissions, the many components and complex network of small gathering lines have the potential for fugitive emissions.

Processing

Although some gas is pure enough to be used as-is, most gas is first transported by pipeline from the wellhead to a gas processing plant. The gathering system has pneumatic devices and compressors that vent gas as well as potential fugitive emissions. Gas processing plants remove additional hydrocarbon liquids such as propane (and higher hydrocarbons) as well as gaseous impurities from the raw gas, including CO_2, in order to refine the gas to pipeline-quality for subsequent compression and transmission. Such plants are another source of fugitive and vented emissions. From the gas processing plant, natural gas is transported, generally over long distances by interstate pipeline to the “city gate” hub and then to consumers. The vast majority of the compressors that pressurize the pipeline to move the gas is fueled by natural gas, although a small share is powered by electricity. Compressors emit CO_2 and methane emissions during fuel combustion and are also a source of fugitive and vented methane emissions through leaks in compressor seals, valves, and connections and through venting that occurs during operations and maintenance.

Compressor station

Compressor stations constitute the primary source of vented methane emissions in natural gas transmission. Some power plants and large industrial facilities receive gas directly from transmission pipelines, while others as well as residential and commercial consumers have gas delivered through smaller distribution pipelines operated by local gas distribution companies (LDCs).

City gate and distribution line

Distribution lines normally require less compression power, also due to the lower pressures. However, also here compression is needed which causes vented emissions. Further methane emissions occur as fugitive emissions due to leakage from older distribution lines and valves, connections, and metering equipment.

4.3 Sources of CH_4 emissions in Europe

As European natural gas supply is mainly imported from Russia, Norway and Northern Africa while only parts of the transmission pipelines are within Europe, there is only very information on emissions regarding the entire European supply network from production to distribution as illustrated in Figure 25. The Technical Association of the European Natural Gas Industry (Marcogaz) estimates the distribution of methane emissions from the natural gas supply system within Europe as illustrated in Figure 27. The Figures are based on official data of the European greenhouse gas inventory report (EEA 2019).

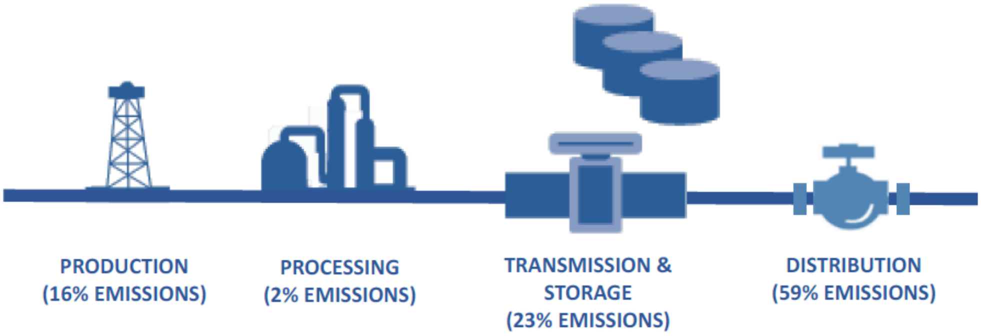


Figure 27 Distribution of emissions along the natural gas supply chain within the EU. It has to be considered, that most natural gas consumed within the EU is exploited and processed outside the EU and, hence, these indirect emissions are not considered in the EU methane balance (Marcogaz 2019)

Several studies estimate upstream emissions of European gas consumption with partly varying results. Exergia for instance quantified the methane emissions per kWh natural gas consumption excluding dispensing in Europe in the year 2012 with 53 gCO_2eq (Exergia 2015), while DBI quantifies the upstream emissions with 32 gCO_2eq/kWh in the same year (DBI 2016). The German Environment Agency (UBA) provides the following estimates of upstream emissions based on the study conducted by DBI (Köppel et al. 2018).

Table 12 Upstream CH_4 emissions in g/GJ based on the origin of natural gas supply as weighted average values (Köppel et al. 2018)

Origin	Transport and storage within the EU	Gas treatment within the EU	Gas transport outside the EU	Gas production	Total
Germany	67 g/GJ	6 g/GJ	0 g/GJ	18 g/GJ	91 g/GJ
Netherlands	67 g/GJ	6 g/GJ	0 g/GJ	11 g/GJ	83 g/GJ
Norway	67 g/GJ	2 g/GJ	2 g/GJ	15 g/GJ	86 g/GJ
Russia	67 g/GJ	0 g/GJ	70 g/GJ	12 g/GJ	149 g/GJ

It can be generally stated, that the distribution of emissions shown in Figure 27 would be stronger towards production and transmission when incorporating these upstream emissions from outside the EU, however it is difficult to clearly quantify these emissions due to insufficient data. Most information on CH_4 emissions covering the entire value chain from production, processing and transmission are from North America as the Canadian and US natural gas supply is based on domestic production. Figure 28 illustrates the distribution of methane emissions across the supply chain within the USA. Overall annual methane emissions from the natural gas supply system in the USA are estimated at around 7 Million tons/a while as depicted in Figure 28 major emissions occur during production, processing and transmission.

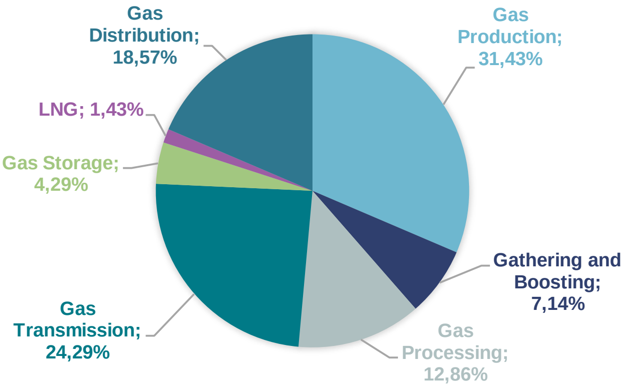


Figure 28 Distribution of methane emissions along the supply chain in the USA (ICF International 2014)

However, it is clear that there are differences in the natural gas production systems. While fracking, which is widespread in the US leads to higher emissions in production, the Russian and Ukrainian transmission system is in a worse condition than that in North America. In the European supply system, these processing steps mainly take place in Russia and some pipelines, especially the pipeline system via Ukraine is in a desolate condition with failure rates more than 10 times higher than in the EU (KPMG 2017). This also indicates high shares of production, processing and transmission emissions of natural gas consumed within the EU, even though it is very difficult to quantify these emissions based on current literature data. Le Fevre (2017) quantifies the emissions along the entire supply system in different countries as shown in Table 13. These data underline higher emissions during production in the US as compared to Russia, while the emissions during transmission are very high in Russia. These data further show higher emissions during production in Russia as indicated in Table 12, which additionally underlines the unclear data basis regarding upstream emissions.

Table 13 Methane emissions by country in kt/a along the natural gas supply chain (Le Fevre 2017). The rate refers to emissions either as percentage of a country's production or consumption of natural gas

	Production	Transmission	Distribution	Other	Total	Rate
Australia*	42	12	172	0	226	0.2%
Canada	104	46	38	295	483	0.2%
France	0	24	20	-	44	0.1%
Germany	1	76	89	27	193	0.2%
Italy	9	31	142	-	182	0.2%
Netherlands	0	7	6	-	13	Neg
Poland	16	6	13	-	35	0.1%
Romania	138	7	20	20	185	1.2%
Russia	1164	3715	497	-	5376	0.6%
Spain	0	2	24	-	26	0.1%
Turkey	2	24	54	-	80	0.1%
Ukraine	75	54	433	575	1137	1.4%
UK	3	2	149	-	154	0.1%
USA	4709	1349	439	-	6497	0.5%

As discussed before, the European natural gas grid is dominated by transmission, compression and distribution lines while production and processing increasingly takes place outside of Europe (cf. Figure 24). The reason of that is that all indigenous gas sources in the EU are in decline. Most literature about emissions from the natural gas grid and emission abatement technologies focus on North America. However, there are some information about methane emissions from the natural gas grid in Europe in the literature (see also Figure 27). Between 1990 and 2015, methane emissions from European gas operations decreased by 46% due to technical and operational measures taken by the natural gas suppliers (Gas Naturally 2018). In this context it has to be taken into account that in many cases emission abatement is directly linked to a reduction of losses or higher efficiency and, hence, to higher profits. This is in contrast to classical emission abatement that usually has no direct economic intensives. As discussed before, there are various sources of methane emissions from the natural gas grid and the overall emissions by source can only be estimated. Vorhang (2009) provide assumptions of sources of methane emissions from the European natural gas grid based on a survey within the natural gas industry. The classification of these emissions is not fully in line with the concept shown in Figure 26, however, fugitive emissions can be distinguished from venting while pneumatic emissions can be accounted to continuous routine venting as illustrated in Figure 26. Figure 29 summarizes the sources of emissions identified in Europe. The left pie chart is simply an aggregation of the more detailed emission sources shown on the right side.

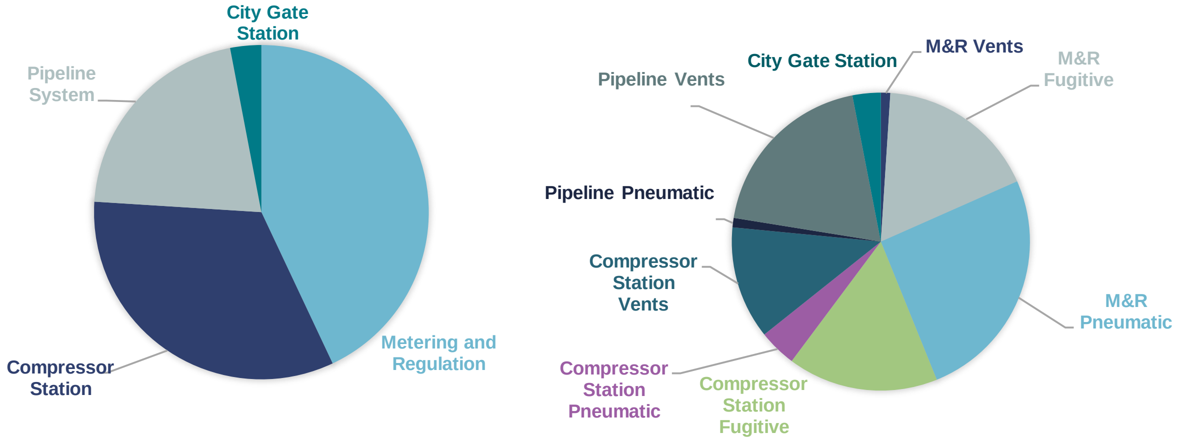


Figure 29 Major sources of methane emissions from the natural gas grid in Europe (Vorhang 2009). M&R stands for metering and regulation. Note that city gate stations may be accounted to metering and regulation, however, in this depiction they are listed separately

4.4 Potentials for emission reduction from the natural gas grid

In analogy to the numerous sources of emissions from the natural gas grid, there are various options for reducing emissions. A comprehensive overview on potential technical reduction measures is provided by the US Environmental Protection Agency within the Natural Gas STAR program (US EPA 2020c). Natural Gas STAR is a voluntary partnership between natural gas companies and facilitated by the US Environmental Protection Agency. Partners within the Program share project ideas to reduce methane emissions, and most projects achieve the goal of saving methane with positive economics. Many of these projects replace worn out equipment or begin new operating practices, and the new measures are often less expensive than what is currently in place. Reduced methane emissions to the atmosphere is an important consequence, but the primary project justification in many cases is cost savings (Lechtenböhmer et al. 2007). Vorhang et al. (2009) additionally provide best practices for reducing methane emissions. Generally, these measures can be categorized as technical measures by replacing existing equipment and organizational or management measures by replacing common practices e.g. for maintenance and inspection. In the upstream supply chain (production, processing and transmission) the detection of leakages is often difficult as methane is odorless and non-colored. However, there are recent approaches to detect leakages by infrared wave length cameras that are capable to visualize methane and fume methane releases in combination with aircraft and drone tools to monitor emissions over long distances of transmission pipelines, storage tanks and compressor stations in between[4]. These detection methods build upon the low volumetric density of methane compared to air.

Potential measures for emission reduction are listed below, while we describe the most promising technical solutions (equipment based) in the following section (ICF International 2014; Vorhang 2009; US EPA 2020c; Marcogaz 2019):

- Reduction of operating emissions: Use of low or zero emitting pneumatic and compressor systems with re-use of the gas instead of venting (see next section).
    - Replace centrifugal compressor seal oil systems (recover methane from seal oil).
    - Install low bleed pneumatic devices.
    - Use gas recompression when shutting down a compressor or pipeline.
- Reduction of maintenance emissions
    - Use of a mobile compressor to pump gas from a section to be vented into a neighboring section.
    - Use of a mobile flare unit to burn vented gas at pipeline maintenance works.
    - Convert the gas to power and heat for local use, e.g. for the gas processing equipment.
- Inspection and maintenance programs: Organizational measures to detect emissions earlier and stop them, also referred to as leak detection and repair (LDAR).
    - Optimize compressor shutdown practices
    - Minimize venting before pipeline maintenance
    - Perform periodic cost-effective leak inspections

The listed measures are generally relevant along the entire supply chain, however, several technical solutions might be restricted to their specific field of application. As methane emissions are gaining increasing importance and political attendance there are several collaborative industry initiatives working to improve understanding the scale of methane emissions, potential sources and opportunities for reductions. The most well-known of these include: the American Natural Gas STAR Program, the World Bank Global Gas Flaring Reduction Program, the Global Methane Initiative, the Oil & Gas Climate Initiative, the Methane Guiding Principles Coalition, the Climate and Clean Air Coalition – Oil and Gas Methane Partnership (Marcogaz 2019). The World Bank for instance has extensively worked on reducing direct methane emissions. A couple of conferences have been held on the subject in the first decade of this century.

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[4] See for example ConocoPhillips: http://www.conocophillips.com/sustainability/sustainability-news/story/testing-drone-technology-to-detect-and-quantify-emissions/

4.4.1 Technical Reduction Measures

The Natural Gas STAR program initiated by the US Environmental Protection Agency (US EPA 2020c) provides a comprehensive overview on mainly technological measures, by replacing current equipment and by optimizing inspection, maintenance and leakage detection (US EPA 2020c).

- Compressors/Engines
- Pneumatics/Controls
- Dehydrators
- Tanks
- Valves

The most promising and also cost efficient measures (low payback periods of investment, see next section) are the recovery of methane from seal oil in wet seal compressors and the replacement of high-bleed pneumatic devices (ICF International 2014). It is not fully clear to what extent these measures have already been implemented as their economic viability is obvious (in the EU high-bleed pneumatic devices are no longer in use). Nonetheless, one has to keep in mind that there might be split incentives between those shareholders providing and maintaining the infrastructure and those taking advantage from reduced losses. As discussed before, especially in the eastern European transmission systems there seems to be high potential for improvements. Both technologies are briefly described in the following, while detailed information and factsheets are available from (US EPA 2020c).

Wet seal compressors are a common and broadly used technology for natural gas compression in the transmission grid. These wet seal compressors cause emissions of methane, which is dissolved in the seal oil. A promising option to reduce these emissions is to install equipment to capture and use or flare the gas that flashes out during the degassing of the seal oil. This system uses two separators, one at high pressure, and one at lower pressure. The high pressure separator operates at the seal oil pressure, and the gas flow is controlled by a critical orifice. This high pressure captured gas is then routed to a seal oil demister to remove any remaining seal oil before being routed to beneficial use. The oil then flows from the high pressure separator to the atmospheric degassing separator where the remaining entrained gas is removed and vents to the atmosphere. This volume of gas is usually minimal, as most of the gas can be removed in the high pressure separator. The regenerated seal oil can then be recirculated back to the compressor seal oil system. Figure 30 displays the concept of seal oil degassing in wet centrifugal compressors. An alternative to wet compressors would be the use of dry seal compressors. However, their performance and especially maintenance costs are less beneficial as compared to wet seal compressors (ICF International 2014).

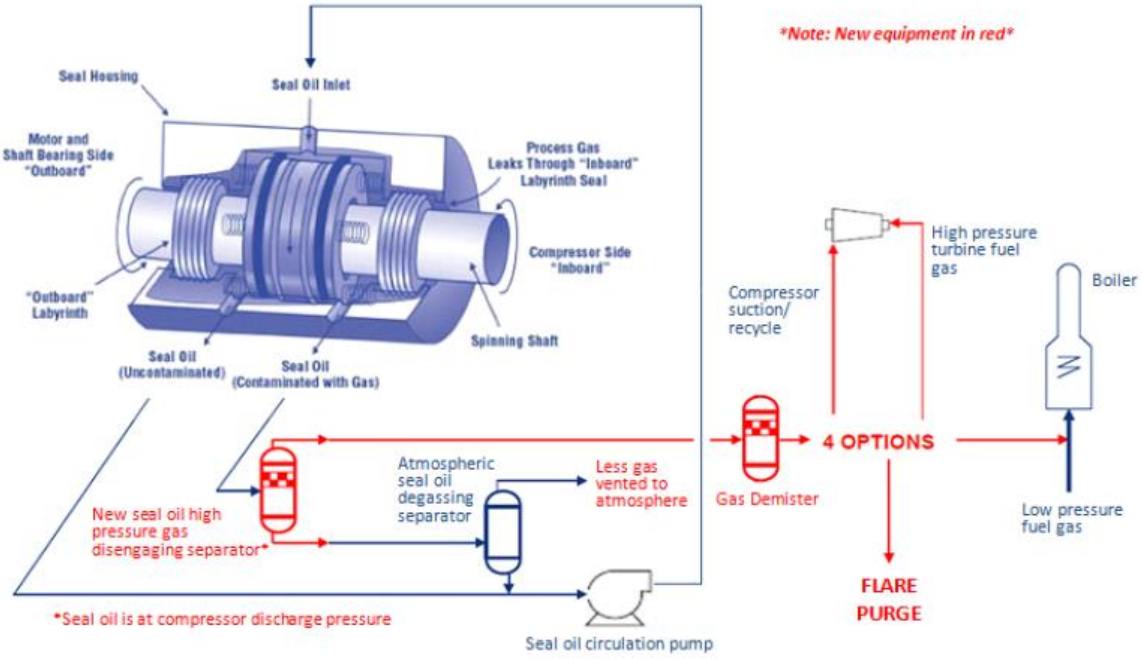


Figure 30 Example of a wet seal degassing recovery system for centrifugal compressors (US EPA 2014)

These systems have been installed and operated successfully as original equipment at several gas compression stations. Their use as a retrofit technology is a new application. Wet seal degassing recovery systems could potentially be installed at most locations with wet seal centrifugal compressors, though there may be limitations due to site-specific operating requirements. In order to implement this system, there must be a use for the recovered gas. Operators have several options on how to best utilize this gas, and these choices will impact the economics of the project. The most common options are (ICF International 2014):

- Use as high pressure turbine fuel
- Route the recovered gas as low pressure fuel
- Route back to compressor suction
- Use as a flare sweep gas

Not all of these applications may be available at all sites. In addition, gas recovered from the low pressure side of the compressor may not be usable for high pressure applications or may require compression depending on the application (US EPA 2014).

Beside wet seal compressors, high bleed pneumatic controllers are a major source of methane emissions in all sections of the natural gas supply chain (US EPA 2006b). A pneumatic controller means an automated instrument used for maintaining a process condition such as liquid level, pressure, pressure difference and temperature. Based on the source of power, two types of pneumatic controllers are defined for this report:

1. Natural gas-driven pneumatic controller means a pneumatic controller powered by pressurized natural gas.
2. Non-natural gas-driven pneumatic controller means an instrument that is actuated using other sources of power than pressurized natural gas; examples include solar/electric, and instrument air.

Modern installations do not have natural gas based pneumatic controllers anymore. Most controllers are electric. Only in hazardous environments, air-based pneumatic controllers might be an option, but also intrinsically safe electric controllers exist

Natural gas-driven pneumatic controllers come in a variety of designs for a variety of uses. They can be characterized by their emission behavior.

1. Continuous bleed pneumatic controllers are those with a continuous flow of pneumatic supply natural gas to the process control device (e.g., level control, temperature control, pressure control), where the supply gas pressure is modulated by the process condition, and then flows to the valve controller where the signal is compared with the process set point to adjust gas pressure in the valve actuator. Continuous bleed controllers can be further subdivided into two types based on their bleed rate (ICF International 2014):
    a. Low bleed, having a bleed rate of less than or equal to 6 standard cubic feet per hour (6 scfh = 0,17 m^3).
    b. High bleed, having a bleed rate of greater than 6 scfh.
2. Intermittent pneumatic controller means a pneumatic controller that vents non continuously. These natural gas-driven pneumatic controllers do not have a continuous bleed, but are actuated using pressurized natural gas.
3. Zero bleed pneumatic controller means a pneumatic controller that does not bleed natural gas to the atmosphere. These natural gas-driven pneumatic controllers are self-contained devices that release gas to a downstream pipeline instead of to the atmosphere.

The basic principle of a pneumatic controller is illustrated in Figure 31.

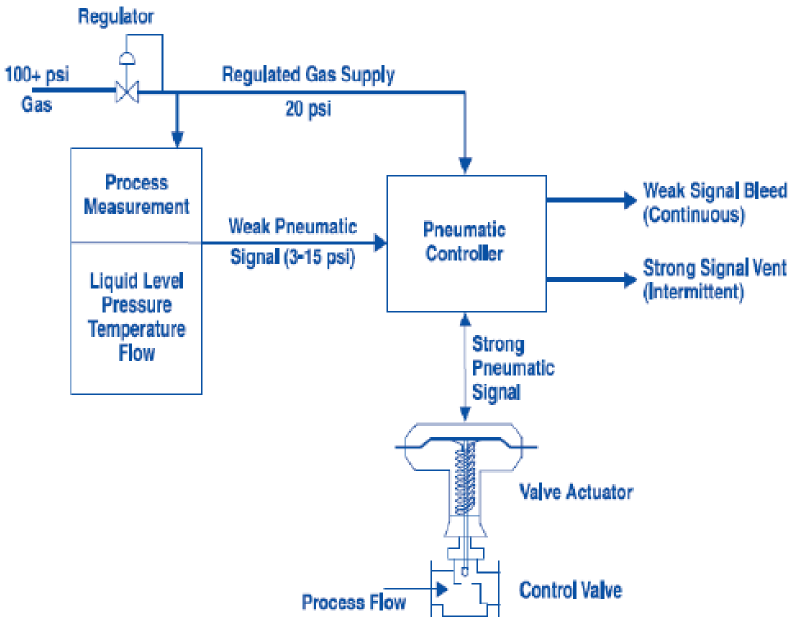
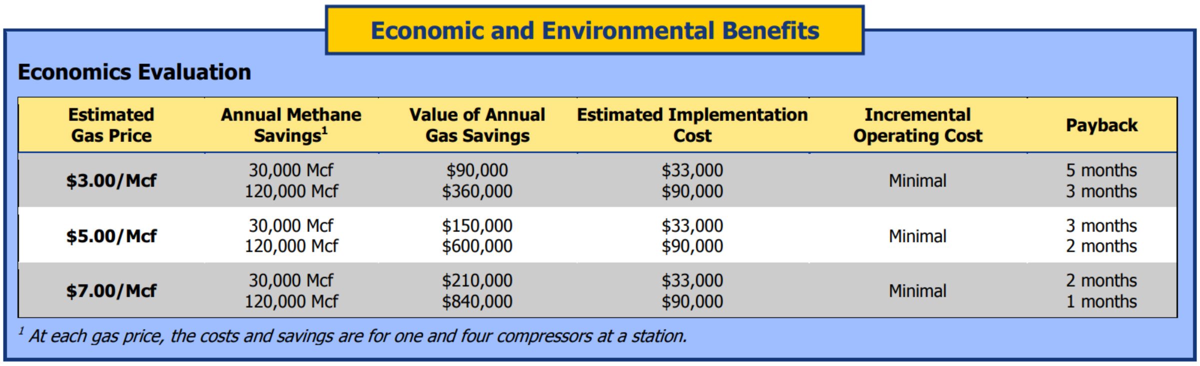


Figure 31 Concept of a pneumatic valve control system (US EPA 2006b)

Replacing continuous bleed and especially high bleed pneumatic devices may reduce emissions significantly. According to (Vorhang 2009), emissions from pneumatic devices still play an important role in the European gas system (cf. Figure 11) and also in the US, there are potential for emission reduction from pneumatic devices (US EPA 2020c). Beside management measures to reduce emissions such as optimized maintenance and early detection of leakages, seal oil gas recovery and the replacement of continuously bleeding pneumatic devices are considered promising measures for reduction of methane emissions. However, this requires site specific assessments of used equipment.

4.4.2 Techno-Economic issues of emission reduction in the natural gas grid

As described before, the Natural Gas STAR program is a voluntary partnership between natural gas companies, which is supported and facilitated by the US Environmental Protection Agency (US EPA). Partners within the Program share project ideas to reduce methane emissions and provide detailed economic data particularly regarding investment cost and potential savings (emission reduction costs). In contrast to classical environmental emissions, a reduction of methane emissions within the natural gas supply system by avoiding unintended leakages is in many cases associated with positive economic effects. (US EPA 2020c) provides detailed information on investments for various technical measures (see especially the Natural Gas STAR website[5]). The site specific collection includes both classical technical measures as described before and directed inspection and maintenance measures including expected costs and savings. Figure 32 provides an example of the economic evaluation of the implementation of wet seal degassing systems as described in the previous section (Figure 30).



Economic and Environmental Benefits

Economics Evaluation

Estimated Gas Price	Annual Methane Savings[1]	Value of Annual Gas Savings	Estimated Implementation Cost	Incremental Operating Cost	Payback
$3.00/Mcf	30,000 Mcf 120,000 Mcf	$90,000 $360,000	$33,000 $90,000	Minimal	5 months 3 months
$5.00/Mcf	30,000 Mcf 120,000 Mcf	$150,000 $600,000	$33,000 $90,000	Minimal	3 months 2 months
$7.00/Mcf	30,000 Mcf 120,000 Mcf	$210,000 $840,000	$33,000 $90,000	Minimal	2 months 1 months

[1] At each gas price, the costs and savings are for one and four compressors at a station.

Figure 32 Economic savings from the implementation of a wet seal degassing recovery system as an example of the information collected in the Natural Gas STAR program and provided by (US EPA 2020c)

ICF International (2014) has developed cost curves for emission reduction measures of which many show very low payback periods and have negative marginal abatement costs in the long run. Figure 33 provides an example of such a cost curve. Several measures such as wet seal degassing and the replacement of continuous bleed pneumatic devices have negative abatement costs and, hence, are desirable from an economic perspective. However, several non-technical measures such as higher frequency of inspection, maintenance and repair, which is also referred to as leak detection and repair (LDAR) are often associated with higher personnel cost and therefore less economical. Nonetheless, various measures for emission reduction are feasible with very low or no additional costs when considering the savings of valuable methane.

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[5] https://www.epa.gov/natural-gas-star-program/recommended-technologies-reduce-methane-emissions

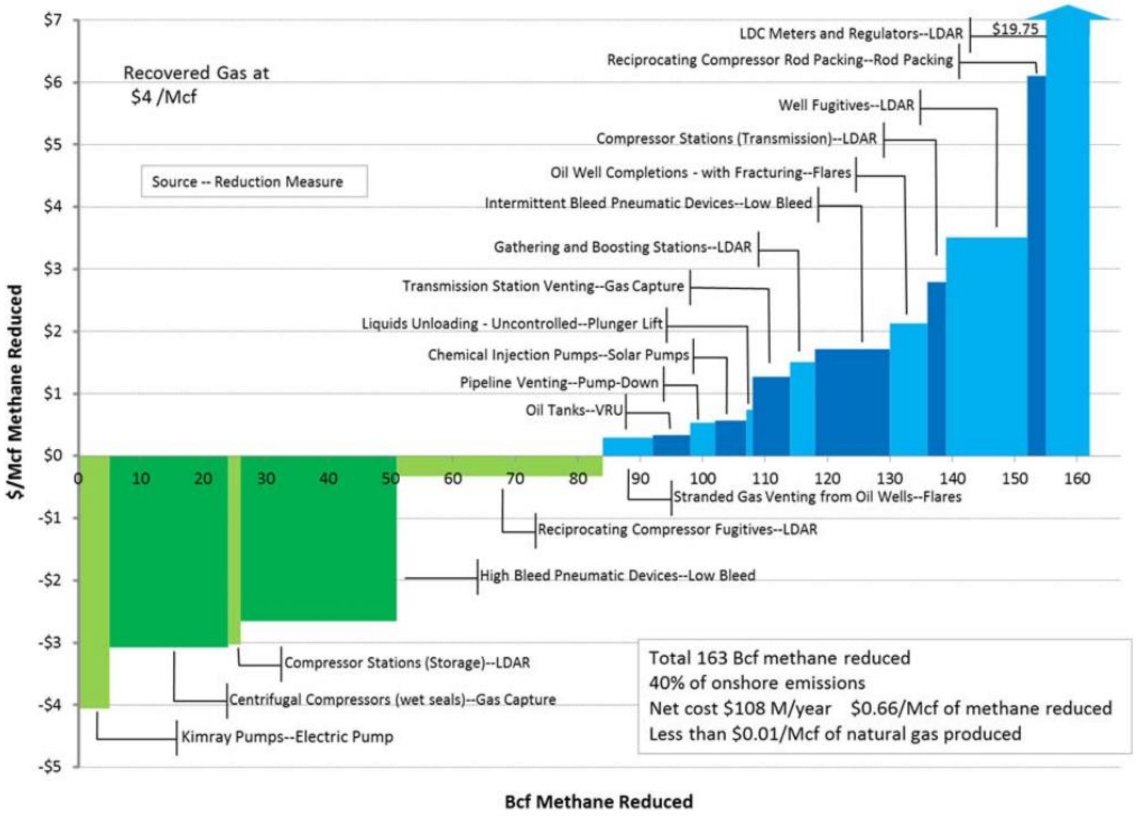


Figure 33 MAC curve (Marginal Abatement Cost) of various technical and organizational measures to reduce methane emissions from the US natural gas system (ICF International 2014)

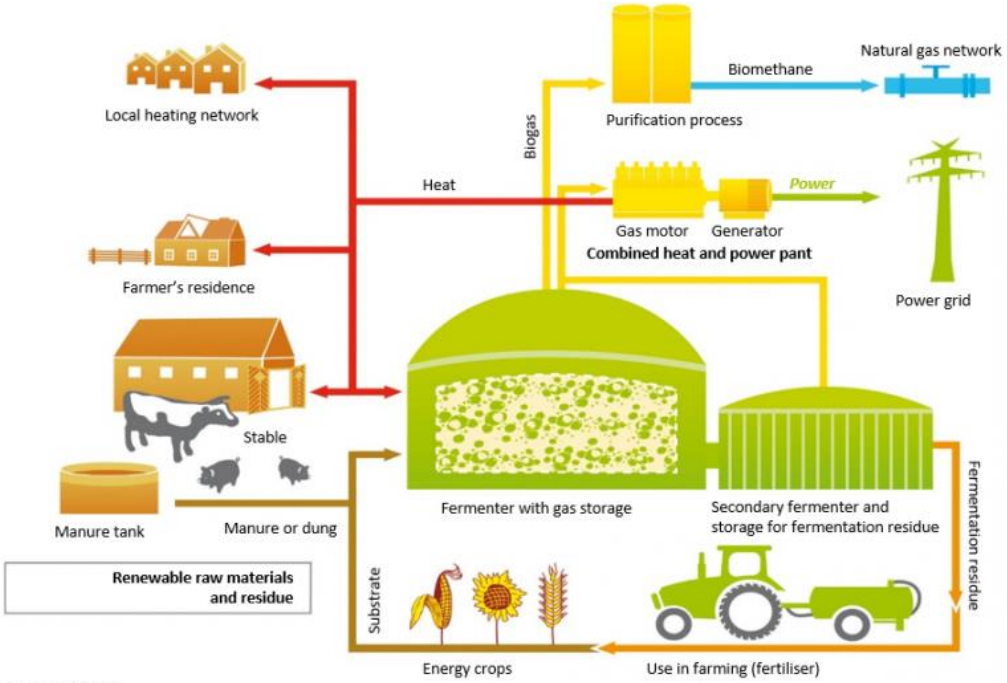
The United States Environmental Protection Agency (EPA) has recently published an assessment of global abatement potential for natural gas and oil systems by country. The data used to develop the marginal abatement cost curves in the report are also based on information from ICF international comparable to those shown in Figure 33. The authors find that in 2030 for the EU, roughly 26% of projected emissions from the natural gas sector can be abated, with roughly 20% of the abatement coming in a zero or negative cost (US EPA 2019a).

5 Emissions from biogas facilities

An increasingly discussed source of methane emissions that is not separately listed in common statistics in most cases (cf. Figure 1), are emissions from biogas facilities.
At least in the German emission inventory, several emissions of biogas facilities are already listed and assigned either to the sector agriculture, energy or waste. However, the list is missing out on several uncontrolled emissions which are not taken into account by the calculations yet. The results of the emissions inventory are therefore not suitable for calculating the greenhouse gas efficiency of biogas production overall. This is only possible with separate greenhouse gas balances. (Wulf et al. 2019)
Biogas facilities are commonly directly linked to a cogeneration plant for electricity production and local heat provision. Due to extensive subsidy policy, the number of biogas units has strongly increased in some EU member states such as Germany. These emissions cannot directly be accounted to classical agricultural emissions (these emissions are not in the focus of TFTEI) but may have technical origin and are therefore also shortly considered in this report. As leakages during fermentation or incomplete burning within the power plant may strongly contribute to local methane emissions, we provide some additional information on methane emissions from biogas facilities in the following section. Because literature data on these emissions are rare, we provide some basic projections on the example of Germany, which is an EU member state with a large spread and number of biogas plants (cf. Figure 36).

5.1 Structure of a biogas plant

Agricultural biogas plants are operated with liquid manure, dung, harvest residues, energy crops or biowaste (Hirn and Milles 2014, p. 3). The spectrum ranges from mono-digestion plants for the sole fermentation of a single substrate to the co-digestion of mixture (Balussou 2018, p. 7, 15).



Source: FNR e.V.

Figure 34 Flow chart of a biogas / biomethane plant (FNR e.V.) based on anaerobic digestion of various sources of biomass

The liquid manure is collected in a tank near the digester and from there it is fed discontinuously by pump (cf. Figure 34). Energy crops (maize, grass, whole cereal plants) are mostly ensiled or stored. If necessary the substrates are pre-treated, e.g. crushed and subsequently fed into the digester. The anaerobic fermenter (and secondary fermenter) consists of an air-tight, coated steel or concrete tank with membrane roof. The most common type of roof construction has become a double membrane system, which also fulfills the function of an internal storage. However, construction designs with external, separate gas storage tanks are also at option, in which the fermenter can be covered gas-tight with a less expensive single membrane or with constructions made of concrete and steel (Rettenberger 2017, p. 30).

The fermenter system is provided with insulation and often also with a heater, as a constant temperature must be maintained inside for the microorganisms. Either the fermenter is designed for mesophilic temperatures (about 35°C) or thermophilic temperatures (about 55°C). Inside the fermenter there is a central agitator or one or more other agitators which ensure the required complete mixing of the fermenter contents.

The average minimum residence time in the digester is 20 days for liquid manure. Energy crops and harvest residues mostly have retention times of at least 40 days. During this time the organic substances are converted by the microorganisms. This results in two different end products: Biogas (methane: 50 -75 vol.-%) and digested fermentation residues. The digestate, which is temporarily stored on site, is mostly used as fertilizer due to its high ammonium content.

The biogas is temporarily stored in gas storage tanks, which are located e.g. on the first fermenter, the secondary fermenter and on the fermentation residue tank. In Germany, in most of the biogas plants the biogas is used to supply combined heat and power plants (CHP), which in addition to electricity also provide heat.

A further issue is the purification of biogas to biomethane. This is increasingly stimulated because it can replace natural gas, which is from fossil sources. However, offgas produced during biogas upgrading still contains a certain amount of methane depending on the methane recovery of the applied gas separation technology (Severn Wye Energy Agency 2012). Mainly older installations using outdated gas separation technology have relatively high methane emissions. On the market already modern technologies are available that are able to produce biomethane with very small emissions of methane and their installation can therefore help to avoid substantial methane emissions (Klimstra 2009).

The focus of the studies conducted so far were the methane emissions which are directly related to the operation of biomass fermentation installations and a connected CHP unit. However, it must be taken into account that especially the fermentation residues are a potential source of greenhouse gas emissions and the emission of air pollutants such as ammonia.

Depending on the substrate used and the time the substrate remains in the fermenter, a gas-tight covering of the fermentation residue storage is therefore mandatory (Bayerisches Landesamt für Umwelt 2011, p. 19). In addition to gas-tight covering also other, non-constructional options are available to reduce the methane emissions significantly, such as acidification of the fermentation residues (Rettenberger 2017).

5.2 Sources of CH_4 emissions in biogas facilities

However, for some years, it has been known that in biogas plants significant amounts of methane (the main component of biogas) can escape, not only through leaks but also through the methane slip of certain plant components. This applies not only to digestion units, but also to plants for cleaning the raw biogas as well as to gas engines used to generate electricity from biogas.

The following diagram summarizes the results of two studies in which sources of methane emissions were determined in 302 installations (cf. Figure 35).

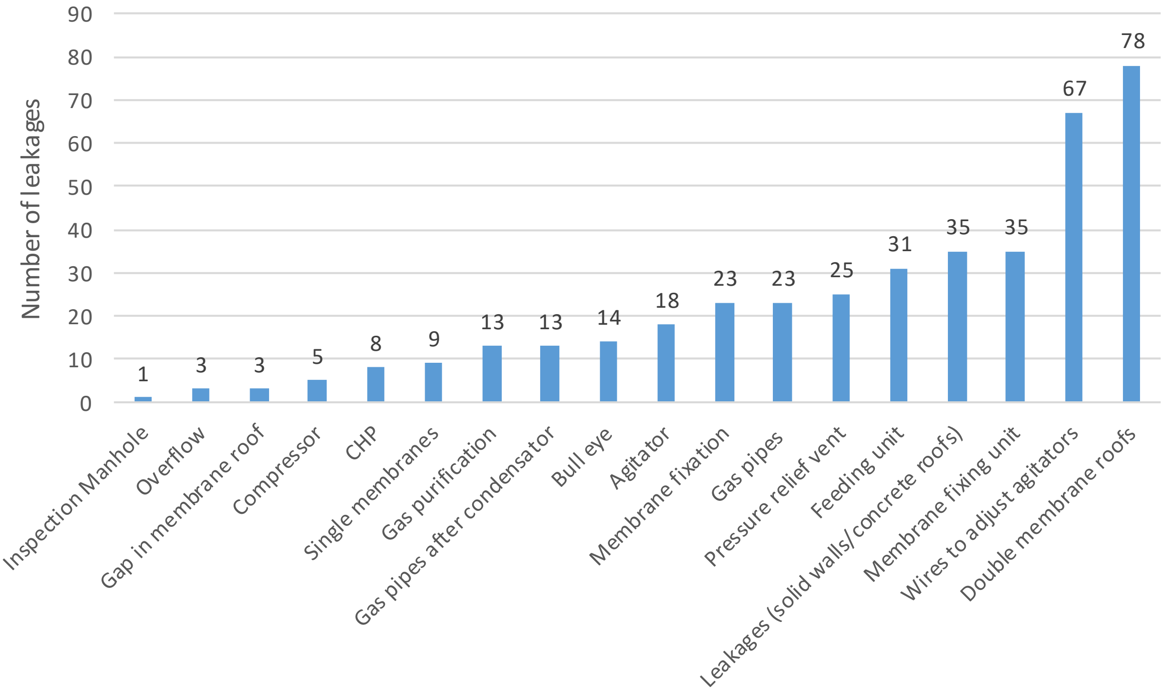


Figure 35 Identified leakages from biogas plants in Germany (data from Schreier (2011) and Clemens (2014) based on an overall number of 302 installations that have been determined)

It illustrates the frequency with which emissions were measured at different parts of biogas plants. The results of Schreier (2011) and Clemens et al. (2014a) show that a significant number of installations have leaks. Out of a total of 302 installations examined, 78 leaks were found in the double membrane roof alone (cf. Figure 35).

For locating the methane leakages in the first step, different measurement equipment was used. As methane-specific equipment e.g. portable methane laser were used and as not methane-specific equipment e.g. IR cameras, which provide no concentration data but only visualization (Reinelt et al. 2017, p. 175; Clemens et al. 2014b).

However, the number of leaks does not yet tell anything about the absolute amount of methane leaking from a source. For example, one case was recorded in which 5 % of the methane produced escaped from an improperly closed maintenance hatch (IEA 2017b, p. 29). Whereas according to Reinelt et al. (2017) the level of leaks was usually below 0,044 % of methane produced.

For the next step of quantification measurements also multiple methane-specific devices were used, like photo-acoustic analyzer or FID-Cutter (flame ionization detection) (Reinelt et al. 2017, p. 175).

The causes for leakages are numerous and leaks can be found at almost any component of the plant in sections containing biogas (cf. Figure 35). Reasons for that can be partly obsolete or insufficient technology. It should also be mentioned that a certain methane diffusion rate is tolerated in components such as membranes. The Safety Guidelines of the German Agricultural Employer's Liability Insurance Association, for example, define a threshold of permeability related to methane $< 1000 \text{ cm}^3 / (\text{m}^2 \text{ x d x bar})$ (SVLFG 2016, p. 24). Emissions lower than that are therefore not included in the statistics above.

Due to differences in measurement methods and the lack of legally binding guidelines, the comparability of measurement results is currently limited. In future, a harmonization of the methods could also improve the precision, reproducibility and representativeness of the measured values (IEA 2017b, p. 35). For balancing purposes, a total leakage rate of 1% is assumed as a plausible estimate for the current biogas plant inventory in Germany (UBA 2012, p. 76).

It might be unexpected that the CHP unit is also a potential methane emission source, but unfortunately, combustion in the engine is not complete, so that a certain amount of methane slip can occur; methane then escapes with the exhaust gas. The amount of the methane slip is dependent on the type of engine and, if applicable, the exhaust gas after-treatment, as well as on the gas quality and operating conditions. Therefore, not only the use and further development of modern plant technology are crucial, but also having the plants operated and maintained by trained personnel.

Depending on how the system boundaries are defined, the methane emissions from substrate storage prior to the actual digestion and the storage or spreading of digested residuals on agricultural land must also be taken into account. Adding all that, experts assume that about 5% of the methane produced in biogas plants escapes uncontrolled into the atmosphere (UBA 2012, p. 80).

By using this percentage emission value and additional data on biogas production, which can be found in the literature, basic projections of methane emissions from biogas plants can be carried out.

5.3 Basic projections of methane emissions from biogas plants

Favored by political support measures, the number of installed biogas plants in Germany has increased significantly in the last 20 years and currently amounts to over 9.400 units (Fachverband Biogas e.V. 2019, p. 2), which produce about 31.9 TWh (2019) of electricity per year (AGEE-Stat 2020, p. 6). (cf. Figure 36). With an average methane content in biogas of 60 vol-% and 6 kWh per m^3 biogas and knowing that the maximum electrical efficiency of a CHP unit is approximately 47% and the minimum efficiency is approximately 28% (FNR 2018, p. 48), a quantity of methane between 6,79 x 10^9 m^3 and 11,39 x 10^9 m^3 is required to obtain this amount of electricity.

Further considering the loss value of 5% already mentioned above: the lower range of the uncontrolled CH_4 emission is around 244.340 t per year and a calculated upper range around 410.143 t of methane per year, in Germany. This result supports the current projection made by the Federal Environment Agency experts, which assume approx. 300.000 t methane per year (UBA 2019, p. 8).

In the rest of Europe (former EU28), about another 29.5 TWh of electricity are generated by biogas plants (eurostat 2020b). Ceteri paribus in addition to the calculations for Germany, an amount of annual CH_4-emission between 225.957 t in the best case and 379.286 t in the worst case seems to be realistic. Regarding overall European emission levels of methane (see Figure 1), this makes around 3-4% of overall emissions, which seems very high compared to 5% emissions from the natural gas grid.

If only the fermentation of farmyard manure is considered, the total emissions of methane are reduced. This is mainly due to the gas-tight covering of a large part of the fermentation residue storage tanks and use of the resulting CH_4. On the other hand, including the fermentation of energy crops in the agricultural emissions inventory leads to an increase in overall methane gas emissions, since the total amount of fermentation residues is greater than the amount of farm manure used for fermentation. Calculations of the FNR e.V. from 2019 with the data of 2017 show, that the additional emissions [CO_2eq] in the agricultural sector amount to only 17% of the emissions saved in the energy sector by using biogas. But again, not all of the emissions from biogas production were considered. (Wulf et al. 2019)

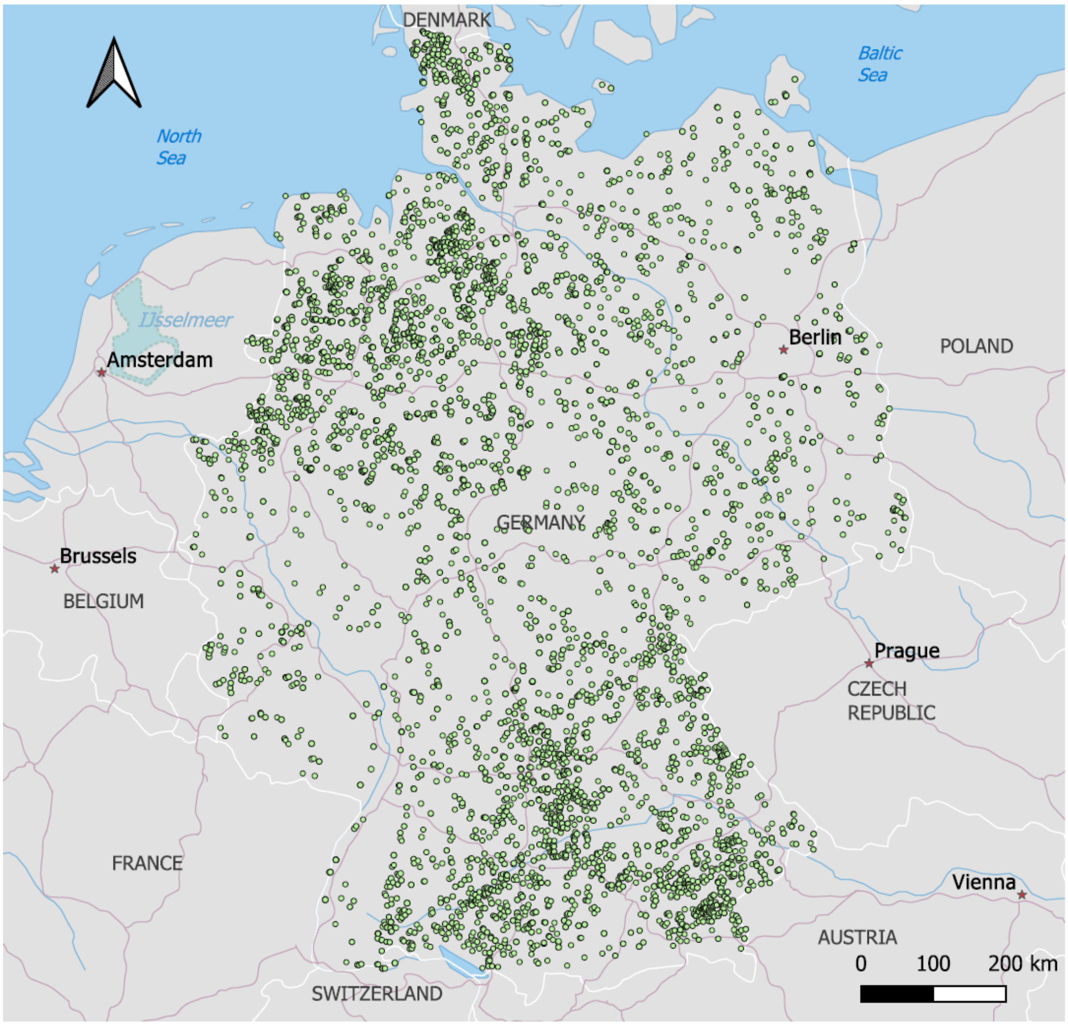


Figure 36 Locations of biogas plants in Germany (own illustration based on data from Marktstammdatenregister 2020[6])

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[6] See official registration data of the German Federal Network Agency for Electricity, Gas, Telecommunications, Post and Railway: https://www.marktstammdatenregister.de/MaStR

The studies show how biogas plants become sources of methane emissions over several process steps and a multitude of technical functional units. This leads to the conclusion that GHG emission mitigation –which is a main reason for the production of biogas– is significantly reduced.

Further research and development in this field can help to expand the practically usable methane saving potential and thus further exploit the current theoretical saving potential.

6 Conclusions and outlook on further work of TFTEI regarding methane emissions

After CO_2, which is the most important GHG, methane is considered the second largest source of GHG emissions. Methane is responsible for about 18% of the global overall GHG emissions. Beside the importance of CH_4 emission abatement for climate change mitigation, methane is a precursor of ground-level ozone formation. Hence, also from an air pollution and human health perspective, CH_4 emissions are an important issue. This makes CH_4 both a greenhouse gas and an air pollutant.

The goal of this report was to give a short but comprehensive overview on non-agricultural sources of methane emissions in Europe as well as related abatement technologies. As indicated in the different sections, there is still technical potential for improvement but also organizational aspects such as early leakage detection and repair are of high importance for reducing methane emissions. The specific focus of the work was Europe in a first step, however, it seems reasonable to take into account further regions in future TFTEI work. The report focused on methane emissions from landfills, the natural gas grid and biogas facilities. Landfill gases are the most important source of methane emissions in Europe with around 20% of overall emissions. Due to the reduction of landfilled waste in recent decades and gas collection and utilization systems, emissions in Europe will decline in the coming years. However, at a global level landfill emissions, also due to the strong increase in disposed solid waste in the previous decades, will remain a key source of methane emissions. The natural gas grid only contributes to overall methane emissions in Europe with around 5%. The analysis clearly showed that the majority of emissions caused by natural gas consumption do not occur in the European distribution grid but mainly during production, processing, compression and transmission of natural gas, which often takes place outside of Europe, mainly in Russia and Northern Africa. Therefore, it seems reasonable to focus on gas producing regions rather than on European consumption in future TFTEI work. A source of methane emissions that is an upcoming issue in academic literature are emissions from biogas facilities. As these emissions are not directly accountable to agriculture but have technical background, this report also briefly discussed CH_4 emissions from biogas facilities. With an estimated contribution of 3-4% to overall European emissions, this source should be stronger tackled in the future as the main intention of biogas facilities is to reduce GHG emissions by replacing fossil fuels. When considering the much higher GWP of methane compared to $CO_{2,}$ these emissions are highly counterproductive. The decentralized production of biogas and operators with little technical specialization make the mitigation of emissions from biogas facilities difficult.

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