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Addendum

Guidance document on technical measures for reduction of methane emissions from landfill, the natural gas grid and biogas facilities

Summary

With its decision 2023/2 made at the forty-third session (Geneva, 11–14 December 2023), the Executive Body adopted the Guidance document on technical measures for reduction of methane emissions from landfill, the natural gas grid and biogas facilities, and requested the secretariat to issue a final version of the document (ECE/EB.AIR/154, annex I). The Guidance document is aimed at supporting Parties in reducing their methane emissions from key non-agricultural sources, such as municipal solid waste landfills, natural gas supply systems and biogas facilities.

I. Introduction

1. The present Guidance document on measures for the reduction of methane (CH_4) emissions, developed by the Task Force on Techno-economic Issues, is aimed at supporting the Parties in reducing CH_4 emissions from the main non-agricultural sources. The Guidance document covers CH_4 emissions from municipal solid waste landfills, natural gas supply systems and biogas facilities. The document includes information on landfill gas emissions and techno-economic analyses of landfill gas collection and utilization systems. Furthermore, information on emissions from the natural gas grid and associated emissions along the entire value chain is addressed. Besides technical aspects of emission reduction through, for example, the application of zero-emitting pneumatic and compressor systems, more management measures, such as the reduction of maintenance emissions and inspection programmes, to identify non-intended fugitive emissions early on, also referred to as “leak detection and repair”, are of key importance in reducing CH_4 emissions from the natural gas supply system. An outlook on CH_4 emissions from biogas plants, which are also considered to be an important source of CH_4 emissions from technical applications, is additionally provided in the present document. The guidance on co-mitigation for CH_4 and NH_3, developed by the Task Force on Reactive Nitrogen in collaboration with the Task Force on Techno-economic Issues, is also relevant to CH_4 emissions from biogas.

2. Anthropogenic CH_4 emissions have become an emerging field of interest regarding emission reduction measures because CH_4 is both an important greenhouse gas (GHG) and air pollutant because it acts as a precursor of ground-level ozone formation. Ground-level ozone is an important air pollutant with both human health and environmental impacts, as well as being the primary component of smog. Therefore, mitigating CH_4 emissions is considered of interest both for climate change and air pollutant policies.

3. Due to the diversity in CH_4 emissions from various sources and industry sectors, measures to reduce CH_4 emissions are manifold and cannot be reduced to a simplified collection of technical measures. In many cases, for example, the reduction of emissions from the natural gas grid, management aspects such as maintenance procedures and early leakage detection are among the most important reduction measures. However, leakage detection can also be supported by modern mobile sensor technologies, as described in section III.B below.

4. The synthesis provided below sets out the main issues concerning CH_4 emissions and the emission reductions that can be achieved through the implementation of suitable measures to landfills (gas formation) and the natural gas supply grid, including some considerations on biogas facilities. The information reported is based on the latest information available from different scientific and industry sources, as well as from public institutions, such as environmental agencies.

II. Background information

A. Methane emissions

5. CH_4 is considered to be the second-largest source of GHG emissions after carbon dioxide (CO_2), which is regarded as the most important GHG. CH_4 is responsible for about 19 per cent of global overall GHG emissions.[1] In addition to the importance of CH_4 emission abatement for climate change mitigation, CH_4 is a precursor of ground-level ozone, which is an environmental and human health concern. Hence, CH_4 emissions are also of the utmost importance from an air pollution and human health effects perspective. Consequently, CH_4 has to be considered as being both a GHG and an air pollutant.[2]

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[1] J. G. J. Olivier and J.A.H.W. Peters, *Trends in global CO_2 and total greenhouse gas emissions: Summary of the 2019 Report* (The Hague, PBL Netherlands Environmental Assessment Agency, 2019).

[2] European Environment Agency (EEA), “Annual European Union greenhouse gas inventory 1990–2017 and inventory report 2019: Submission under the United Nations Framework Convention on Climate Change and the Kyoto Protocol”, EEA/PUBL/2019/051 (n.p., 2019).

6. According to basic estimates, about 40 per cent of global CH_4 emissions come from biogenic (natural) sources, such as wetlands, while the remaining 60 per cent come from to anthropogenic sources.[3] Atmospheric CH_4 concentration has tripled since the beginning of industrialization in 1750.[4] CH_4 emission growth is highly related to increasing emissions from human activities, such as agriculture, fossil fuel production and solid waste and wastewater treatment, while agriculture is the largest anthropogenic source of global CH_4 emissions.

7. Nowadays, around 50 per cent of anthropogenic CH_4 emissions are generated by activities in agriculture (mainly due to livestock farming and enteric CH_4 formation by cattle and sheep, or emissions from liquid manure and rice production).[5] Gases from municipal solid waste landfills and oil and gas production are the largest non-agricultural sources of CH_4 emissions.

8. As an example, in the European Union, since 1990, actions have been implemented to reduce CH_4 emissions, which, in combination with the introduction of structural measures, have led to a decrease in CH_4 emissions of about 37 per cent within the European Union region. However, said decrease is mainly driven by the reduction of both waste stored in landfills and coal mining activities, which directly affected CH_4 emission levels in Europe. At the global level, there has been a continuous increase in anthropogenic CH_4 emissions from agricultural activities, fossil fuel extraction and waste landfills.[6] Hence, significant potential exists for CH_4 emission reduction, especially a number of options regarding landfill emissions and natural gas operations, which are discussed in the following sections. Subsequently, the present guidance briefly assesses the issue of CH_4 emissions from biogas facilities, which are also considered as technology-related emissions and therefore fall under the revised mandate of the Task Force on Techno-economic Issues. Agricultural emissions, although highly relevant, are not considered in the present guidance because agricultural sources are the competence of the Task Force on Reactive Nitrogen.

B. Emissions from landfill

Landfill gases

9. Global CH_4 emissions from landfills are estimated to be 500–800 megatons of CO_2 equivalent per year ($MtCO_2$-eq/yr).[7] Direct emissions from the urban waste sector almost doubled during the period 1970–2010. Globally, only approximately 20 per cent of municipal solid waste is recycled, and approximately 13.5 per cent is treated with energy recovery, while the rest is deposited in open dumpsites or landfills.[8] In the European Union, landfilled waste has continuously decreased in recent years and is currently at around 15 per cent.[9] However, there are still significant differences between the European Union member States. In Eastern Europe, the Caucasus and Central Asia, landfill rates in the past were up to 100 per cent[10] (with respect to total waste) and, despite the lack of up-to-date data, it can be assumed that current landfill rates of municipal solid waste are not significantly below the

[3] International Energy Agency (IEA), *World Energy Outlook 2017* (n.p., 2017).

[4] Shushi Peng and others, "Inventory of anthropogenic methane emissions in mainland China from 1980 to 2010", *Atmospheric Chemistry and Physics*, vol. 16, No. 22 (2016), pp. 14545–14562.

[5] EEA, "Annual European Union greenhouse gas inventory 1990–2017".

[6] Zosia Staniaszek and others, "The role of future anthropogenic methane emissions in air quality and climate." *npj Climate and Atmospheric Science*, vol. 5, art. No. 21 (2022).

[7] United States Environmental Protection Agency (US EPA), "Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990–2020" (Washington, D.C., 2006).

[8] Ottmar Edenhofer and others, eds., *Climate Change 2014: Mitigation of Climate Change – Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (New York, Cambridge University Press, 2014).

[9] EEA, "Diversion of water from landfill in Europe", available at www.eea.europa.eu/ims/diversion-of-waste-from-landfill.

[10] United Nations Environment Programme (UNEP) and EEA, *Sustainable Consumption and Production in South-East Europe and Eastern Europe, Caucasus and Central Asia: Joint UNEP-EEA Report on the Opportunities and Lessons Learned*, EEA Report No. 3/2007 (Luxembourg, Office for Official Publications of the European Communities, 2007).

global average. It has been estimated that, annually, about 50 Mt of CH_4 is generated in global landfills, 6 Mt of which is collected or eliminated at sanitary landfills.[11]

10. 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 CO_2 and CH_4.[12]

11. Landfill gas generation occurs under a four-phase process. First, CO_2 is produced under aerobic conditions. Then, oxygen (O_2) is depleted, and CO_2 and hydrogen (H_2) are produced under anaerobic conditions. Then CO_2 production depletes in proportion to the formation of CH_4. Lastly, CH_4, CO_2 and nitrogen (N_2) production stabilize. CH_4 produced by anaerobic methanogenic microorganisms in landfills can then take the paths listed below:

(a) Emission into the atmosphere;

(b) Recovery via gas wells;

(c) Oxidation by aerobic methanotrophic microorganisms in cover soils.

12. Facility CH_4 recovery (also referred to as "capture efficiency") varies by landfill type and ranges from 10 per cent, for open dumps, to 75 per cent for basic landfills, and 85 per cent for engineered landfills.[13] However, significantly higher collection efficiencies have been demonstrated in certain well designed and operated landfills, with final covers of up to 95 per cent.[14] A detailed description of the respective technical measures for CH_4 emission reduction from landfills is provided in section III below.

C. Emissions from the natural gas grid

13. The oil and gas sector, which includes natural gas processing and transportation, is one of the major sources of CH_4 emissions globally. Emissions can occur during various stages, such as production, processing, transportation and storage. While the percentage of CH_4 leaked compared to the total volume of natural gas produced might seem small (typically cited in the range of 1–3 per cent), given the large volume of natural gas production, these emissions are significant. Due to the comparatively low production volumes of natural gas within the European Union-28, the emission share is only around 5 per cent of overall emissions.[15]

14. The different processing steps of gas collection, compression, transmission and distribution are briefly described below. There are many sources of CH_4 emissions across the entire gas supply chain. Such emissions are characterized as either "fugitive" or "vented" emissions:[16]

(a) Fugitive emissions occur when CH_4 "leaks" unintentionally from equipment, such as incorrectly operating flanges or valves. Also, leakages in pipelines or tanks generally account for fugitive emissions;

(b) Vented emissions occur when CH_4 is released due to equipment design or operational procedures, such as pneumatic device bleeds, blowdowns, incomplete combustion or equipment venting. Venting emissions may be considered routine or non-routine.

[11] See definition of the term "Landfill gas" in Eduardo Calvo Buendia and others, eds., *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Glossary* (n.p., Intergovernmenal Panel on Climate Change, 2019); and Nikolas Themelis and Athanasios Bourtsalas, "UK waste management: Growing old or growing clean", Waste Management World, 5 June 2013.

[12] Buendia and others, *2019 Refinement*.

[13] US EPA, "Global non-CO_2 greenhouse gas emission projections and marginal abatement cost analysis: Methodology documentation", Report No. EPA-430-R-19-012 (n.p., 2019).

[14] Themelis and Bourtsalas, "UK Waste Management".

[15] EEA, "Annual European Union greenhouse gas inventory 1990–2017".

[16] Alberta Energy Regulator, "Directive 060: Upstream Petroleum Industry Flaring, Incinerating, and Venting" (n.p., 2018).

15. The natural gas supply network consists of the basic production facilities, where raw natural gas is collected from various well sites. The raw gas containing water, sulfur, additional hydrocarbons and further impurities is then transferred to the processing plant, where it is refined and prepared for transmission. Since natural gas is usually transported via transmission pipelines over very long distances, high-pressure values are required that are generated in proper compressor stations installed along the transmission lines. Large consumers, such as electrical power plants, are sometimes directly connected to the transmission lines. However, most of the natural gas is transferred from transmission lines to the "city gate". The city gate is the place where the transmission system feeds into a lower pressure distribution system that brings natural gas directly to the consumer (homes and businesses). At the city gate, the pressure of the gas is reduced and normally an odourant (typically mercaptan) is added to the gas to enable detection of leaks thanks to the characteristic odour. In some countries, such as France and Spain, odourant is added directly in the transmission line. While transmission pipelines may operate at pressures of over 70 bar (1,000 pounds per square inch (psi)), distribution systems operate at much lower pressure values (1.5–10 bar).[17]

16. General sources of emissions and related processes along the entire supply network are listed and briefly explained below:[18]

(a) **Production.** Raw gas (including CH_4) 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 supply, gas pressure is used to control and power a variety of control devices and onsite equipment, such as pumps. Such 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 captured. Water is removed from the 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 overpressuring within different parts of the gas extraction and delivery system. Flaring generates CO_2 but flaring efficiency is lower than 100 per cent, and, in any case, some CH_4 emissions are released 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, particularly in non-conventional deposits, which are exploited through fracking;[19]

(b) **Processing.** Although, in some cases, the gas is pure enough to be used as it is, most of the gas is transported by pipeline from the wellhead to a gas-processing plant, first. The gathering system is equipped with pneumatic devices and compressors to vent gas, as well as potential fugitive emissions. The gas-processing plants remove additional hydrocarbon liquids, such as propane (and further liquid hydrocarbons), as well as gaseous impurities from the raw gas, including CO_2, in order to refine the gas and to achieve 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 inter-State pipeline, to the "city gate" hub, and then to the final consumer. The vast majority of the compressors used to pressurize the pipeline needed to move the gas are fuelled by natural gas, although a small share is powered by electricity. Compressors are a source of CO_2 and CH_4 emissions due to fuel combustion, and are also a source of fugitive and vented CH_4 emissions through leaks in compressor seals, valves and connections, and through venting occurring during operations and maintenance;

(c) **Compressor station.** Compressor stations are the primary source of vented CH_4 emissions in natural gas transmission. This is mainly due to pressure control or gas release for maintenance and repair;

[17] Marcogaz, "Potential ways the gas industry can contribute to the reduction of methane emissions: Report of the Madrid Forum (5–6 June 2019)" (n.p., n.d.).

[18] Pipeline Safety Trust, "Pipeline Basics and Specifics About Natural Gas Pipelines", Pipeline Briefing Paper No. 2 (n.p., 2015).

[19] European Commission, *Fourth Biennial Report from the European Union under the United Nations Framework Convention on Climate Change* (n.p., 2019).

(d) **City gate and distribution line.** Distribution lines normally require less compression power, also due to the lower pressures needed. However, compression is needed and it causes vented emissions. Further CH_4 emissions occur as fugitive emissions, due to leakage from older distribution lines and valves, connections and metering equipment.

D. Emissions from biogas facilities

17. Emissions from the rising number of biogas facilities are an increasingly relevant source of CH_4 emissions that is not, in most cases, listed separately in common statistics. At least in the German emission inventory, several emissions of biogas facilities are listed already, and assigned either to the agriculture, energy or waste sector. However, in the list, several uncontrolled emissions are missing and are not yet taken into account by the calculations. Biogas facilities are commonly directly linked to a cogeneration plant for electricity production and local heat supply. Due to an extensive subsidy policy, the number of biogas units has greatly increased in some European Union member States, such as Germany. Given that leakages, during fermentation or incomplete burning within the power plant, may strongly contribute to local CH_4 emissions, some additional information on CH_4 emissions from biogas facilities is provided below. Because data on such emissions are rare in the literature, some basic projections are provided regarding the example of Germany, where a large spread and number of biogas plants exist, due to extensive subsidy policies implemented in the past.

18. Due to the differences existing in measurement methods, and the non-binding nature of the guidelines, the comparability of measurement results is currently limited. In future, a harmonization of the methods could also improve the accuracy, reproducibility and representativeness of the measured values.[20] For balancing purposes, by way of example, a total leakage rate of 1 per cent is assumed, as a plausible estimate for the current biogas plant inventory in Germany.[21]

19. Depending on how the system boundaries are defined, the CH_4 emissions from substrate storage, prior to the actual digestion and storage or spreading of digested residuals on agricultural land, must also be taken into account. With the addition of all these latter sources, experts assume that about 5 per cent of the CH_4 generated in biogas plants is released into the atmosphere uncontrolled.

III. Overview of existing technical measures

20. The following section contains a brief overview of landfill gas formation and related CH_4 emissions, as well as technical solutions for gas collection and combustion systems. Subsequently, some literature-based techno-economic figures on investment and operation costs are provided.

A. Reduction of CH_4 emissions from landfills

21. Anaerobic decomposition of landfilled municipal solid waste is the most important non-agricultural source of anthropogenic CH_4 emissions at the global level. Gas collection systems and combustion for heat and power generation, in combination with decreasing shares of landfilled waste, has led to the reduction of annual emissions since 1990; however, further potential exists for emission reduction, particularly through the systematic implementation and application of gas collection and combustion systems for heat and power generation.

[20] Jan Liebetrau and others, "Methane emissions from biogas plants: Methods for measurement, results and effect on greenhouse gas balance of electricity produced", IEA Bioenergy Task 37 (n.p., IEA Bioenergy, 2017).

[21] German Environment Agency, "Bioenergie: Datengrundlagen für die Statistik der erneuerbaren Energien und Emissionsbilanzierung–Ergebnisbericht zum Workshop vom Juli 2011" (Dessau-Roßlau, 2012) (German only).

22. By way of example, with the introduction of the Landfill Directive,[22] the European Union established a powerful tool for reducing the amount of biodegradable municipal waste disposed of in landfills. The Landfill Directive instructs the members States to include specific aspects in the landfill permit. With respect to the control and treatment of landfill gas, annexes to the Landfill Directive contain the following specifications for gas control:

(a) Appropriate measures shall be taken in order to control the accumulation and migration of landfill gas;

(b) 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;

(c) The collection, treatment and use of landfill gas shall be carried out in a manner which minimizes damage to or deterioration of the environment and risk to human health.

23. A wide range of technologies is available for the treatment and disposal of solid waste with co-benefits in the mitigation of GHG emissions. Solid waste can be recycled, landfilled, incinerated or biologically treated.[23] The use of landfills is reduced through recycling, waste minimization and waste diversion to alternative treatment and disposal methods, such as composting and incineration.[24] Therefore, the mitigation of GHG emissions from waste relies on a combination of multiple technologies, the application of which depends on local, regional and national drivers for both waste management and GHG mitigation.[25]

24. It should also be taken into account that the different technologies are complementary over the lifetime of the landfill. Generally, collection and energy use of landfill gas is the recommended option that should be maximized. However, at the beginning of the landfill's life, gas quality and quantity will not be adequate for gas utilization for a certain time period. During this period, the operator should maximize the quantity of CH_4 collected and oxidized, prior to gas utilization. When the landfill's lifetime comes to an end and gas generation declines, the operator should consider using different CH_4 oxidation techniques to maximize the quantity of CH_4 collected and oxidized.[26]

25. Several of the main technologies for mitigating GHG emissions from landfills are briefly described below:

(a) **Oxidation (biocovers and biofiltration)**. The oxidation of CH_4 is a process that naturally takes place through different layers of cover soil, due to the profusion of methanotrophic organisms.[27] 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 these products are much less harmful for the environment than the initial substrate.[28] CH_4 oxidation rates at landfills can vary over several orders of magnitude, ranging from negligible to 100 per cent of the CH_4 flux to the cover. Under circumstances of high oxidation potential and low flux of CH_4 from the landfill, it has been demonstrated that atmospheric CH_4 may be oxidized at the landfill

[22] Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste, *Official Journal of the European Communities*, L 182 (1999), pp. 1–19.

[23] Rafiu Olasunkanmi Yusuf and others, "Methane emission by sectors: A comprehensive review of emission sources and mitigation methods", *Renewable and Sustainable Energy Reviews*, vol. 16, No. 7 (April 2012), pp. 5059–5070.

[24] Izzet Karakurt, Gokhan Aydin and Kerim Aydiner, "Sources and mitigation of methane emissions by sectors: A critical review", *Renewable Energy*, vol. 39, No. 1 (2012), pp. 40–48.

[25] Bert Metz and others, eds., *Climate change 2007: Mitigation of climate change –Working Group III Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge and New York, Cambridge University Press, 2007).

[26] European Commission, "Guidance on the landfill gas control requirements of the Landfill Directive" (n.p., 2013).

[27] Alireza Majdinasab and Qiuyan Yuan, "Performance of the biotic systems for reducing methane emissions from landfill sites: A review", *Ecological Engineering*, vol. 104, Part A (July 2017), pp. 116–130.

[28] J. Nikiema, R. Brzezinski and M. Heitz, "Elimination of methane generated from landfills by biofiltration: A review", *Reviews in Environmental Science and Biotechnology*, vol. 6 (2007), pp. 261–284.

surface. In such cases, the landfill cover soils have the function of a sink, rather than a source, of atmospheric CH_4.[29] The co-oxidation of many non-CH_4 organic compounds, especially aromatic and lower chlorinated compounds, thereby reducing their emissions into the atmosphere,[30] is a secondary benefit of CH_4 oxidation in cover soils. The technologies suitable to increase the CH_4 oxidation rate include biocovers and biofiltration beds.[31] A biocover is an additional final cover that functions as an enhancer of CH_4 oxidation 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. Such media are usually seeded with methanotrophic bacteria by the waste decomposition.[32] Similarly to biocovers, biofiltration beds aim to further oxidize CH_4, from passively collected landfill gas. The collected landfill gas is passed through a vessel containing CH_4-oxidizing media, prior to venting to the atmosphere or to a control system. Such 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;

(b) **Landfill aeration.** In situ aeration is a technology that introduces ambient air into municipal solid waste landfills to enhance biological processes and inhibit CH_4 production.[33] Ambient air is introduced into the landfill via a system of gas wells, resulting in accelerated aerobic stabilization of deposited waste. The resulting gas is collected and treated.[34] Biological stabilization of the waste, using in-situ aeration, provides the possibility to reduce both the current emissions and the emission potential of the waste material.[35] Landfill aeration, which is not widely applied yet, is a promising technology for treating the residual CH_4 from landfills, when energy recovery becomes economically unattractive.[36] In the absence of mandatory environmental regulations requiring 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. In the case of an in situ aerated landfill, located in northern Germany for example, landfill aeration achieved a reduction in CH_4 emissions of 83–95 per cent, under strictly controlled conditions. Depending on the landfill site, aeration of the landfill may be feasible at different stages of the landfill operation. Early aeration means that energy generation is forfeited, but it 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 reached a plateau and the operation[37]is no longer cost-effective to be continued;

[29] Metz and others, eds., *Climate change 2007*.

[30] Charlotte Schuetz and others, “Comparative oxidation and net emissions of methane and selected non-methane organic compounds in landfill cover soils”, *Environmental Science and Technology*, vol. 37, No. 22 (2003), pp. 5150–5158.

[31] US EPA, “Lessons Learned from Natural Gas STAR Partners: Options for Reducing CH_4 Emissions From Pneumatic Devices in the Natural Gas Industry” (2006).

[32] US EPA, “Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from Municipal Solid Waste Landfills” (2011).

[33] Xiaoli Chai and others, “The effect of aeration position on the spatial distribution and reduction of pollutants in the landfill stabilization process: A pilot scale study”, *Waste Management and Research: The Journal for a Sustainable Circular Economy*, vol. 31, No. 1 (January 2013), pp. 41–49.

[34] K. U. Heyer and others, “Pollutant release and pollutant reduction: Impact of the aeration of landfills”, *Waste Management*, vol. 25, No. 4 (2005), pp. 353–359.

[35] R. Prantl and others, “Changes in carbon and nitrogen pool during in-situ aeration of old landfills under varying conditions”, *Waste Management*, vol. 26, No. 4 (2006), pp. 373–380.

[36] Charlotte Rich, Jan Gronow and Nikolaos Voulvoulis, “The potential for aeration of MSW landfills to accelerate completion”, *Waste Management*, vol. 28, No. 6 (2008), pp. 1039–1048; and M. Ritzkowski and R. Stegmann, “Generating CO(2)-credits through landfill in situ aeration”, *Waste Management*, vol. 30, No. 4 (April 2010), pp. 702–706.

[37] X. F. Lou and J. Nair, “The impact of landfilling and composting on greenhouse gas emissions: A review”, *Bioresource Technology*, vol. 100, No. 16 (August 2009), pp. 3792–3798.

(c) **Gas collection and utilization.** When gas extraction and utilization are considered, which might also be attractive from an economic perspective due to heat and power generation, a distinction should be drawn between gas collection and subsequent utilization, which includes flaring, power generation, direct gas use in, for example, boilers, and further utilization, as a fuel or for chemical synthesis. All the available options are briefly described below:

(i) **Gas collection.** Requirements can be set specifying that energy has to be recovered from the collected landfill gas. For example, the European Union Landfill Directive specifies that, if the operator considers the landfill gas unusable at the landfill, then it has to be demonstrated to the competent authority that, at that individual landfill, there are site-specific reasons why utilization is unfeasible.[38] The implementation of an active landfill gas extraction system, using vertical wells or horizontal collectors, is the single most important mitigation measure for reducing emissions. Intensive field studies of CH_4 mass balance, at cells, with a variety of design and management practices, have shown that over 90 per cent recovery can be achieved at cells, with use of final covers and efficient gas extraction systems.[39] Some sites may have less efficient, or only partial, gas extraction systems, with 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 per cent.[40] In the case of closed landfills, reported efficiencies are 10–90 per cent. For landfills in operation, efficiencies are 10–80 per cent.[41] For active gas collection systems, the collection efficiency depends primarily on the design and maintenance of the collection system, and the type of materials used to cover the landfill. The gas collection, by vertical wells and horizontal trenches, typically begins after a section of a landfill (also called a cell) is closed for new waste and covered by soil. 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 the operator can monitor and adjust the gas flow, if necessary. Once the landfill CH_4 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.[42] Extraction wells are typically composed of slotted plastic pipes, surrounded by stone or other aggregate material, that are installed in borings in the waste mass below the surface of the solid waste disposal site. Above the surface of the waste mass, the extraction well typically has a wellhead to allow for vacuum adjustment and sampling of the landfill gas. The layout of these wells can either be vertical or horizontal, and the choice between vertical and horizontal wells will depend on site-specific factors.[43] Vertical wells are usually installed in areas where the site no longer receives waste, or where waste filling will not occur for one year or more. However, vertical wells can be installed and operated in areas with continued waste placement, although the 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 in cases where 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 aggregates such as tire chips or broken glass), and the perforated pipe is installed in the centre of the trench;

26. Different utilization options exist for landfill gases:

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[38] European Commission, "Guidance on the landfill gas control".

[39] K. Spokas and others, "Methane mass balance at three landfill sites: What is the efficiency of capture by gas collection systems?", *Waste Management*, vol. 26, No. 5 (2006), pp. 516–525.

[40] Hans Oonk, "Efficiency of landfill gas collection for methane emission reduction", *Greenhouse Gas Measurement and Management*, vol. 2, No. 2–3 (October 2012), pp. 129–145.

[41] ibid.

[42] Karakurt, Aydin and Aydiner, "Sources and mitigation".

[43] Global Methane Initiative (GMI), "International Best Practices Guide for Landfill Gas Energy Projects" (n.p., US EPA, 2012).

(a) **Flaring**. Collecting and flaring landfill gas is part of the normal operation of the landfill, independently of additional heat or power generation systems. The landfill gas generation rate will decline over time, producing lower volumes of gas, with a low CH_4 content. For example, according to the European Union guidance on landfill gas control, operators should follow the following hierarchy of treatment techniques over the landfill's lifetime, to ensure that the maximum amount of landfill gas is oxidized over the whole lifecycle of the landfill:[44] (a) high-temperature flaring; (b) low calorific flaring; and (c) other techniques for oxidation of CH_4. There are generally two types of flares: (a) open flares (candlestick flares); and, (b) enclosed flares (ground flares), which, when properly engineered and operated, may achieve removal efficiencies of 99 per cent or more. Higher combustion temperatures and residence times result in the destruction of unwanted constituents, such as unburnt hydrocarbons. However, a significant drawback to this type of flare system is that installation and operation are more expensive compared to open flares;[45]

(b) **Gas utilization.** Electricity generation. Landfill gas collected at the waste disposal site can be used for electricity generation. After pumping out, the gas usually has to undergo pre-treatment, to remove liquids, sulfur and siloxanes. If the cleaned landfill gas is to be upgraded to bioCH_4, CO_2 also has to be removed. Reciprocating engines for co-generation of electricity and heat are able to operate even when the landfill gas contains up to 40 per cent of CO_2, by volume. Energy production also requires temporary gas storage, or a flare station to burn the CH_4 production[46] in excess. Typical technologies for electricity generation from landfill gas are[47] listed below:

(i) **Reciprocating internal combustion engines.** These are the most widely used technology for the conversion of landfill gas to electricity. Advantages of this technology include: low capital cost, high efficiency, flexibility with respect to the CH_4 content, and adaptability to variations in the output of gas from landfills;

(ii) **Gas turbines using landfill gas.** These require a dependable gas supply for effective operation, and are generally suitable for landfills where the gas production generates at least 3 MW (thermal energy). However, such small gas turbines are very sensitive to contamination in the fuel gas, and require more specialized and expensive maintenance, as compared to reciprocating engines;

(iii) **Microturbines.** These are generally the best choice for small-scale recovery projects that supply electricity to the landfill or to a site located in close proximity to the landfill. Single microturbine units have capacities of 30–250 kW, and are most suitable for applications below 1 MW (thermal energy) output. Sufficient landfill gas treatment is generally required for microturbines and it implies removal of moisture and other contaminants.

(c) **Direct gas use for heat generation.** Landfill gas can also be used as fuel for boilers or industrial processes, such as drying operations, kiln operations and cement and asphalt production. In these projects, the cleaned and dried gas is piped directly to a nearby customer for use as replacement or supplementary fuel;[48]

(d) **Other use (gas grid injection, fuel cells).** Landfill gas can be sold to the natural gas pipeline system once the gas 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 vehicle liquid fuel, for use in trucks hauling refuse to a landfill. Fuel cells are another available technology for energy generation from landfill gas. Fuel cells have the advantage, as compared to combustion technologies, that the energy efficiency is typically higher and combustion by-products such as NO_X, CO, and sulfur oxides are not generated. If fuel cells are used to generate electricity from landfill CH_4, then a high-efficiency gas clean-up system is required to ensure that the catalyst within the fuel cell is not contaminated by trace constituents present in the gas. To date, the high

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[44] European Commission, "Guidance on the landfill gas control".
[45] GMI, "International Best Practices Guide".
[46] Karakurt, Aydin and Aydiner, "Sources and mitigation".
[47] US EPA, "Available and Emerging Technologies".
[48] Karakurt, Aydin and Aydiner, "Sources and mitigation".

sensitivity of fuel cells to contamination has proved a significant barrier for the utilization of landfill gas.

B. Reduction of CH_4 emissions from the natural gas grid

27. Generally, measures to reduce CH_4 emissions from the natural gas supply system can be categorized as technical measures: improving equipment; organizational or management measures; replacing common practices, for example, for maintenance and inspection or leakage detection. In the upstream supply chain (production, processing and transmission) leakage detection is often difficult because of the odourless and non-coloured properties of CH_4. However, recent approaches have been developed to detect leakages using infrared wavelength cameras or specific sensors able to visualize CH_4 leakages, in combination with aircraft and drone tools to monitor emissions over long distances of transmission pipelines, including storage tanks and compressor stations. These detection methods build upon the low-volumetric density of CH_4 as compared to air.

28. Potential measures for emission reduction are listed below, while the most promising technical solutions (equipment-based) are described in subsequent sections:[49]

(a) Reduction of operating emissions: Use of low- or zero-emitting pneumatic and compressor systems, with reuse of the gas instead of venting (see sect. IV):

(i) Replacement of centrifugal compressor seal oil systems (recovery of CH_4 from seal oil;

(ii) Installation of low-bleed pneumatic devices;

(iii) Use of gas recompression when shutting down a compressor or pipeline.

(b) Reduction of maintenance emissions:

(i) Use of a mobile compressor to pump gas from a section to be vented into a neighbouring section;

(ii) Use of a mobile flare unit to burn vented gas during pipeline maintenance works;

(iii) Use of gas to generate power and heat for local use, for example, for gas processing equipment.

(c) Inspection and maintenance programmes: organizational measures to detect emissions early on and stop them, also referred to as “leak detection and repair”:

(i) Optimization of compressor shutdown practices;

(ii) Minimization of venting before pipeline maintenance;

(iii) Implementation of periodic cost-effective leak inspections (also supported by sensor-based mobile leak detection systems).

29. The above-mentioned measures are generally relevant along the entire supply chain. However, several technical solutions might be limited to their specific field of application. As CH_4 emissions are attracting increasing interest, several collaborative industry initiatives are working to improve understanding of the scale of CH_4 emissions, their potential sources and opportunities for emission reductions. The most well-known of these initiatives include: the Natural Gas STAR Programme (initiated by the United States Environmental Protection Agency (EPA)), the World Bank Global Gas Flaring Reduction Partnership, the Global Methane Initiative, the Oil and Gas Climate Initiative, the Methane Guiding Principles Coalition and the Climate and Clean Air Coalition – Oil and Gas Methane Partnership.[50] As an example, the Natural Gas STAR Programme provides a comprehensive overview of

[49] Marcogaz, “Potential ways”; and US EPA, “Natural Gas STAR Programme: Recommended Technologies to Reduce Methane Emissions”, available at www.epa.gov/natural-gas-star-program/recommended-technologies-reduce-methane-emissions.

[50] Marcogaz, “Potential ways”.

mainly technological measures, by replacing current equipment and by optimizing inspections, maintenance and leakage detection.[51]

30. The recovery of CH_4 from seal oil in wet seal compressors and the replacement of high-bleed pneumatic devices[52] are the most promising and cost-efficient measures (low payback periods of investment, see next section). However, the status of implementation of these measures is not completely clear, although their economic viability is obvious (e.g., in the European Union, high-bleed pneumatic devices are no longer in use). As discussed before, especially in Eastern European transmission systems, great potential for improvements seems possible. Both technologies (seal compressors and high-bleed pneumatic devices) are briefly described below, while detailed information and factsheets are available from the Natural Gas STAR Programme.[53]

31. Wet seal compressors are a common and widely used technology for natural gas compression in the transmission grid. Wet seal compressors cause emissions of CH_4 dissolved in 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 seal oil degassing process. This system consists of 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 used. The oil then flows from the high-pressure separator to the atmospheric degassing separator, where the remaining entrained gas is removed and then vented to the atmosphere. This volume of gas is usually minimal, because 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. These systems have been installed and operated successfully at several gas compression stations. Their use as retrofit technology is a new application. Wet seal degassing recovery systems could potentially be installed at most locations with wet seal centrifugal compressors, although there might be limitations due to site-specific operating requirements. In order to implement this system, the use of the recovered gas is required. Operators have several options for the best use of the gas, and these choices will have an economic impact on the project. The most common options are:[54]

(a) Use as high-pressure turbine fuel;

(b) Routing the recovered gas as low-pressure fuel;

(c) Routing back to compressor suction;

(d) Use as a flare sweep gas.

32. Besides wet seal compressors, one major source of CH_4 emissions in all sections of the natural gas supply chain[55] is high-bleed pneumatic controllers. A pneumatic controller is an automated instrument for maintaining a process parameter, such as liquid level, pressure, pressure difference or temperature. Based on the power source, two types of pneumatic controllers are defined in this report:

(a) Natural gas-driven pneumatic controllers, for example, a pneumatic controller powered by pressurized natural gas;

(b) Non-natural gas-driven pneumatic controllers, for example, an instrument powered by sources other than pressurized natural gas, such as electric power from, for example, solar panels and storage systems.

33. Modern installations no longer use natural gas-based pneumatic controllers. Most controllers are electrically operated. It is only in hazardous environments that air-based pneumatic controllers might be an option, although intrinsically safe electric controllers also

[51] US EPA, "Natural Gas STAR Programme".
[52] ICF International, "Economic Analysis of Methane Emission Reduction Opportunities in the U.S. Onshore Oil and Natural Gas Industries" (n.p., 2014).
[53] US EPA, "Natural Gas STAR Programme".
[54] ICF International, "Economic Analysis".
[55] US EPA, "Lessons Learned".

exist. Natural gas-driven pneumatic controllers come in a variety of designs, for a variety of uses, and can be characterized by their emission characteristics:

(a) Continuous bleed pneumatic controllers are characterized by 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 the gas flows to the valve controller, where the value (signal) is compared with the process set point value, to adjust the gas pressure in the valve actuator. Continuous bleed controllers can be further subdivided into two types based on their bleed rate:[56]

(i) Low bleed, having a bleed rate of less than or equal to 6 standard cubic feet per hour (scf/h, 6 scf = 0.17 m^3);

(ii) High bleed, having a bleed rate higher than 6 scf/h.

(b) Intermittent pneumatic controllers are pneumatic controllers with non-continuous venting. These natural gas-driven pneumatic controllers do not have a continuous bleed but are actuated using pressurized natural gas;

(c) Zero-bleed pneumatic controllers are pneumatic controllers that do 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.

34. Besides the replacement of high-bleed pneumatic devices or the recovery of CH_4 from wet seal compressors, the avoidance of unintended fugitive emissions, in particular, is of the utmost importance in order to reduce CH_4 emissions. Early leakage detection, in this context, is the most important action. Recent advances in sensing, analytics and mobile technology have created a number of gas leak detection solutions that perform significantly better than traditional methods. Such devices can detect CH_4 from natural gas leaks, at concentrations of 1 part per billion (ppb) or less, and respond in less than one second. Current mobile gas leak detection solutions leverage advanced laser-based sensors, global positioning system technology and analytic software, in order to improve the speed and accuracy of gas leak identification and location.

35. In addition to the sensors, mobile leakage detection can be facilitated by machine vision through infrared cameras and drones, to cover larger spatial areas, for example, along natural gas pipelines. Also, satellite images used for the detection of large CH_4 emission sources may contribute to early detection of fugitive emissions in the natural gas grid. Using data from the Copernicus Sentinel-5P satellite, the European Space Agency has developed a conceptual system to track and attribute CH_4 emissions around the world.[57]

C. Reduction of CH_4 emissions from biogas facilities

36. The measures to reduce CH_4 emissions from biogas facilities are comparable to those applicable to the natural gas supply system. Besides the use of up-to-date technology, as well as correct plant operation and maintenance, particularly, early leakage detection is a key factor in reducing emissions. However, due to relatively small and decentralized production facilities, this is a challenging option and early leakage detection is difficult.

37. The causes for leakages are numerous and leaks can be found at almost any component of the plant, in sections containing biogas. The reasons can be partly identified in obsolete or insufficient technology. Moreover, a certain CH_4 release rate is tolerated in components, such as fermenter cover foils. The Safety Guidelines of the German Agricultural Employer’s Liability Insurance Association, for example, in relation to CH_4, define a permeability

[56] ICF International, “Economic Analysis”.

[57] European Space Agency, “Mapping methane emissions on a global scale”, 4 May 2020, available at www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-5P/Mapping_methane_emissions_on_a_global_scale.

threshold lower than 1,000 cm^3*mm/(m^2*d*bar).[58] Emissions below the threshold level are therefore not included in the statistics.

38. It might sound unexpected, but combined heat and power generation is also a potential CH_4 emission source. When combustion in the engine is not complete, a certain amount of CH_4 slip may occur, thus resulting in CH_4 escape in the exhaust gases. The amount of the CH_4 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, although the use and further development of modern plant technology is crucial, it is also important that plants be operated and maintained by trained personnel.

IV. Conclusions

39. The best techniques to avoid CH_4 emissions depend heavily on the emission source and the site-specific conditions. In contrast to classical industrial emissions, which are in most cases mitigated/abated through end-of-pipe equipment or through feedstock substitution, CH_4 emissions are diverse, and a broad range of measures is required for their reduction. The most important techniques regarding emissions from waste landfills and from the natural gas grid are described in the present document.

40. At the global level, the share of landfill gas emissions is in a similar range as in Europe. In landfills, CH_4 is formed through anaerobic digestion of hydrocarbon waste. The reduction of landfilled waste is the most important measure to avoid/reduce such emissions and can be achieved through composting of biodegradable waste, more efficient separation and recycling, or incineration of non-biological hydrocarbon waste (e.g., for combined heat and power generation). For the reduction of CH_4 emissions from existing landfills, the most relevant options are (see para. 25):

(a) Gas collection and utilization;

(b) Oxidation of CH_4 in biocovers or through biofiltration based on methanotrophic organisms (bacteria) that transfer CH_4 into CO_2 and H_2O;

(c) Landfill aeration to avoid anaerobic digestion and to enhance biological processes to inhibit CH_4 production.

41. The natural gas production and distribution network is a further important source of CH_4 emissions. Since production technologies, compressions and pressure regulations partly show regional differences, not all options listed hereafter are equally applicable to all countries. Furthermore, a general distinction between production, transmission and distribution to final end-users, should be made, because, for example, from the European Union perspective, production and transmission mainly takes place outside of the European Union (Russian Federation as one of the most important natural gas supplier). Generally, these measures can be categorized as technical measures, by replacing existing equipment, and organizational or management measures, by modifying common practices for example, in maintenance and inspection. In summary, the following measures have been identified in the present document to be the most relevant (see para. 28):

(a) Reduction of operating emissions through the use of low- or zero-emitting pneumatic and compressor systems with reuse of the gas instead of venting;

(b) Reduction of maintenance emissions by avoiding venting;

(c) Inspection and maintenance programmes to identify leakages and fugitive emissions early on.

42. Biogas plants have also become sources of CH_4 emissions over several process steps and a multitude of technical functional units. Further research and development in this field may contribute to increasing the amount of CH_4 that is practically usable, and thus further exploit the current theoretical emission saving potential.

[58] Sozialversicherung für Landwirtschaft, Forsten und Gartenbau, “Sicherheitsregeln für Biogasanlagen: Technische Information 4” (n.p., 2016) (German only).

43. Further details on the above-mentioned abatement technologies, including illustrative figures and tables, are provided in the informal background technical document on techniques to reduce CH_4 emissions in Europe from landfill gases, the natural gas supply system and biogas facilities, made available by the Task Force on Techno-economic Issues to the Working Group on Strategies and Review at its fifty-eighth session (Geneva, 14–17 December 2020).[59]

[59] Available at https://unece.org/fileadmin/DAM/env/documents/2020/AIR/WGSR/TFTEI_methane_background_document-december_2020.pdf.