DBI GUT
Gas- und Umwelttechnik GmbH

Methane Emission Estimation Method for the Gas Distribution Grid (MEEM)

Requirements for a Benefit-Effort Optimized Method, Potential for Improvements and Need for Further Research

Project Partners:	Bursagaz | Turkey DGC | Denmark E.ON Technologies | Germany Gas Natural Fenosa | Spain Gasnet | Czech Republic GRDF/ENGIE | France ITALGAS RETI | Italy Kiwa Technology B.V.| Netherlands Schweizer Verein des Gas- und Wasserfaches SVGW | Switzerland Synergrid vzw /Eandis | Belgium Westnetz | Germany
Project Execution:	Gert Müller-Syring (DBI GUT) E-Mail: gert.mueller-syring@dbi-gruppe.de Charlotte Große (DBI GUT) E-Mail: charlotte.grosse@dbi-gruppe.de Anja Wehling (DBI GUT) E-Mail: anja.wehling@dbi-gruppe.de Melanie Eyßer (DBI GUT) E-Mail: melanie.eysser@dbi-gruppe.de
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Gert Müller-Syring   Charlotte Große

Executive Summary

The project *Methane Emission Estimation Method for the Gas Distribution Grid* (MEEM) is the second phase of the project *Analysing the Methods for Determination of Methane Emissions of the Gas Distribution Grid* which was initiated in November 2014 by members of the European Gas Research Group (GERG). The project was motivated by the target to improve the accuracy and reliability of national emission estimations, the transparency of the associated results, and consequently the reputation of natural gas in general.

The first project phase was finished in October 2015 and developed the fundamentals of MEEM. Best practices and optimization potential of existing methods of determining methane emissions of the gas distribution grid were identified. System boundaries have been aligned for the scope of the gas distribution grid, and sources, as well as categories of emissions were defined. It was found that some of the methods in place are very detailed with a high effort to collect input data. Other methods are less detailed, leading to less accurate and often too high results but are easier to apply. The most successful solution for the development of a pan-European method for the determination of emissions from the gas distribution grid would combine these different methods depending on their relevance to different emission categories. Another finding of phase I was that emission reduction measures, which already have been conducted by the natural gas industry for several years, are not always rewarded by the emission estimation methods in place.

The new developed method (MEEM) combines best practice approaches of individual countries and is the foundation of an Europe-wide trusted emission estimation. Moreover, MEEM helps distribution system operators (DSO) to identify and show already achieved emission reductions, to control further measures and to display further improvements.

The project's committee (Phase II) comprises eleven representatives from gas companies, research institutes and associations of ten European nations: Belgium, Czech Republic, Denmark, France, Germany, Italy, the Netherlands, Spain, Switzerland and Turkey. Together with representatives from Marcogaz and Eurogas (who joined selected meetings and contributed to the discussion of important documents) the partners provided information and practical expertise from which a method for the estimation of methane emissions of the gas distribution grid was developed.

External requirements (e.g. for the reporting of greenhouse gas emissions for the United Nations Framework Convention on Climate Change) were collected within the project by contact to national environmental agencies and considered for the development of the method.

To evaluate the effort of different promising methods for the emission estimation, a questionnaire was prepared and sent to several DSO in the participating countries. The results of the questionnaire showed which data are available or missing in several countries and helped to evaluate the effort to collect missing data. The benefit of the existing methods was investigated with an Excel workbook, especially developed for the MEEM project. This workbook includes a sample grid and shows the results of different methods as well as the contribution of several emission types to the total emissions. It is therefore suitable to make sample calculations which are provided in the Annex of this report.

Moreover, the requirements for a possible verification of MEEM via CEN were collected and the MEEM report is written in the format of a CEN Technical Report (structure). However, the decision on the delivery of this scientific work from GERG to CEN is open, subject to the partners and the process should be guided via Marcogaz after the finalization of MEEM. The method should be tested

by several DSO/ countries to verify the effects and the sensitivity of implementing the method before any further use.

Basically, methane can either be emitted from pipelines (main lines and service lines) or gas facilities (e.g. pressure regulating stations, above ground storages[1], etc.). Since many different names exist for the same categories of emissions occurring from the different sources, it was agreed by the partners in the MEEM-Project to use the terms *Intrinsic Emissions*, *Incident Emissions*, and *Operational Emissions*. According to the definition in this project, Intrinsic Emissions include all technical leaks, permeation, as well as minor holes or cracks, which are detected by survey. Incident Emissions are the result of damage to the pipeline and are reported by own staff of a DSO or third-parties (e.g. the public) but are not detected by survey. Operational Emissions occur during commissioning and decommissioning, as well as during the renewal and maintenance of existing pipelines or facilities (Table 1).

Table 1: Categories of Emissions and Types of Emissions

Category of Emissions	Type of Emissions comprised by the Category
Intrinsic emissions	• Underground leaks detected by survey • Above ground leaks detected by survey • Only for main lines: emissions of gate valves • Only for plastic pipelines (e.g. PE, PVC): permeation
Incident emissions	• Incidents reported after third-party damage • Other incidents reported by third-parties or own staff of DSO (e.g. gas smell)
Operational emissions	• Venting and purging during (de-)commissioning, renewal and maintenance

For all types of emissions, emission factors (EF) can be determined (e.g. an emission factor for venting emissions of a pressure regulating station in low pressure), which are multiplied with activity data (AD, e.g. number of maintenance operations on pressure regulating station in low pressure) in order to determine total emissions. The report describes different possibilities to determine EF (e.g. related to the pipeline length or related to a single event).

For some emission types an accurate emission estimation is possible without high effort. For instance, for permeation emissions most input parameters (length of the pipelines, diameter, wall thickness, etc.) are well known to the DSO. The only challenging parameter is the permeation coefficient, which describes the ability of a certain gas (e.g. methane) to permeate through a certain material (e.g. PE100) at a certain temperature (e.g. 8 °C). However, this coefficient can be determined by measurement in a laboratory for different materials and can be applied by several DSO in several countries.

For operational emissions an accurate emission estimation is also rather easy, since only parameters which are exactly known to the operator (e.g. pipeline diameter and length, operating pressure before the measure) need to be taken into account. Nevertheless, the data collection for

[1] Above ground storages (pipe storage or spherical storage) are not available in each country and are therefore considered an optional element within the system boundaries. They need to be distinguished from underground gas storages, which are only present in the transmission grid.

event-based approaches is time-consuming and the contribution of operational emissions to the total emissions of the distribution grid is relatively low. Therefore, for the determination of operational emissions, MEEM suggests not only one approach but gives two opportunities depending on the data availability and the user's capacity for emission estimation. The first one is the event-based approach which considers each event that causes operational emissions individually and is the most accurate one. The second opportunity is a simplified approach, which takes into account a percentage of the grid which is maintained/ commissioned/ decommissioned per year. In terms of benefit and effort, it is sufficient to use the simplified approach, but it leads to higher total emissions, especially since the consideration of emission reduction measures is hardly possible.

For intrinsic emissions (except from permeation) as well as for certain incident emissions, the estimation is challenging. For instance, the emissions of leaks detected by survey can be estimated by defining the amount of gas escaping in a certain time span (i.e. emission rate), and by defining a duration of gas escape as well as the number of leaks detected per year by survey. The number of leaks is known to the operator. The emission rates are not known, and more than one approach exists for their determination: On the one hand, emission rates can be determined by direct measurements. On the other hand, it is possible to determine soil coefficients and calculate the emission rates with the help of leak size and pipeline pressure. Both approaches have advantages and disadvantages. It is questionable for direct measurements how statistical representativeness can be ensured when making an average for several hundreds of leaks. For the calculation-approach, difficulties exist in determining the equivalent radius of leaks in a meaningful way and in determining the soil coefficients by laboratory measurements for every relevant soil type and allocating them to real leaks afterwards. For this reason, both approaches, as well as the need for further research, are mentioned within this report.

Similar challenges occur in the determination of the duration of gas escape for leaks detected by survey. A conservative but verifiable approach is to take into account the monitoring period and dividing it by two, since a leak can either be detected at the beginning or the end of a monitoring period. However, it is presumed, that emissions are overestimated with this approach, since most leaks do probably not exist for several years without being reported as an incident. For this reason, another approach is to make expert assumptions for the durations. However, these assumptions need to be verified by considering the pressure of the pipelines or facilities, the size of the leak, the location, etc.

The key findings of Project Phase II can be summarised as:

- MEEM (the method) addresses all the relevant sources and types of emissions in the gas distribution grid within the boundaries as defined in the project
- MEEM is as accurate as possible with reasonable effort, enabling application in most of the countries.
- MEEM provides the potential for a very detailed emission estimation by using more input data within the same framework. Some countries in Europe already have the capacity to do a complex emission estimation with high data collection effort.
- Additionally, MEEM provides opportunities for a less complex emission estimation if data is not available at the required level of detail.
- Some challenging input parameters have been identified. Those parameters are currently estimated by expert assumptions from the group and should be validated in future follow-up research.

- Not all relevant input parameters are available in every country. Data lacks as well as the need for further measurements, updating of statistics, etc. have been identified.
- MEEM contributes to a more consistent methane emission estimation within Europe.

The following post-project activities are in discussion and partly already initiated:

- Decision of GERG Autumn 2017 Board Meeting: Task Force to plan actions on methane emissions research needed, in follow-up to the MEEM-project
- GERG/ Kiwa Technology (Netherlands) project proposal on suction measurements and a coordinated measurement program
- DVGW project on methane emissions of the gas distribution grid in Germany, including measurements
- GNF/ SEDIGAS project on intrinsic emissions of PE network in Spain.

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List of Symbols and Abbreviated Terms

Table 2: Symbols applied within this Report

Symbol	Explanation	Unit (if not specified otherwise)
A	Area	m^2
AD	Activity data	$km\ or\ No.$
β	Forchheimer coefficient	m^{-1}
c	Concentration	$vol - \%$
C_D	Discharge coefficient	$-$
d	Diameter	m
E	Emissions	$\frac{m^3}{yr}$
EF	Emission factor	$\frac{m_{NG}^3}{leak \cdot yr}$
F_{pv}	Super compressibility factor	$-$
f_{purge}	Purge factor	$-$
K	Compressibility number of natural gas	$-$
k	Permeability of the ground	m^2
$\kappa;\ \gamma$	Adiabatic Index of natural gas	$-$
l	Length of pipelines	km
M	Molar Mass	$\frac{kg}{kmol}$
μ	Viscosity of the gas in the Pipeline	$Pa \cdot s$
n	Number (e.g. of leaks, incidents, events, etc.)	$\frac{leaks}{yr}\ or\ \frac{leaks}{km \cdot yr},\ etc.$
PC	Permeation coefficient	$\frac{cm^3}{m \cdot bar \cdot d}$
P	Perimeter	
p	Pressure	bar
q	Emission rate (e.g. per leak)	$\frac{m^3}{leak \cdot h}$
R	Gas constant of a gas	$\frac{J}{kg \cdot K}\ or\ \frac{J}{mol \cdot K}$
r	Radius	m
ρ	Density	$\frac{kg}{m^3}$

Symbol	Explanation	Unit (if not specified otherwise)
SDR	Standard Dimension Ratio	$-$
s	Wall thickness	m
T	Temperature	K
t	Duration of gas escape	h
V_{geo}	Geometric volume of the pipeline [m³]	m^3
x	Fraction	$-$
Z	Compressibility factor	$-$

Table 3: Indices applied within this Report

Symbol	Explanation
0	universal
atm	atmospheric
CH_4	methane
eq	equivalent
ext	external
i	specific
inc	incident
int	internal
m	mass
NG	natural gas
n	normalized/ standardized
op	operational
$perm$	permeation
$purge$	purging
$survey$	survey
$total$	total
v	volume
$vent$	venting

Table 4: Abbreviated Terms applied within this Report

Abbreviation	Explanation
AD	Activity Data (also known as Activity Factor)
CNG	Compressed Natural Gas
DN	Nominal Diameter
DSO	Distribution System Operator
EF	Emission Factor
EPA	Environmental Protection Agency
FID	Flame Ionization Detector
GERG	European Gas Research Group
HFS	High Flow Sampler
HP	High Pressure
LNG	Liquefied Natural Gas
LP	Low Pressure
MEEM	Methane Emission Estimation Method
MP	Medium Pressure
PGC	Process Gas Chromatograph
PN	Nominal Pressure
PRMS	Pressure Regulating and Meter Station
PRS	Pressure Regulating Station
SDR	Standard Dimension Ratio
UGS	Underground Storage
UNFCCC	United Nations Framework Convention on Climate Change

Normative References

ISO 5167-1:2003, *Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full - Part 1: General principles and requirements*

EN 15446:2008, *Fugitive and diffuse emissions of common concern to industry sectors - Measurement of fugitive emission of vapours generating from equipment and piping leaks*

EN ISO 12213:2009, *Natural gas – Calculation of compression factor*

EN ISO 13443:2005, *Natural gas – Standard reference conditions (ISO 13443:1996, including Corrigendum 1:1997)*

Introduction

The European research project „Development of an Accurate and Consistent Method for Methane Emission Estimation of the Gas Distribution Grid” (MEEM) is the second phase of the project “Analysing the Methods for Determination of Methane Emissions of the Gas Distribution Grid”, which was initiated in October 2014 by several members of the European Gas Research Group (GERG).

The project was motivated by the high uncertainty of current emission estimations. Many different methods are in place and insufficient transparency limits the credibility of the results, and accordingly the reputation of natural gas.

During phase I, the existing methods for estimating emissions from the gas distribution grid which are applied throughout different European countries have been evaluated. It was found that none of the already applied methods considers all technical sources of methane emissions defined in the system boundaries. Some methods are very detailed leading to a high degree of effort for data collection, others are rather simplified and partly incomplete.

In continuation to the effort undertaken in phase I, the aim of this second project phase is to develop an accurate and consistent method for the estimation of methane emissions of the gas distribution grid which presents a reference method for the countries of Europe. A consistent, accurate and transparent determination of methane emissions at the European level is of great importance for the reputation of natural gas in the ongoing discussions about the environmental impact of energy carriers. It provides a methodical approach for national reporting of greenhouse gas emissions for the natural gas distribution infrastructure and therefore a basis for the political communication at the European level. However, for this pan-European method to be applicable, it needs to be practical and effective. The trade-off between effort and benefits in the estimation of emissions and for the level of detailedness of the input data shall be identified.

The following report is divided into three chapters. The first chapter defines the work scope and objectives of the project. After this follows a description of technical terms in chapter 2. Chapter 3 describes how emissions are estimated in general and in detail for the elements main lines, service lines and facilities. An overview about the recommended equations for the MEEM method as well as the need for further research is provided at the end of Chapter 3.

1. Scope of Work and Objectives

1.1 Scope of Work

This report considers the methane emissions resulting from the natural gas distribution grid. This comprises:

- Intrinsic,
- Incident, and
- Operational emissions

from the following elements:

- Pipelines
    - Main lines and service lines, including valves (e.g. gate valves, stopcocks)
- Facilities
    - City gate stations and pressure regulating (and metering) stations
    - Above ground storages
    - LNG-facilities (satellite stations and liquefaction plants)
    - Natural gas filling stations (for LNG and CNG)
    - Biogas injection plants
    - End customer facilities (internal piping, house pressure governor, gas meter)

The following emissions are not scope of this report:

- Methane emissions due to incomplete combustion
- All other combustion emissions
- Emissions from elements which are before a city gate station (exploration, production, processing, transmission, underground gas storage) and from elements which are behind the customer´s gas meter (all end user appliances)
- Emissions from compressors
- Biogas plants (fermenters), which belong generally to the sector “agriculture”. Within the sector gas distribution, only the biogas injection plants are considered.

1.2 Objectives

The first priority of this project is to develop a pan-European method for an accurate and consistent estimation of methane emissions from the gas distribution grid that is suitable to fulfil the obligations within the United Nations Framework Convention on Climate Change (UNFCCC). This method should be as accurate as possible with reasonable effort.

A basis for the verification of the method should be provided (second priority) and the understanding of existing emission factors and their accuracy should be improved in order to identify the need for further development (third priority).

2. Terms and Definitions

2.1 Emissions

2.1.1

Activity Data

AD

Activity Data, sometimes also called Activity Factors, are reference data for Emission Factors. This could be event data (like the number of incidents or maintenance operations) or inventory data (like the number of kilometres pipeline).

2.1.2

Adiabatic Index

κ

According to ISO 5167, γ is the ratio of the specific heat capacities and κ is the adiabatic or isentropic index [1]. γ should only be used if κ is not known and for ideal gases γ and κ are equal. However, the meaning can be different, especially in different linguistic areas. This report follows the definition of ISO 5167.

2.1.3

Discharge Coefficient

C_D

Coefficient, which relates the actual flowrate to the theoretical flowrate through an opening and accommodates the friction of the real flow as well as boundary layer effects (jet contraction).

Needs to be determined experimentally and is nearly one for well-rounded openings. According to several data sources, a value of about 0.6 can be applied for sharp edged holes, welding cracks or ruptures (ref. [2]. [3, p. 19]. [4]).

2.1.4

Emission

E

Emissions are substances discharged into an environmental medium such as air. In this project, it is the amount of gas released into the atmosphere during one year.

2.1.5
Emission Factor

EF

Emission Factors are default values for the emissions of a kilometre pipeline, a facility or a certain event (e.g. a maintenance operation) and can have units like $\frac{m^3}{km \cdot yr}$ or $\frac{m^3}{event}$.

2.1.6
Emission Rate

q

The term emission rate describes the amount of gas escaping in a certain time span and can have units like $\frac{m^3}{h}$ or $\frac{l}{h}$.

2.1.7
Forchheimer Coefficient

β

Coefficient which describes the inertial resistance of a porous medium and is also known as non-Darcy flow coefficient. It needs to be determined experimentally.

2.1.8
Incident Emissions

Emissions arising from: incidents/ accidents occurring e.g. due to landslide or third party damage and are reported by third-parties or own staff of the operator, not detected by survey.

2.1.9
Intrinsic Emissions

Emissions arising from minor holes or cracks which are detected by survey, all technical leaks, as well as permeation.

2.1.10
Operational Emissions

Emissions resulting from planned venting and purging of pipelines which is usually done during commissioning, decommissioning, renewal and maintenance of pipelines.

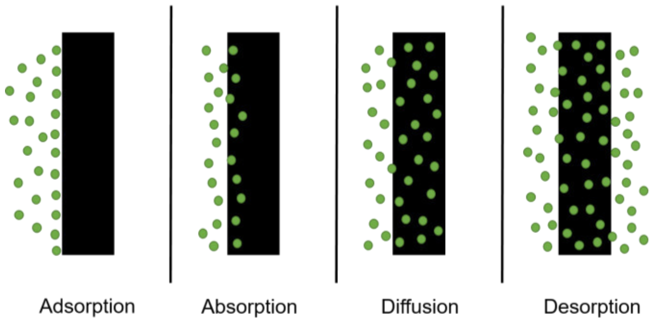
2.1.11

Permeation

Emission from permeation are classified as intrinsic emissions (Table 5). Permeation is the passage of a substance through a solid body. Along with the concentration gradient of the substance between inside and outside of the solid (pipe) and the temperature, the pipe material has the strongest effect on the velocity of permeation. For natural gas appliances, the permeation of methane is in general not relevant for steel pipelines, only for pipes made of plastic [5]. The process has four stages (Figure 1):

1. Adsorption of gas molecules at the pipe surface
2. Absorption into the pipe wall
3. Diffusion through the pipe wall
4. Desorption to the environment

Figure 1: Permeation of Gas Molecules through a Wall



Source: [6]

2.1.12

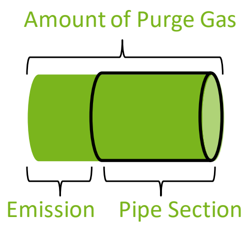
Purge factor

f_{purge}

Factor, which accounts for the emissions caused by purge operations. Purging of the air inside a pipeline or facility is necessary to prevent the risk of explosions. The purge factor herein not refers to the amount of purge gas used but to the amount of the purge gas vented. Example: If purging is done with 1.5 times the pipeline volume, one volume stays in the pipe and 0.5 volumes are vented to the atmosphere. The purge factor is in this case 0.5. If the actual purge factor is not known for an operation, country specifications should be taken into account[2].

[2] For instance, in Germany, pipelines need to be purged at least with 1.5 times the pipeline volume according to DVGW code of practice G 466-1 [7 S. 18].

Figure 2: Simplified Illustration of the Amount of Purge Gas



Source: Own Illustration DBI Gas- und Umwelttechnik

2.2 Natural Gas Infrastructure

2.2.1

Above Ground Storage

An above ground storage (pipe storage or spherical storage) is a metal reservoir which stores rather small amounts of natural gas at different pressure levels and is placed above ground.

2.2.2

Biogas Injection Plant

Plant which processes the biogas coming from fermenters to biomethane and feeds it into the natural gas grid.

2.2.3

City Gate Station

City gate stations (or 'city gates') are metering and pressure regulating facilities located at the custody transfer points where natural gas is delivered from transmission pipelines into the high-pressure lines of a local distribution company. They typically contain metering equipment as well as pressure regulators, that reduce the transmission line pressure to a suitable pressure for the distribution system. If necessary, they also contain preheating systems.

2.2.4

Compressed Natural Gas (CNG)

Natural gas stored in gaseous form at very high pressures and used as fuel for motor vehicles.

2.2.5 Facilities

The term “facilities” comprises all plants/ appliances of the natural gas grid. The system boundaries of this report include: pressure regulating (and meter) stations, LNG liquefaction plants, LNG satellite stations, above ground storages, natural gas filling stations, biogas injection plants, stop cocks.

2.2.6 Gate Valves

Gate valves can close a section of a distribution line, e.g. for maintenance works. If there is a group of valves (one main gate valve and several bypass valves), the term “gate valve” only refers to the main valve. The stop cock is excluded of this definition.

2.2.7 Liquefied Natural Gas (LNG)

Natural gas that is converted to liquid stage for transport or storage. The volume of LNG is 1/600 of a volume of natural gas in gaseous form at standard temperature and pressure with the same energy content.

2.2.8 LNG Liquefaction Plant

Plant which converts gaseous natural gas into its liquid phase.

2.2.9 LNG Satellite Station

Facilities which treat LNG transported from major LNG receiving stations by way of tank trucks or trains. This system consists of LNG storage tanks, vaporizers, calorie control devices, etc. LNG satellite systems are built either directly at the consumer or as a source for a local pipeline network at the storage tank.

2.2.10 Main Lines

Main lines are the network of pipelines (typically underground) that move gas through a gas distribution service area from city gate stations to connected service lines. They operate at different pressure levels and they are typically made of steel or various types of plastic and sometimes also of ductile iron or grey cast iron (with lead yarn joints).

2.2.11

Natural Gas Filling Station

A natural gas filling station is a plant for refilling of motor vehicles with CNG or LNG. Sometimes also called natural gas fuelling station.

2.2.12

Pressure Regulating (and Meter) Station (PR(M)S)

PR(M)S regulate (in one or more stages) the network pressure from the transmission grid to a lower pressure level which is necessary for the connected customers. A PRMS is a PRS with additional measurement equipment (e.g. a process gas chromatograph). Sometimes, PRS also have measurement equipment for measuring the gas quantity. However, gas quantity measurement does not lead to additional emissions and is therefore not relevant for the definition applied here.

2.2.13

Pressure Relief Valve

Valve which is installed in a gas pressure regulating (and meter) installation to protect the downstream equipment from temporarily increased pressures. Triggering of the valve leads to a discharge of a little amount of gas into the atmosphere to prevent a closure of the safety shut-off valve, which would block the entire station.

2.2.14

Service Lines

Services lines transfer the gas from a main line to the customers (households/ industry) and can be installed under or above the ground.

2.2.15

Stop Cock

A stop cock is a type of valve which is used to completely open or close the gas flow at the customer side. The stop cock can be installed inside or outside a customer´s house/ industrial buildings.

2.2.16

Transmission Lines

Transmission lines transport natural gas across long distances and occasionally across interstate boundaries. They are connected to the distribution grid via city gate stations (ref. 2.2.3).

2.2.17
Underground Storage (UGS)

An underground gas storage is a natural or designed reservoir which stores large amounts of natural gas and is placed underground.

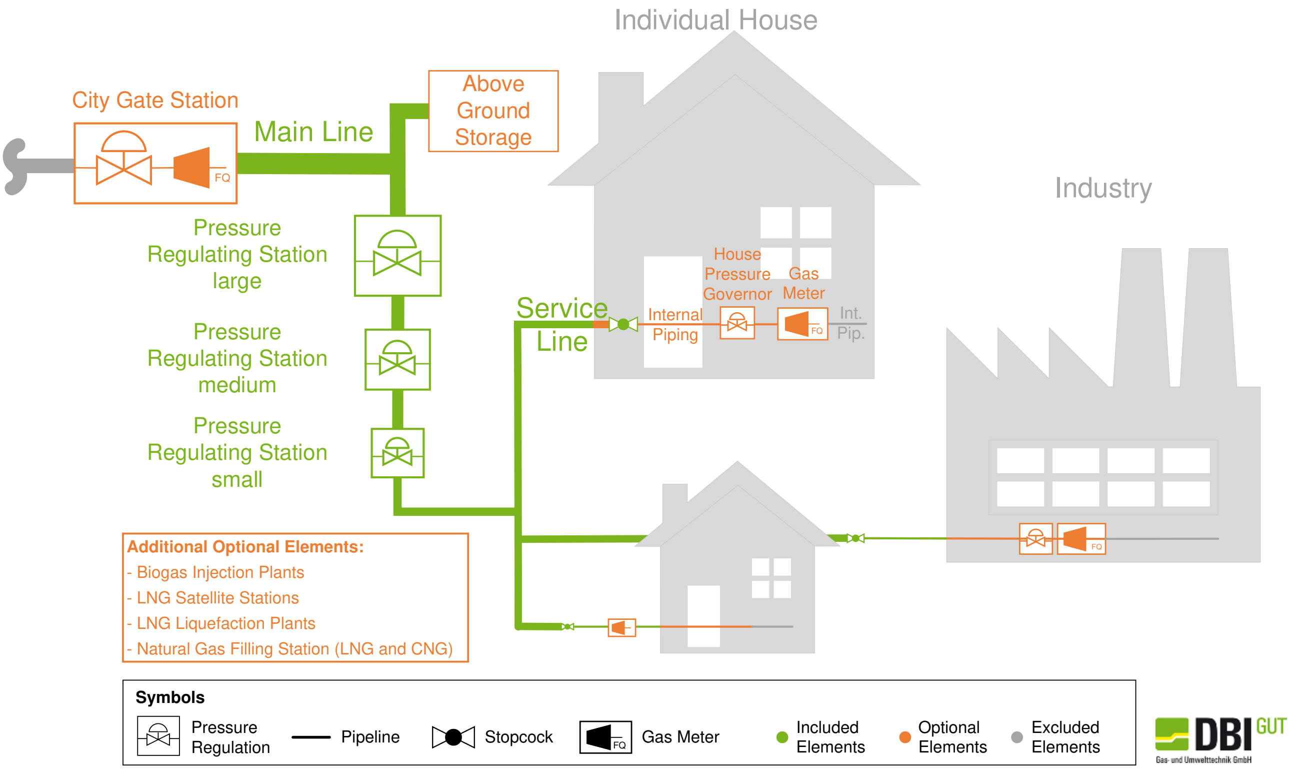
2.2.18
Vault

Vaults are below ground enclosures around natural gas facilities (e.g. pressure regulating stations).

3. Emission Estimation for the Gas Distribution Grid

The natural gas distribution grid is defined within the scope of the project at hand by the following system boundaries (Figure 3):

Figure 3: System Boundaries of the Distribution Grid

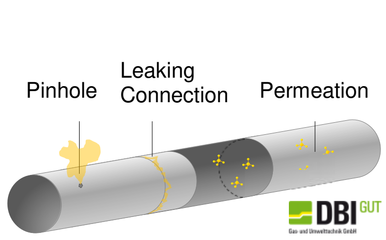
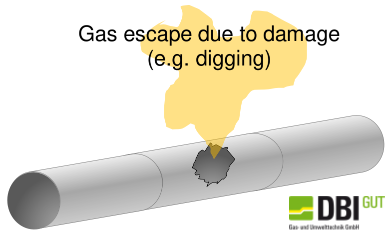
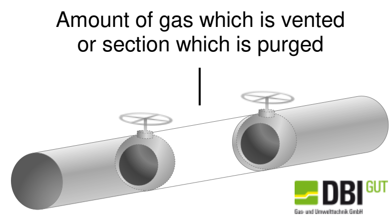


Source: Own Illustration DBI Gas- und Umwelttechnik[3]

[3] Optional elements are not considered in general within the distribution grid. Each country has to decide if these elements belong to the distribution grid or to transmission grid/ end customers. If being considered, country-specific emissions should be assessed.

The emission categories covered are shown in Table 5.

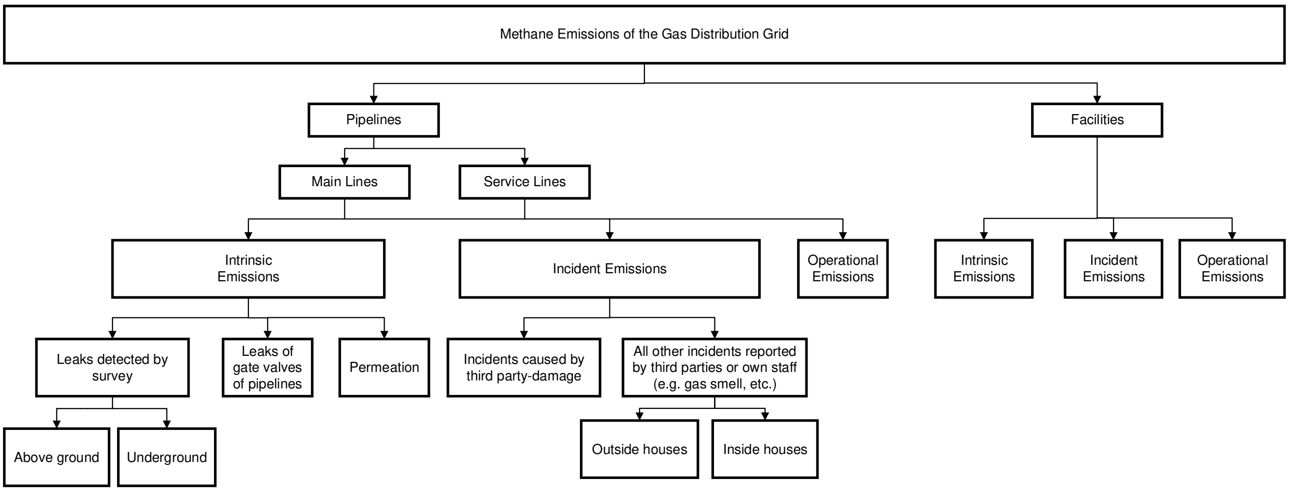
Table 5: Categories of Emissions and Emission Types Covered by the Categories

Intrinsic Emissions	Incident Emissions	Operational Emissions
		
Emissions arising from: minor holes or cracks which are detected by survey, all technical leaks, as well as permeation.	Emissions arising from: incidents/ accidents occurring e.g. due to landslide or third party damage and reported by third-parties or own staff	Emissions arising from: venting and purging during commissioning, renewal, and decommissioning
Note: A comparison to other classifications of emissions is presented in Annex 1.		

Source: Own Illustration DBI Gas- und Umwelttechnik

Figure 4 gives an overview about the emission sources which should be addressed within the emission estimation. Basically, emissions of main lines, service lines and facilities need to be considered. For the emission estimation, it makes a significant difference, how leaks or incidents are noticed because this indicates the duration of gas escape.

Figure 4: Overview of Methane Emission Sources within the Gas Distribution Grid



Source: DBI Gas- und Umwelttechnik

The following sections give an overview some general information about emission estimation (section 3.1), and detailed information about the emission estimation of main lines (section 3.2), service lines (section 3.3) and facilities (section 3.4).

3.1 Basic Information

Emissions are generally estimated with equation (3.1)

$$E = EF \cdot AD \tag{3.1}$$

Where

E are the emissions per year, e.g. in $[\frac{m^3}{yr}]$,

EF is the emission factor, e.g. in $[\frac{m^3}{No.}]$ or $[\frac{m^3}{km}]$,

AD are the activity data, e.g. in $[\frac{No.}{km \cdot yr}]$ or $[\frac{No.}{yr}]$.

Emissions can be given in mass units or volume units. In this report, volume units are the preferred option. If m³ is applied as a unit, the reference conditions should be given. To characterize standard conditions, EN ISO 13443:2005 states that good practice requires to include reference conditions as part of the symbol, not of the unit, and suggests to use the following notation [7]:

$$V(273.15\ K, 101.325\ kPa) = \ \dots m^3$$

The reference conditions can differ in several countries and certain industries. EN ISO 13443:2005 suggests 288.15 K and 101.325 kPa as standard reference conditions for natural gas [7]. In this report, the following notation is applied to allow the use of country-specific reference conditions:

$$V(T, p) = \ \dots m^3$$

The equations in the following sections often include data for pressures. A difference is made between the operating pressure (=overpressure of the system), the atmospheric pressure, and the absolute pressure (=overpressure plus atmospheric pressure). Equations (3.2) describes the link between them.

$$p_{abs} = p_{int} + p_{atm} \tag{3.2}$$

Where

p_{abs} is the absolute pressure of the system in $[Pa]$,

p_{int} is the operating pressure (internal pressure) of the system in $[Pa]$,

p_{atm} is the atmospheric pressure in $[Pa]$.

3.1.1 Determination of Emission Factors

Emission factors (EF) can be determined for several elements (e.g. main lines, service lines or facilities like pressure regulating stations) or for single events (e.g. leaks on pipelines, maintenance operations on pipelines or on facilities, etc.). Further distinction can be made among materials, pressure levels, locations (above ground or underground), diameters, etc. Moreover, EF can be determined related to the pipeline length (EF per km) or related to a single event.

EF per km are determined by equation (3.3)

$$EF = q_v \cdot t \cdot n \tag{3.3}$$

Where

EF is the emission factor in $[\frac{m^3}{km \cdot yr}]$,

q_v is the emission rate (e.g. per leak) in $[\frac{m^3}{leak \cdot h}]$,

t is the duration of gas escape in $[h]$,

n is the number (e.g. of leaks per km per year) in $[\frac{leaks}{km \cdot yr}]$.

Emission factors per event are determined with equation (3.4)

$$EF = q_v \cdot t \tag{3.4}$$

The difference between the equations (3.3) and (3.4) is that the number of leaks is not part of the EF within equation (3.4). This is not necessary for EF per event, since the number of leaks is represented by the activity data (not per km, but absolute).

Including the number of leaks in the formula has the consequence that the EF changes, when the number of leaks changes (every year and for each operator). This problem could be solved by including only stable factors in the EF and taking changing factors as AD (ref. Table 6, section 3.1.2). Following this approach, country-specific EF can be determined and can be combined with AD for one country or for a specific operator and for several years. Moreover, this approach allows a better comparability of the EFs of different countries/ DSO. For this reason, this report focuses on the determination of EF with equation (3.4), however, the application of equation (3.3) is also possible.

The number of EF which are determined for one country or one operator depends on the available database. If there are emission rates and durations of gas escape available for each leak or incident, EF could be determined for each of those leaks/ incidents. If such a detailed database is not available, or a distinction of several data is not made, less EF can be determined and general assumptions need to be made. However, a more detailed emission estimation often leads to lower total emissions, because conservative generalization can be avoided.

For the different categories of emissions, different EF can be determined. The specific requirements for the emission rate and the duration of gas escape are described later in chapter 3.

3.1.2 Determination of Activity Data

In general, AD need to fit to the respective EF. If EF are determined by equation (3.4), the respective activity data are either the number of leaks per year (absolute or per km), incidents or events (Table 6). A further distinction of EF according to different materials, pressure levels, etc. is possible.

Table 6: Examples for the Determination of EF and the correlated AD

Examples for EF		Examples for AD	
$EF = q_v \cdot t$	$EF = 0.1 \frac{m^3}{leak \cdot h} \cdot 2h = 0.2 \frac{m^3}{leak}$	Absolute number of leaks (e.g. 100 leaks)	$AD = 100 \frac{leaks}{yr}$
$EF = q_v \cdot t$	$EF = 0.1 \frac{m^3}{leak \cdot h} \cdot 2h = 0.2 \frac{m^3}{leak}$	Number of leaks per km (e.g. 0.01 leaks/km)	$AD_1 = 0.01 \frac{leaks}{km \cdot yr}$ $AD_2 = 10{,}000\ km$

Moreover, other activity data can exist. For instance, the United Kingdom applies correction factors for the emission rate of pipelines, describing, for instance, differences of the operating pressure during a year (ref. section 3.1.3).

3.1.3 Determination of Methane Emissions and other Emissions

The emissions per year can be calculated with equation (3.5) or (3.6) depending on the data available.

$$E = EF \cdot AD \quad (3.5)$$

$$E = EF \cdot AD_1 \cdot AD_2 \quad (3.6)$$

Where

- E are the emissions per year in $[\frac{m^3}{yr}]$,
- EF is the emission factor (e.g. per leak or event, etc.) in $[\frac{m^3}{leak}]$ or $[\frac{m^3}{event}]$,
- AD is the number (e.g. of leaks or events per year, etc.) in $[\frac{leaks}{yr}]$ or $\left[\frac{events}{yr}\right]$,
- AD_1 is the number of leaks per km pipeline per year in $[\frac{leak}{km \cdot yr}]$,
- AD_2 is the length of pipeline kilometres in $[km]$.

The number of AD can be extended. For instance, the UK applies an AD_3, which is a correction factor for rewarding dynamic pressure control[4].

By including the methane content of natural gas in the equations, the methane emissions can be determined with equation (3.7)

$$E_{CH4} = E_{NG} \cdot x_{CH4} \quad (3.7)$$

Where

- E_{CH4} are the methane emissions per year in $[\frac{m^3_{CH4}}{yr}]$,
- E_{NG} are the natural gas emissions per year in $[\frac{m^3_{NG}}{yr}]$,
- x_{CH4} is the fraction of CH_4 in the natural gas in $[-]$.

[4] Dynamic Pressure Control is a measure for reducing emissions of pipelines. During times of low gas consumption, the system pressure is reduced to reduce the pressure difference to the atmosphere and accordingly the driving force for leaks.

Since this report focuses on methane emissions, the following equations generally show the determination of methane emissions. However, by substituting x_{CH4} by the fraction of the relevant component, the same equations can be applied for calculating CO_2-Emissions or other hydrocarbon emissions than CH_4.

3.2 Emission Estimation of Main Lines

The following sections explain which types of emissions need to be considered for main lines and how they can be estimated.

3.2.1 Underground Leaks Detected by Survey

Natural gas distribution grids are inspected within surveys regularly to detect very small leaks and to ensure operational safety. The emissions of leaks, which are detected by survey are classified as intrinsic emissions (Table 5) and can be estimated by equation (3.8a) or (3.8b)

$$E_{CH4} = q_v \cdot t \cdot n \cdot x_{CH4} \tag{3.8a}$$

$$E_{CH4} = q_v \cdot t \cdot n \cdot l \cdot x_{CH4} \tag{3.8b}$$

Where

E_{CH4}	are the methane emissions of leaks detected by survey in $[\frac{m^3}{yr}]$,
q_V	is the average emission rate of a leak in $[\frac{m^3}{leak \cdot h}]$,
t	is the average duration of gas escape of a leak in $[h]$,
n	is the number of leaks detected per year in $\left[\frac{leaks}{yr}\right]$ or $\left[\frac{leaks}{km \cdot yr}\right]$,
x_{CH4}	is the methane content of the natural gas in [-].
l	is the length of main lines in $[km]$.

A sample calculation is shown in Annex 7, Figure A.5.

3.2.1.1 Emission Rate

Two types of approaches can be applied to determine emission rates q_V for underground leaks:

1.) Indirect approaches (determination of the emission rate of a pipe section)
2.) Direct approaches (determination of the emission rate of one leak)

Indirect approaches do not measure the emission rate of a certain leak directly but take into account auxiliary quantities. For instance, in the so called pressure variation method, not the emission rate but the flow rate in a control section (e.g. a pipeline section between two valve stations), which is necessary to keep the operating pressure of a pipeline constant in a certain time span, is measured. The control section can include several leaking points (sealings, pinholes, cracks, etc.) as pictured in Table 5 for intrinsic emissions. Another indirect approach is the pressure decay method. Here, the auxiliary quantity is the pressure loss of a pipeline section during a certain time span.

The main disadvantage of indirect approaches is, that the number of leaks is included in the emission rate. This is visible in the unit of the emission rate. Whereas direct approaches determine the emission rate for one leak (unit [$\frac{m^3}{leak \cdot h}$]) and emissions are calculated by multiplying this emission rate with the number of leaks (equation (3.5) or (3.6)), indirect approaches determine an emission rate for one section (unit [$\frac{m^3}{km \cdot h}$]) which can include several leaks and which is only multiplied by the pipeline length, not by the number of leaks. If the number of leaks decreases, this cannot be made visible without doing new measurements, since there is no reference to the leak survey data. This significantly increases the effort for a continuous emission estimation. For this reason, the report focuses on direct approaches.

Several studies indicate a significant influence of soil microbes oxidizing methane to carbon dioxide (i.e. soil oxidation) [8, p. 14], [9, p. 27]. Depending on the leak rate, a range of 0 to 40.3 % is given for the reduction of methane emissions due to soil oxidation but mostly, rates up to 3 % are applied [10, p. 38]. However, it is challenging to include the soil oxidation effect into the emission estimation, because the process is influenced by many factors like soil type, soil moisture, and temperature of the soil. For this reason, the effect is not considered in the methods described in this report, which is a conservative approach since emissions might be overestimated a little.

Two approaches are in place to determine the emission of an underground leak detected by survey:

1.) Direct measurement of the emission rate of a leak
2.) Determination of soil coefficients and calculation of the emission rate with leak size and pipeline pressure

3.2.1.1.1 Direct Measurement of the Emission Rates

The emission rate of a single leak can be measured directly, e.g. by suction method. In this case, the leak first needs to be identified with a gas detector, e.g. carpet probe (ref. [11]) or a car with optical methane detection (ref. [12]). The detector measures a concentration of methane in the air. This concentration is only loosely related with to the actual emission rate, because the concentration measured above ground is influenced by many factors (e.g. wind influences, the distribution of leaking gas the soil). Thus, the emission rate needs to be determined with another measurement device (e.g. a suction measurement device, ref. Annex 5).

Not all leaks are suitable for a direct measurement, because, for instance, the location is not well accessible, or the distance to crucial points (e.g. building, cellars) requires an immediate repair without time for measurement procedures.

In general, it is not necessary to measure the emission rates of all leaks occurring in a grid. A representative selection is sufficient, which leads to average emission rates for several leaks. However, as yet a well-defined procedure how to make this representative selection does not exist. Many influencing factors need to be considered (ref. Annex 5, Table A.9).

3.2.1.1.2 Determination of Soil Coefficients and Calculation of the Emission Rate from Leak Size and Pipeline Pressure

Emission rates underground can be determined by using soil properties and calculating the emission rates depending on the size (radius) of the leak and the pipeline pressure (equation (3.9)).

$$q_V(T,p) = 3600 \cdot \frac{6\pi\mu r_{eq}^2}{\rho(T,p)k\beta} \cdot \left[-1 + \sqrt{1 + \frac{k^2}{\mu^2} \cdot \frac{2\beta}{3r_{eq}R_iT_{int}} \cdot (p_{abs}^2 - p_{atm}^2)}\right] \quad (3.9)$$

Where

q_V	is the volume flow rate of a leak at reference conditions in $[\frac{m^3}{leak \cdot h}]$,
r_{eq}	is the equivalent radius of the leak in $[m]$,
ρ	is the density of the natural gas at reference conditions in $[\frac{kg}{m^3}]$,
k	is the permeability of the ground $[m^2]$,
β	is the Forchheimer coefficient (ref. 2.1.7, p. 15) in $[m^{-1}]$,
μ	is the viscosity of the gas in the pipeline in $[Pa \cdot s]$,
R_i	is the specific gas constant of the natural gas in $[\frac{J}{kg \cdot K}]$,
T_{int}	is the temperature of the gas in the pipeline in $[K]$,
p_{abs}	is the absolute pressure in the pipeline in $[Pa]$, and
p_{atm}	is the atmospheric pressure in $[Pa]$.

The specific gas constant can also be expressed as $R_i = \frac{R_0}{M_i}$.

Where

R_0	is the universal gas constant = $8.31448 \frac{J}{kg \cdot K}$,
M_i	is the specific molar mass of natural gas in $\left[\frac{kg}{kmol}\right]$.

The permeability of the ground k and the Forchheimer coefficient β should be determined experimentally. GRDF/ENGIE uses a ground environment coefficient K_{sol} instead of the Forchheimer coefficient, which is determined by equation (3.10).

$$K_{sol} = \frac{0.3}{\sqrt{k}} \quad (3.10)$$

Where

K_{sol}	is ground environment coefficient in $[m^{-1}]$,
k	is the permeability of the ground $[m^2]$.

The equivalent radius r_{eq} corresponds to the radius which a sphere of the same surface as the leak would have and is calculated by equation (3.11)

$$r_{eq} = \sqrt{\frac{A}{4\pi}} \quad (3.11)$$

Where

r_{eq}	is the equivalent radius of the leak in $[m]$,
A	is the area (surface) of the leak in $[m^2]$.

The determination of A is described in section 3.2.5.1, p. 34, Table 8.

The mass flow rate is calculated by multiplying the volume flow with the density ρ of the escaping natural gas at reference conditions (3.12)

$$q_m = q_V(T,p) \cdot \rho(T,p) \tag{3.12}$$

Using this approach enables to consider many different categories of leaks, and avoids averaging and therefore eliminates the need for generating representative emission rates, if individual leaks are considered. However, challenges occur in the determination of the equivalent radius r_{eq} and the coeffiecients β and k.

Measuring the r_{eq} of each leak is a huge effort for the operator. Furthermore, it is not always possible to measure the leak size (e.g. in case of annular gaps). For this reason, assumptions can be made for the size of the leak depending on the type of the damage, the pressure level and the type of pipeline (main line or service line) but these assumptions again need to be representative, which reduces the advantage of the individuality of the approach.

The same accounts for the coefficients β and k, which need to be determined experimentally for the relevant soil types and need to be allocated to the leaks by the operator who does the leak survey. This can be avoided by taking average factors, but those need to be representative, too.

A sample calculation is shown in Annex 7, Figure A.6.

3.2.1.2 Duration of Gas Escape

Next to the emission rate, the duration of a gas escape needs to be determined in order to estimate emissions of underground leaks (equation (3.13))

$$t = t_1 + t_2 \tag{3.13}$$

Where

- t is the time from the beginning of the gas escape until the gas flow is stopped (at least by provisional measures),
- t_1 is the time from the beginning of the gas escape until it is detected and
- t_2 is the time from the detection of the gas escape until the leak is stopped (at least by provisional measures).

The time t_1 is difficult to determine since the network operator knows when the leak is detected but not when the gas escape began exactly.

The maximum duration for time t_2 is regulated in most countries and depends on the perceived urgency of repair and may be determined by various factors, e.g.:

- Location of the gas leak (distance to buildings, cellars, canalisation,…)
- Concentration of methane measured in the survey

Leaks are classified according to these factors and maximum repair times for the different classes are available.

Two basic approaches are in place to determine t:

1.) t depends on the monitoring period and the maximum repair time
This approach was developed by the Fraunhofer Institut für Systemtechnik und Innovationsforschung in 2000 (ref. [13]). The time t_1 is derived from the maximum time between two surveys. For t_2 it is assumed that the leak can be repaired immediately or at the end of the allowed time frame. Assuming the average value of the extremes of the two time periods, t_{total} is calculated as:

$$t = \frac{t_{1,max} + t_{2,max}}{2} = \frac{t_{mon} + t_{rep}}{2} \tag{3.14}$$

2.) Verified expert estimations for t
GRDF/ENGIE assumes a total time of leaks detected by survey of $t = 8{,}760\ h$ based on the assumption that leaks grow within their lifetime and a leak would not exist longer than one year without being reported as an incident.

At the reporting time, no scientific investigation is known, which states that leaks grow within their lifetime. However, this is considered to be possible. There is need for research to evaluate this phenomenon and its relation for certain pipeline materials or causes of leaks.

3.2.1.3 Number of Leaks

The emission rate q_V and the duration of gas escape t should be multiplied by the number of leaks (absolute or per km) n. Different categories of leaks (e.g. leaks on low pressure plastic pipelines) can be defined by taking into account different q_V and t and multiplying them with the respective number of leaks of the category.

Depending on where the monitoring takes place and how many kilometres of the grid are surveyed per year, significant differences could occur in the number of leaks found in one year, which is hard to explain to authorities, the public, etc. For this reason, taking an average of several years for the number of leaks within the emission reporting period could be beneficial but it is not mandatory.

If an averaging is made, it should be done in accordance to the monitoring periods or multiples of the monitoring period. That means, if the monitoring is done every four years, the average should be defined for four years or eight years. If the monitoring is done every five years, the average should be defined for five years or 10 years and so on. This leads to the fact, that different time horizons might need to be taken into account, since the monitoring period can depend on pressure levels, materials, leak frequencies of previous years, locations (industrial area or commercial area), etc. If no data about the monitoring periods is available, an average should be defined for five years.

It is important to update the number of leaks regularly for the emission reporting to reward emission reduction measures like lining, pipeline exchange or joint treatment, which lead to a decreased number of leaks and accordingly to lower intrinsic emissions.

For emission reporting, it can be helpful to explain the number of leaks reported. Table 7 summarizes some influencing parameters.

Table 7: Parameters influencing the Number of Leaks

Parameter	Influences on Number of Leaks
Diameter	Small diameters of grey cast iron pipes are presumed to be more vulnerable to landslide and traffic loads [14, pp. 4.4-9].
Material/ Technology	The number of leaks detected by survey depends on the materials available in the grid. Plastic pipelines show significantly less leaks than steel pipelines [15].
Soil	Soils with large fractions of clay and loam, salt or moor are more aggressive than soils with large sand fractions and lead to higher numbers of leaks [14, pp. 4.4-12].
Age/ Maintenance State	Younger and well maintained grids/ facilities show lower numbers of leaks than older ones.
Pipeline Pressure	The number of leaks per km often decreases with increasing pipeline pressure [14, pp. 4.4-41].
Joint Treatment	The number of leaks decreases if joint treatment is applied (e.g. conditioning with MEG[5]).
Location	Increased frequency or weight of traffic can lead to a higher number of leaks.

3.2.2 Above Ground Leaks Detected by Survey

Most of the main lines are buried pipes. If leakages are found detected by survey, they are often underground. However, also a minor part of main lines above ground exists which could show leaks that are not covered by soil.

3.2.2.1 Emission Rate

The emission rates of above ground leaks are generally larger than the emission rates for underground leaks since there is no soil acting as a barrier.

The missing barrier effect of the soil is also relevant for incidents reported by third-parties after a third-party damage (ref. section 3.2.5.1, p. 34). For this reason, the related equations and parameters described in section 3.2.5.1, p. 34 can be used to calculate the emission rates of above ground leaks.

3.2.2.2 Duration of Gas Escape

If a leak is found during survey, the duration of gas escape does not depend on the fact whether it is underground or above ground. The influencing factors for the duration are the same. For this reason, the same equations and parameters as given in section 3.2.1.2, p. 29 can be applied.

5 A conditioning with Monoethylene Glycol (MEG) is, for instance, applied in the UK as treatment of lead-yarn joints. Leakage decreases according to the MEG saturation.

3.2.2.3 Number of Leaks

The emission rate q_V and the duration of gas escape t should be multiplied by the number of leaks (absolute or per km) n. Different categories of leaks (e.g. leaks on low pressure plastic pipelines) can be defined by taking into account different q_V and t and multiplying them with the respective number of leaks of the category.

3.2.3 Emissions of Gate Valves on Pipelines

Gate valves exist each 7 to 15 km on main lines to enable the shut-off of a pipeline section, e.g. for maintenance activities. The gate valves can show a continuous leakage, in particular on the sealing systems. Gland packings show higher emission rates than O-ring seals [14, pp. 4.4-43].

If it is not proven else, a continuous leakage of all valves should be assumed additionally to the leaks detected by survey (section 3.2.1, p. 26). Battelle assumes an average emission rate q_v of 0.001 m³NG/h for a duration of gas escape t of 8,760 h/yr for well-maintained gate valves in all pressure levels [14, pp. 4.4-44]. n represents the number of gate valves in the grid (absolute or per km). The emissions should be determined by equation (3.15a) or (3.15b)

$$E_{CH4} = q_v \cdot t \cdot n \cdot x_{CH4} \tag{3.15a}$$

$$E_{CH4} = q_v \cdot t \cdot n \cdot l \cdot x_{CH4} \tag{3.15b}$$

Where

E_{CH4} are the continuous methane emissions of gate valves in $[\frac{m^3}{yr}]$,

q_V is the average emission rate of one valve in $[\frac{m^3}{valve \cdot h}]$,

t is the duration of gas escape in $[\frac{h}{yr}]$ (= 8,760 h/yr),

n is the number of valves (absolute or per km main line) in $[valves]$ or $\left[\frac{valves}{km}\right]$,

l is the length of main lines in $[km]$,

x_{CH4} is the fraction of CH_4 in the natural gas in $[-]$.

3.2.4 Permeation

Permeation emissions can be determined by calculation, the only parameter that needs to be determined by measurements is the permeation coefficient, which describes the ability of a certain gas (e.g. methane) to permeate through a certain material (e.g. PE100) at a certain temperature (e.g. 20 °C). Annex 2 provides an overview of certain permeation coefficients given in the literature.

The following equations (3.16) to (3.18) should be used to calculate permeation emissions. These equations are already applied by many countries in Europe and can be regarded as the best available method. Differences in the calculations of several countries only occur in the use of different symbols or transformed equations.

$$E_{CH4} = PC_{CH4} \cdot \pi \cdot SDR \cdot p_{CH4} \cdot l \cdot t \qquad (3.16)$$

Where

E_{CH4}	are the emissions of a certain gas (e.g. methane) caused by permeation in $\left[\frac{m^3}{yr}\right]$,
PC	is the permeation coefficient of a certain gas (e.g. methane) through a certain material, (e.g. PE100) at a certain temperature (e.g. 20 °C) in $[\frac{m^3}{m \cdot bar \cdot d}]$,
SDR	is Standard Dimension Ratio in $[-]$,
p_{CH4}	is the partial pressure of methane in the pipeline in $[bar]$,
l	is the length of the pipeline in $[m]$,
t	is the duration of the permeation in $[\frac{d}{yr}]$.

The Standard Dimension Ratio (SDR) should be calculated by equation (3.17)

$$SDR = \frac{d_e}{s} \qquad (3.17)$$

Where

d_e	is the external diameter of the pipeline in $[mm]$,
s	is the wall thickness of the pipeline in $[mm]$.

If there is no information about the SDR of the pipes, the assumption can be made that pipelines with a maximum operating pressure lower than or equal 5 bar[6] are SDR17[7] and pipelines with a maximum operating pressure greater than 5 bar are SDR11.

The partial pressure of a component should be calculated by equation (3.18)

$$p_{CH4} = x_{CH4} \cdot p_{abs} \qquad (3.18)$$

Where

p_{CH4}	is the partial pressure of methane in the pipeline in $[bar]$,
x_{CH4}	is the fraction of methane in natural gas in $[-]$; if the mole fractions of the components in the natural gas are not known, the volume fractions can be taken in a good approximation.
p_{abs}	is the absolute pressure in the pipeline in $[bar]$.

The influence of the soil temperature around a pipeline on permeation is often neglected but was assessed to be significant in a recent study, since the permeation rates drop significantly with decreasing temperatures (more detailed information in Annex 3). If no detailed information about soil temperatures and about permeation coefficients for these temperatures is available, the coefficients based on 20 °C should be selected for a conservative estimate.

A sample calculation is given in Annex 7, Figure A.7.

6 Absolute pressure = 6 bar

7 Pipelines with a maximum operating pressure lower than or equal 5 bar can also be SDR11 but for a conservative consideration, SDR17 should be taken.

3.2.5 Incidents reported after Third-Party Damage

The emissions of incidents, which are reported after third-party damage (ref. Table 5 - incident emissions) can be estimated by equation (3.19a) or (3.19b)

$$E_{CH4} = q_v \cdot t \cdot n \cdot x_{CH4} \tag{3.19a}$$

$$E_{CH4} = q_v \cdot t \cdot n \cdot l \cdot x_{CH4} \tag{3.19b}$$

Where

E_{CH4} are the methane emissions after third-party damages in $[\frac{m^3}{yr}]$,

q_V is the emission rate in $[\frac{m^3}{inc \cdot h}]$,

t is the duration of gas escape in $[h]$,

n is the number of incidents (absolute or per km main line) in $\left[\frac{inc.}{yr}\right]$ or $\left[\frac{inc.}{km \cdot yr}\right]$,

l is the length of main lines in $[km]$,

x_{CH4} is the fraction of CH_4 in the natural gas in $[-]$.

3.2.5.1 Emission Rate

Third-party damages mainly occur due to digging. For this reason, the pipelines damaged or ruptured after third-party damages are usually not covered by soil anymore.

First, it is important to determine if the gas flow from the leak is supersonic or subsonic. For this evaluation, the critical pressure ratio is used [16, p. 224]. The critical pressure ratio is determined by equation (3.20). For natural gas ($\kappa \approx 1{,}3$), a critical pressure ratio of about 0.54 is valid.

$$\left(\frac{p_{atm}}{p_{abs}}\right)_{crit} = \left(\frac{2}{\kappa+1}\right)^{\frac{\kappa}{\kappa-1}} \tag{3.20}$$

Where

p_{atm} is the atmospheric pressure,

p_{abs} is the absolute pressure and

κ is the adiabatic index of natural gas.

If the pressure ratio $\frac{p_{atm}}{p_{abs}}$ is equal or greater than the critical pressure ratio, the flow is subsonic (equation (3.21)). If it is smaller, the flow is supersonic (equation (3.22))

$$\frac{p_{atm}}{p_{abs}} \geq \left(\frac{p_{atm}}{p_{abs}}\right)_{crit} \rightarrow subsonic\ flow \tag{3.21}$$

$$\frac{p_{atm}}{p_{abs}} < \left(\frac{p_{atm}}{p_{abs}}\right)_{crit} \rightarrow supersonic\ flow \tag{3.22}$$

To determine an emission rate (subsonic as well as supersonic), the area of the damage A needs to be determined. The respective equations are valid for circular holes. To apply them also for holes with a non-circular shape, the hydraulic diameter needs to be considered (equation (3.23)).9o99m

$$d_h = \frac{4A}{P} \qquad (3.23)$$

Where

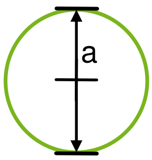
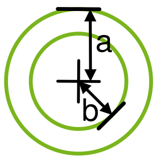
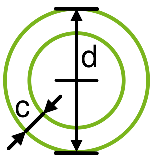
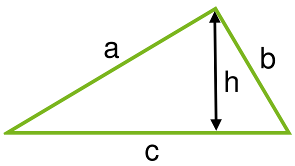
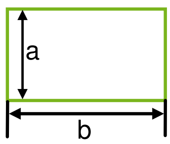
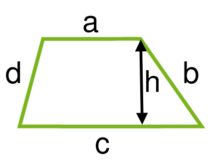
d_h is the hydraulic diameter in $[m]$,

A is the area of the damage (described below) in $[m^2]$,

P is the perimeter of the damage in $[m]$.

The area A and the perimeter P used within equation (3.23) depends on the shape of the damage and on the dimensions a and b (ref. Table 8). The equations for the calculation of the area of damage for different forms are given in Table 8. Since the equations apply for idealized forms, the form which is closest to the real damage can be chosen. The parameters a and b can be determined by measurement with calliper or folding rule.

Table 8: Area and Perimeter of Damages in Different Forms

Form		Area A	Perimeter P
Circle		$A = \frac{\pi}{4} a^2$	$P = \pi a$
Circular ring (annular gap)	 	$A = \pi \cdot (a^2 - b^2)$ or (in good approximation) $A = \pi \cdot c \cdot d$	$P = 2\pi \cdot (a + b)$
Triangle		$A = \frac{1}{2} \cdot c \cdot h$	$P = a + b + c$
Rectangle		$A = a \cdot b$	$P = 2 \cdot (a + b)$
Trapeze		$A = \frac{1}{2}(a + c) \cdot h$	$P = a + b + c + d$

Damage sizes range from a few millimetres up to the nominal diameter of the pipe (in case of ruptures). For digging, a hole diameter of 100 mm, and for damages with a pickaxe, a hole diameter of 20 mm can be conservatively assumed, if the actual damage size is not known. These values are expert estimations analogous to the size of bucket teeth [17].

3.2.5.1.1 Equations for Subsonic Flow

Emissions related with incidents reported by third-parties after third-party damage with a pressure ratio greater than or equal the critical pressure ratio are calculated with equation (3.24). This equation is broadly applied among the partners contributing to this report and can be seen as the best available approach. Country-specific differences just exist due to transformation and usage of different symbols, which is shown in Annex 4. The symbols in the equation were chosen in accordance with ISO 5167 [1].

$$q_V(T,p) = 3600 \cdot \frac{C_D}{\rho_{(T,p)}} \cdot \frac{\pi}{4} d_h^2 \cdot \left(\frac{p_a}{p_{int}}\right)^{\frac{1}{\kappa}} \cdot \sqrt{2 \cdot \frac{\kappa}{\kappa-1} \cdot p_{abs} \cdot \rho_{int} \cdot \left(1 - \left(\frac{p_{atm}}{p_{abs}}\right)^{\frac{\kappa-1}{\kappa}}\right)} \quad (3.24)$$

Where

- q_V is the volume flow rate of an incident in $[m^3/h]$, at reference conditions,
- C_D is the discharge coefficient (ref. section 2.1.3, p. 14) in $[-]$,
- ρ is the density of the natural gas in $\left[\frac{kg}{m^3}\right]$,
- d_h is the hydraulic diameter in $[m]$,
- p_{atm} is the atmospheric pressure in $[Pa]$,
- p_{abs} is the absolute pressure of the pipeline in $[Pa]$,
- κ is the adiabatic index of natural gas in $[-]$,
- ρ_{int} is the density of the natural gas in the pipeline in $\left[\frac{kg}{m^3}\right]$.

The density of the gas in the pipeline can also be expressed with equation (3.25).

$$\rho_{int} = \frac{p_{int}}{R_i \cdot T_{int}} \quad (3.25)$$

Where

- R_i is the specific gas constant of the natural gas in $[\frac{J}{kg \cdot K}]$,
- T_{int} is the temperature of the gas in the pipeline in $[K]$.

The mass flow rate is calculated by multiplying the volume flow with the density ρ of the escaping natural gas at reference conditions (equation (3.12)).

3.2.5.1.2 Equations for Supersonic Flow

Emissions related with incidents reported by third-parties after third-party damage with a pressure ratio smaller than the critical pressure ratio are calculated with equation (3.26)

$$q_V(T,p) = 3600 \cdot \frac{C_D}{\rho_{(T,p)}} \cdot \frac{\pi}{4} d_h^2 \cdot \left(\frac{2}{\kappa+1}\right)^{\frac{1}{\kappa-1}} \cdot \sqrt{\frac{2\kappa}{\kappa+1} \cdot p_{int} \cdot \rho_{int}} \quad (3.26)$$

The mass flow rate is calculated by multiplying the volume flow with the density ρ of the escaping natural gas at reference conditions (equation (3.12)).

3.2.5.2 Duration of Gas Escape

Next to the emission rate, a duration of the gas escape needs to be determined, to estimate emissions after third party-damages. Three aspects influence the duration of gas escape (equation (3.27)).

$$t = t_1 + t_2 + t_3 \tag{3.27}$$

Where

t_{total} is the time from the beginning of the gas escape until the gas flow is stopped (at least by provisional measures),

t_1 is the time from the beginning of the gas escape until somebody notices it and calls the DSO,

t_2 is the time from the call until the DSO is onsite and

t_3 is the time when DSO is onsite until the gas flow is stopped (at least by provisional measures).

In case of a third-party damage, the beginning of the gas escape is well known and all durations after are rather short, since a fast reaction is necessary for safety reasons (e.g. t_3 is regulated and varies, depending on the country, between 15 minutes and one hour as a maximum).

Generally, the times t_1, t_2 and t_3 are known to the DSO who can apply them for estimating the emissions. If the exact times are not known, an operator-specific or country-specific t_{total} can be assumed which should vary between 30 minutes and 6 hours.

3.2.5.3 Number of Incidents

The emission rate q_V and the duration of gas escape t should be multiplied by the number of incidents. Different categories of incidents can be defined by taking into account different q_V and t and multiplying them with the respective number of incidents of the category.

3.2.6 Other Incidents reported by Third-Parties or Own Staff of DSO

Several incidents are not caused by third-parties but are recognized due to gas smell or discolouration of grass by own staff of the operator or by third-parties (e.g. the general public). To estimate the emissions, equations (3.28a) or (3.28b) can be used.

$$E_{CH4} = q_v \cdot t \cdot n \cdot x_{CH4} \tag{3.28a}$$

$$E_{CH4} = q_v \cdot t \cdot n \cdot l \cdot x_{CH4} \tag{3.28b}$$

Where

E_{CH4}	are the methane emissions of other incidents per year in $[\frac{m^3}{yr}]$,
q_V	is the emission rate of the reported incident in $[\frac{m^3}{inc.\cdot h}]$,
t	is the duration of gas escape during the incident in $[h]$,
n	is the number of incidents per year in $\left[\frac{inc.}{yr}\right]$ or $\left[\frac{inc.}{km\cdot yr}\right]$,
l	is the length of main lines in $[km]$,
x_{CH4}	is the fraction of CH_4 in the natural gas in $[-]$.

The estimation of the emission rate q_v and the duration of gas escape t is described in the sections below.

Attention needs to be paid to the number of incidents: It needs to be ensured, that the related emissions are not estimated in another category (e.g. leaks detected by survey or incidents reported after third party damage) to avoid double-counting.

3.2.6.1 Gas Smell Outside Houses (Emission Source Underground)

3.2.6.1.1 Emission rate

Since the DSO has to stop the gas flow immediately when a gas smell is reported, no measurement data is available for emissions rates of incidents which were recognized by a gas smell outside. To estimate the contribution of emissions in case of gas smells, assumptions are made based on the emission rates of leaks detected by survey (ref. section 3.2.1, p. 26). These assumptions have been developed within the experts of the project group, but there is further need for research, since many influencing factors exist which cannot be rewarded at the moment.

Assuming that every leak detected by survey was not smelled earlier, the emission rate for leaks detected by survey is presumably lower than for leaks reported by gas smell. That means, leaks which are smelled, have presumably a higher leak rate than the leaks detected by survey.

In the available data, the highest emission rates were about 900 l/h. Including a margin factor of two, a maximum emission rate of 1,800 l/h for gas smells outside houses can be assumed as a conservative consideration.

If the size of the damage, the pipeline pressure and the soil coefficients are known, the emission rate can also be estimated with equation (ref. section 3.2.1.1.2, p. 27). A typical incident which can cause a gas smell outside, is a leaking connection after ground movements. Assuming an annular gap with a size of 0.2 mm and an absolute pipeline pressure of 4.8 bar, the incident would result in an emission rate of 0.83 l/h according to data from GRDF/ENGIE[8]. The assumption of a hole with a diameter of 1 mm (3 mm) and the pipeline pressure of 4.8 bar absolute leads to an emission rate of 2,747 l/h (6,395 l/h).

8 Value given by GRDF/ENGIE with their soil coefficients.

3.2.6.1.2 Duration of Gas Escape

There are no approaches in place for the determination of the duration of gas escape, thus, assumptions are made. In most areas, in particular in cities, a daily detection by passing people can be presumed. The gas flow is stopped (at least by provisional measures) as soon as possible after the call. For this reason, a t of 2 days (margin factor 2) can be expected.

$$t = 2\ days$$

For rural areas, this assumption might deviate but is difficult to determine. For this reason, a conservative consideration dependent on the date of the last survey can be made (equation (3.29)).

$$t = \frac{date\ of\ the\ detection - date\ of\ the\ last\ survey}{2} \tag{3.29}$$

Another possibility for both, rural areas and urban areas is to take into account recent events such as ground movements or recent works near the incident as indication for the duration of gas escape (equation (3.30)).

$$t = \frac{date\ of\ the\ detection - date\ of\ recent\ events}{2} \tag{3.30}$$

3.2.6.2 Gas Smell Outside Houses (Emission Source Above Ground)

3.2.6.2.1 Emission Rate

The emission rates of above ground leaks are generally larger than the emission rates for underground leaks since there is no soil, which could act as a barrier.

The missing barrier effect of the soil is also relevant for incidents reported by third-parties after a third-party damage (ref. section 3.2.5.1, p. 34).

The equations described in section 3.2.5.1, p. 34 can be used.

3.2.6.2.2 Duration of Gas Escape

The assumptions described in section 3.2.6.1.2, p. 39 can be taken into account.

3.2.6.3 Other Effects Leading to the Reporting of an Incident

Besides gas smell, leaks could be recognized by other effects (e.g. discolouration of grass). Since these events are very rare, a simplified consideration is suggested.

For the emission rate, the same approaches as for underground leaks detected by survey (ref.0, p. 26) or above ground (ref.3.2.2.1, p. 31) can be used.

For the duration of gas escape a conservative consideration can be made based on the time of the last monitoring (ref. equation (3.29) in section 3.2.6.1.2, p. 39).

3.2.7 Operational Emissions

Operational emissions comprise venting and purging of pipelines, which is usually done during commissioning, decommissioning, renewal and maintenance of pipelines for safety reasons to prevent the risk of explosions. If detailed data are available, operational data should be determined with an event-based approach by summing up the venting and purging emissions of each operation (section 3.2.7.1). The event-based approach is the most accurate one and the one which can reward emission reduction measures such as the application of flaring or a vacuum pump.

If the detailed data for the event-based approach is not available, a simplified approach can be used instead (section 3.2.7.2). This simplified approach might overestimate the emissions but is sufficient in terms of benefit-effort, since the contribution of operational emissions to the total emissions of the gas distribution grid is very low according to current information[9].

3.2.7.1 Event-based Approach

The total operational emissions should be calculated by summing up the venting and purging emissions of each operation (equation (3.31a) or (3.31b)).

$$E_{CH4} = EF_{vent} \cdot n \cdot x_{CH4} + EF_{purge} \cdot n \cdot x_{CH4} \qquad (3.31a)$$

$$E_{CH4} = EF_{vent} \cdot n \cdot l \cdot x_{CH4} + EF_{purge} \cdot n \cdot l \cdot x_{CH4} \qquad (3.31b)$$

Where

E_{CH4}	are the operational methane emissions of one year in $[\frac{m^3}{yr}]$,
EF_{vent}	is the emission factor for venting emissions of one operation in $[\frac{m^3}{event}]$,
EF_{purge}	is the emission factor for purging emissions of one operation in $[\frac{m^3}{event}]$,
n	is number of operations per year (absolute or per km mainline) in $\left[\frac{events}{yr}\right]$ or $\left[\frac{events.}{km \cdot yr}\right]$,
l	is the length of main lines in $[km]$,
x_{CH4}	is the fraction of CH_4 in the natural gas in $[-]$.

The emissions related with venting should be estimated with equation (3.32), and (3.33)

$$EF_{vent} = V_{geo} \cdot \frac{p_{abs} \cdot T_n \cdot Z(p_n, T_n)}{p_n \cdot T_{int} \cdot Z_i} \qquad (3.32)$$

$$V_{geo} = \frac{\pi}{4} \cdot d_{int}^2 \cdot l \qquad (3.33)$$

Where

V_{geo}	is the geometrical volume of the pipe section in $[m^3]$,

[9] According to data from Battelle [14], EPA [24, pp. 3-70] and GRDF/ENGIE, the contribution of operational emissions to the total emissions of the gas distribution grid is < 2 %.

p_{abs}	is the absolute pressure in the pipeline in $[bar]$; if emission reduction measures are applied in the form of a pressure reduction, the pressure which is available before the maintenance operation should be applied in the calculation,
p_n	is the standard pressure in $[bar]$,
T_n	is the standard temperature[10] in $[K]$,
T_{int}	is the temperature of the gas inside the pipeline in $[K]$,
$Z(p_n, T_n)$	is the compressibility factor of the gas for reference conditions in $[-]$ (in good approximation = 1 for natural gas),
Z_i	is the compressibility factor dependent on the pressure p_{int} and the temperature T_{int} of the gas in $[-]$; the calculation of compressibility factors is described in EN ISO 12213 [18],
d_{int}	is the internal diameter of the pipeline in $[m]$ and
l	is the length of the pipeline section which is discharged in $[m]$.

In some countries, the super compressibility factor F_{pv} is taken into account instead of Z_i. The relation is described by

$$Z_i = \frac{1}{F_{pv}^2} \tag{3.34}$$

The relation of the compressibility factors can also be expressed by the compressibility number K.

$$K = \frac{Z_i}{Z_n} \tag{3.35}$$

An approximation equation for K is given in [16, p. 42] and is valid for natural gas with a temperature of approx. 12 °C and absolute pressure below 70 bar.

$$K \approx 1 - \frac{p_{int}}{450\ bar} \tag{3.36}$$

The purging emissions should be estimated with equation (3.37).

$$EF_{purge} = V_{geo} \cdot \frac{p_{abs} \cdot T_n \cdot Z_n}{p_n \cdot T_{int} \cdot Z_i} \cdot f_{purge} \tag{3.37}$$

Where

p_{abs}	is the absolute pressure during the purging in $[bar]$,
f_{purge}	is the purge factor (ref. section 2.1.12, p. 16) in $[-]$.

Annex 6 summarizes the relevant data which should be recorded by an operator to enable the emission estimation.

[10] Different temperatures are used in different countries and industries (typically 273.15 K, 288.15 K, and 293.15 K). EN ISO 13443:2005 suggests 288.15 K as standard reference condition for natural gas [32].

3.2.7.2 Simplified Approach

If no detailed information is available on single operations which cause emissions, a simplified approach for estimating the emissions of all operations can be used. This approach is based on an estimated share of all pipelines which are renewed, commissioned or decommissioned. A distinction between venting and purging emissions should be made also in the simplified approach since the operating pressures for venting or purging activities can differ significantly.

$$E_{CH4} = E_{vent} \cdot x_{CH4} + E_{purge} \cdot x_{CH4} \tag{3.38}$$

$$E_{vent} = V_{geo} \cdot \frac{\overline{p_{int}} \cdot T_n}{p_n \cdot T_{int} \cdot K} \tag{3.39}$$

$$V_{geo} = \frac{\pi}{4} \cdot \overline{d_{int}^2} \cdot (x_{op} \cdot l_{total}) \tag{3.40}$$

Where

$\overline{p_{int}}$ is a weighted average operating pressure for all pipelines existing in an operators or countries grid in $[bar]$,

$\overline{d_{int}}$ is an average diameter of all pipelines of a distribution grid in $[m]$,

K is the compressibility number of natural gas in $[-]$,

x_{op} is the share of pipelines which are renewed, commissioned or commissioned per year in $[-]$ and

l_{total} is the total length of the pipelines in the distribution grid in $[m]$.

The Battelle study from 1989 suggests a fraction of 5 % of all pipelines in a low-pressure grid, which is renewed or commissioned within a year [13, pp. 4.4-37]. A data request made within this project among gas grid operators from several countries showed, that the part of pipelines which are renewed or commissioned, differs in several years and amounts to 1-2 % [13] for all pressure levels. Thus, 5 % can be seen as a conservative estimate for all pipelines.

The purging emissions can be calculated by equation (3.41)

$$E_{purge} = V_{geo} \cdot \frac{p_{int} \cdot T_n}{p_n \cdot T_{int} \cdot K} \cdot f_{purge} \tag{3.41}$$

Where p_{int} is an average operating pressure for all purge operations (including atmospheric pressure) in $[bar]$. V_{geo} should be calculated by equation (3.40) and K by equation (3.36).

3.3 Emission Estimation of Service Lines

In general, service lines show the same emission types already mentioned for main lines. For this reason, the same equations suggested in chapter 3.2 should be used for the emission estimation. In the following sections, some aspects, that need to be considered exclusively for service lines, are described.

3.3.1 Underground Leaks Detected by Survey

Refer to section 3.2.1, p. 26.

As long as no specific emission rates for service lines are available, the same values as for main lines can be used. However, this is a conservative approach, since it can be presumed that the emission rates of service lines are smaller [8, p. 5163]. Moreover, construction issues like sleeves around the service lines could have an influence on the emission rate.

3.3.2 Above Ground Leaks Detected by Survey

Refer to section 3.2.2, p. 31.

3.3.3 Permeation

To estimate the emissions due to permeation with equation (3.16), given in section 3.2.3, p. 32, the length of the service lines needs to be known. An average length can be assumed but there seem to be country-specific differences (Table 9).

Table 9: Assumptions for Length of Service Lines

Average Length of Service lines [m]	Valid for	Source
2	New service lines in urban areas	Expert Assumption from Synergrid for the Belgian distribution grid
3	Operating pressure 0.3 bar, material PE	Expert Assumption from GRDF/ENGIE for the French distribution grid
4	Operating pressure 0.02 bar, material PE	Expert Assumption from GRDF/ENGIE for the French distribution grid
5	Old service lines in urban areas	Expert Assumption from Synergrid for the Belgian distribution grid
6	Operating pressure 3.8 bar, material PE	Expert Assumption from GRDF/ENGIE for the French distribution grid
10	Service lines in rural areas	Expert Assumption from Synergrid for the Belgian distribution grid
15	Average for all service lines	DVGW[11] (Germany)

Moreover, the material distribution needs to be known for accurately estimating permeation emissions. This data is not available in every country and service lines can consist of multiple sections of different materials but only one of the sections is registered.

For a conservative consideration, the total length of the service lines can be taken into account to calculate permeation emissions.

Another approach is to take the material distribution of the main lines into account and to make assumptions for the connections. For instance, GRDF/ENGIE assumes:

- 100 % of the connecting service lines to PE main lines are made of PE,
- 40 % of the connecting service lines to steel main lines are made of PE,
- 30 % of the connecting service lines to other main lines are made of PE.

The assumptions can be country-specific or operator-specific.

[11] DVGW collects data for the number as well as for the length of service lines in Germany from the German DSO in its Gas and Water Statistics. The 15 m was calculated by the author as an average number from the DVGW data from 2011 until 2014 [42].

3.3.4 Incidents reported after Third-Party Damage

Refer to section 3.2.5, p. 34.

3.3.5 Other Incidents reported by Third-Parties or Own Staff of DSO

Refer to section 3.2.6, p. 37

3.3.5.1 Gas Smell Inside Houses

Methane is an odourless gas and is odorized for safety reasons. Country legislations strictly regulate the odorization of natural gas so that it is smelled well before the lower explosion limit is reached.

Currently, there is no information available how much gas escapes, when a customer reports a gas smell inside the house. The only information known by country statistics is the number of calls from the customers. Two approaches could deliver results:

1.) Assumption of an emission rate and a duration of gas escape
2.) Estimation based on the odorization regulations and the room volumes.

The first approach was discarded since there are no measurements available for emission rates of incidents reported after gas smell and the duration of gas escape is difficult to determine, since there is only information about the time when the gas was smelled but not about the beginning of the leakage (which could be long before the call if the emission rate is so low that it takes a while until a certain concentration is reached).

With the odorization requirements, it is possible to estimate emissions, taking also into account the volume of a house installation room. However, many influencing factors exist, making it nearly impossible to give an accurate estimation. Those include:

- House installation rooms have different volumes
- Customers might not go to the house installation room every day, so the gas molecules need to be present in another room (e.g. the first floor when the leak is at the cellar)
- A customer could be on holiday
- There could be ventilation or open windows
- Customers don´t call the DSO immediately after they smelled gas for the first time, but wait to see if the smell is noticeable over a period of time
- Some people close the main gas valve as soon as they smell gas, so the leakage is stopped almost immediately after the smell. Others just leave the house and wait for the DSO.

Taking into account all of the influencing factors with conservative assumptions, an estimation was made how much methane emissions are related with gas smells inside houses. The result was negligible compared to the total emissions of the distribution grid. Because of the minor share of the emissions and because of the high uncertainties due to the influencing factors mentioned above, this category is not considered further.

3.3.5.2 Gas Smell Outside Houses (Emission Source Underground)

Refer to section 3.2.6.1, p. 38.

3.3.5.3 Gas Smell Outside Houses (Emission Source Above Ground)

Refer to section 3.2.6.2 p. 39.

In some countries a large fraction of the service lines is installed above ground, which often leads to calls because of gas smell.

There are no measurement data available about the related emission rates. The emission rate can, however, be calculated with the equations described in section 3.2.5.1, p. 34. In case of a leaking connection, it is possible to assume an annular gap for the damage size. With a gap size of 0.1 mm (suggested by GDRF/ENGIE), an nominal diameter of the service lines of DN25, and an overpressure of 0.05 bar, an emission rate of 0.1 m³/h can be calculated (Annex 7, Figure A.8). This value should be verified by measurements on leaking house connections.

3.3.6 Operational Emissions

Refer to section 3.2.3, p. 32.

3.4 Emission Estimation of Facilities

The database for facility emissions is rather small at the moment. A study about new measurements on facilities in the Netherlands might be published soon, but at the reporting time is was not finished. Moreover, a project about facility emissions in Denmark is running, but the results are neither available, yet.

In general, the same emission categories occur on facilities as on pipelines (intrinsic, operational, incident). The three categories can be combined in one EF or can be estimated separately. The contribution of facility emissions to the total emissions is low (in the surveyed studies less than 7 % [13, p. 17], [14, pp. 5-3]), however, the relations might change in the future with a rising share of plastic pipelines, which cause much lower emissions than materials like cast iron or steel.

3.4.1 Intrinsic Emissions of Facilities

Reasons for intrinsic emissions on facilities are leaking connections/ joints and seals, and also low diffusion rates through the membranes of the regulators. Moreover, the safety relief valves release some gas during operation and there can be pneumatic valves which bleed to the atmosphere continuously or intermittently. Furthermore, there can be measurement equipment (e.g. process gas chromatographs) which measure continuously the gas quality and emit the measured sample to the atmosphere. [14, pp. 4.4-14]

Intrinsic emissions of facilities can be estimated with emission factors, that are determined by equation (3.42)

$$EF_{intr} = q_v \cdot t \qquad (3.42)$$

Where

EF_{intr} is the emission factor for intrinsic emissions of one facility per year in $[\frac{m^3}{facility \cdot yr}]$,

q_v is the emission rate per facility in $[\frac{m^3}{facility \cdot h}]$,

t is the duration of gas escape in $[\frac{h}{yr}]$.

To determine the intrinsic methane emissions, the EF needs to be multiplied by the number of facilities (equation (3.43))

$$E_{CH4} = EF_{intr} \cdot x_{CH4} \cdot n \tag{3.43}$$

Where

x_{CH4} is the fraction of methane in natural gas in $[-]$,

n is the number of facilities $[facilities]$.

Table 10 gives an overview of available EF for different facilities.

Table 10: Emission Factors for Facilities in the Natural Gas Distribution Grid

Element	Pressure Level	Value	Unit	Source
Pressure Regulating and Meter Station	LP and MP	225	$\frac{m^3{}_{NG}}{station \cdot yr}$	[13, p. 9]
	HP	924	$\frac{m^3{}_{NG}}{station \cdot yr}$	[13, p. 9]
Above ground storage	all	0.25	$\frac{\%}{m^3 gas\ stored \cdot yr}$	[13, p. 9]
Above ground storage	all[12]	5	$\frac{kg_{CH4}}{1{,}000\ m^3 gas\ stored \cdot yr}$	[19, p. 283]
Natural Gas Filling Stations (CNG)	all	0.022	$wt.\%$	[20]
House installations (Meters, House Pressure Governor, etc.)	all	6.4	$\frac{m^3{}_{NG}}{house\ connection \cdot yr}$	[13, p. 9]

For biogas injection plants, LNG satellite stations, and LNG liquefaction plants no measurement data is available. New measurements are suggested to evaluate the emissions of such plants.

Currently, a classification of pressure regulating (and meter) stations according to the inlet pressure is existing. For this reason, emission factors are available for different pressure levels. It might be possible that facilities with a low inlet pressure produce higher emissions if the flow rate is high. In contrast, facilities with higher inlet pressure might have lower emissions if the flow rate is low. However, no study or project is known by now which investigated if there is a correlation, so this should be subject of further research. A possible classification of pressure regulating (and meter) stations, taking into account the product of inlet pressure and flow rate, is given in (Table 11). This classification could be used for the planning of future measurement programmes.

[12] Related to available volume of working gas, normalized to 273 K and 1013 hPa.

Table 11: Example for a Possible Classification of Pressure Regulating (and Meter) Stations

Criteria	Small	Medium	Large	Large with Preheating	City Gate	City Gate with Analyser
Emission potentials	Valves and fittings	Valves and fittings	Valves and fittings	Valves and fittings, Blow down and pressure relief valve in heating gas line	Valves and fittings, Blow down and pressure relief valve in heating gas line	Valves and fittings, Blow down and pressure relief valve in heating gas line, PGC
P*V	1,000	20,000	250,000	250,000	4,000,000	4,000,000
Further definitions	No heat gas line 1 active gas regulation line	No heat gas line 1 active gas regulation line	No heat gas line ≥ 2 active gas regulation lines	≥1 heat gas lines ≥ 2 active gas regulation lines	≥1 heat gas line ≥ 2 active gas regulation lines	≥1 heat gas line ≥ 2 active gas regulation lines ≥ 1 PGC Dew point measuring device?

Special emission rates should also be determined for vaulted facilities. The study of Lamb, et al. figured out that they showed much lower emissions than above ground facilities (ref. [21, p. 5164]).

3.4.2 Incident Emissions

Incident emissions on facilities occur in case of an emergency shut-off which leads to the venting of the total gas inside the facility. The amount of emissions can be calculated in the same way as the operational emissions (section 3.2.7, p. 40). Only the operating pressure could be different, since there is no time for pressure reduction measures.

If an incident is detected on a facility (e.g. a leaking connection), an emission rate and the duration of the gas escape should be determined by following the procedure described in section 3.2.5.1, p. 34 and p. 37.

Generally, the DSO knows exactly the number of incidents per year and can apply it for estimating the emissions. If the exact number is not known, an operator-specific or country-specific average can be assumed.

3.4.3 Operational Emissions

To ensure well-functioning, gas facilities are maintained regularly. This process involves the venting of the gas included in the facility for safety reasons to prevent the risk of explosions.

Moreover, a functional testing of the safety installations (e.g. safety relief valve) is conducted regularly in many countries.

To determine the operational emissions of facilities, the same equations as for main lines can be applied (ref. 3.2.7.1, p. 40). Therein, the geometric volume is determined by taking into account the piping within the facility.

Table 12 shows the venting emissions of five typical gas regulating stations in Germany (without pressure reduction before the venting) in different nominal diameters and pressure levels. Table 13 gives purging values. The respective calculations are given in detail in Annex 7, Figure A.9.

Table 12: Exemplary Values for Venting Emissions of Pressure Regulating (and Meter) Stations

Criterion	PRS Small (gas cabinet)	PRS Medium	PRS Medium	PR(M)S Large	PR(M)S Large with Preheating
Inlet pressure	2.5 bar	4.0 bar	4.0 bar	16.0 bar	16.0 bar
Outlet pressure	0.5 bar	1.0 bar	1.0 bar	1.0 bar	1.0 bar
Nominal Diameter	DN25/DN50	DN50/DN100	DN80/DN150	DN80/DN150	DN100/ DN300
EF for Venting Emissions (normalized) [m³NG/event]	0.004	0.15	0.33	0.64	3.07

Source: Own Calculation DBI Gas- und Umwelttechnik for selected German Pressure Regulating (and Meter) Stations

Table 13: Exemplary Values for Purging Emissions of Pressure Regulating (and Meter) Stations

Criterion	PRS Small (gas cabinet)	PRS Medium	PRS Large	PR(M)S Large	PR(M)S Large with Preheating
Inlet pressure	≤ 2.5 bar	≤ 4.0 bar	≤ 4.0 bar	≤ 16.0 bar	≤ 16.0 bar
Nominal Diameter	DN25/DN50	DN50/DN100	DN80/DN150	DN80/DN150	DN100/ DN300
EF for Purging Emissions (normalized) [m³NG/event]	0.003	0.1	0.2	0.2	1.3
A purge factor of 1.5 and an absolute purging pressure of 1.1 bar was used for all calculations.					

Source: Own Calculation DBI Gas- und Umwelttechnik for selected German Pressure Regulating (and Meter) Stations

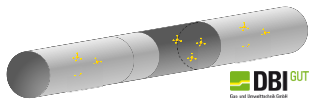
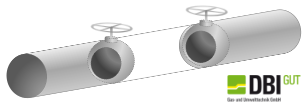
To determine the operational emissions of facilities, the venting and purging emission per activity should be multiplied by the number of activities.

Generally, the DSO knows exactly the number of maintenance operations and functional testings per year and can apply it for estimating the emissions. If the exact number is not known, an operator-specific or country-specific average should be assumed which is oriented on country-regulations. For instance, in France, all meters are maintained every 20 years. In Germany, the functional testing as well as the maintenance of pressure regulating (and meter) stations depends on the maximum volume flow and the inlet pressure (between two times a year and once in 12 years or as required, ref. [22, p. 26])

3.5 Summarising Overview of the Emission Estimation for the Gas Distribution Grid

In the following a condensed overview of all equations necessary for the emission estimation of main lines, service lines and facilities is given.

Table 14: Basic Equations for the Emission Estimation

Emission Type		
Intrinsic and Incident Emissions 	**Permeation** 	**Operational Emissions** 
Basic Equation		
$E_{CH4} = q_v \cdot t \cdot n \cdot x_{CH4}$	$E_{CH4} = P_{CH4} \cdot \pi \cdot SDR \cdot p_i \cdot l \cdot t$	$E_{CH4} = EF_{vent} \cdot n \cdot x_{CH4} + EF_{purge} \cdot n \cdot x_{CH4}$
Description		
q_v is the emission rate, options for determining are given in Table 15; t is the duration of gas escape, options for determining are given in Table 16; n is the number of detected leaks/existing facilities, reported incidents or operational measures, done by the operator and can be expressed as absolute number or per km pipeline and per year; x_{CH4} is the methane content	P_{CH4} is the permeation coefficient; SDR, p_i and l are pipeline data (standard dimension ratio, partial pressure and length) and t is the duration of gas escape, usually 365 days.	EF_{vent} and EF_{purge} are emission factors for venting and purging operations, which are determined with pipeline/facility data (e.g. diameter, operating pressure); n is the number of operations; x_{CH4} is the methane content
Reference to Report		
See tables below	Section 3.2.4, p. 32 and 3.3.3, p. 43).	Section 3.2.7, p. 40 and section 3.4.3, p. 49)

Source: Own Illustration DBI Gas- und Umwelttechnik

Table 15: Options for Determining Emission Rates q_v of Intrinsic and Incident Emissions

Nr.	Option	Application
1	**Direct measurement** of the emission rate (e.g. by suction method)	Underground leaks detected by survey[1,2], emissions of gate valves on pipelines[3], intrinsic emissions of facilities[4]
2	**Determination of soil coefficients and calculation** of the emission rate from leak size and pipeline pressure: $q_v\,(T,p) = \frac{6\pi\mu r_{eq}^2}{\rho(T,p)k\beta} \cdot \left[-1 + \sqrt{1 + \frac{k^2}{\mu^2} \cdot \frac{2\beta}{3r_{eq}R_i T_{int}} \cdot (p_{abs}^2 - p_{atm}^2)}\right]$	Underground leaks detected by survey[1,2], other incidents[5,6]
3	**Calculation of the emission rate** from leak size and pipeline pressure (<u>subsonic</u> flow[7]): $\frac{p_{atm}}{p_{abs}} \geq \left(\frac{p_{atm}}{p_{abs}}\right)_{crit} \rightarrow subsonic\ flow \rightarrow$ $For\ natural\ gas\ a\ critical\ pressure\ ratio\ of\ about\ 0.54\ is\ valid.$ $q_V(T,p) = 3600 \cdot \frac{C_D}{\rho_{(T,p)}} \cdot \frac{\pi}{4} d_h^2 \cdot \left(\frac{p_a}{p_{int}}\right)^{\frac{1}{\kappa}} \cdot \sqrt{2 \cdot \frac{\kappa}{\kappa-1} \cdot p_{abs} \cdot \rho_{int} \cdot \left(1 - \left(\frac{p_{atm}}{p_{abs}}\right)^{\frac{\kappa-1}{\kappa}}\right)}$	Above ground leaks detected by survey[8,9], incidents reported after third-party damage[10,11] and other incidents[5,6], incident emissions of facilities[12]
4	**Calculation of the emission rate** from leak size and pipeline pressure (<u>supersonic</u> flow[9]): $\frac{p_{atm}}{p_{abs}} < \left(\frac{p_{atm}}{p_{abs}}\right)_{crit} \rightarrow supersonic\ flow$ $q_V(T,p) = 3600 \cdot \frac{C_D}{\rho(T,p)} \cdot \frac{\pi}{4} d_h^2 \cdot \left(\frac{2}{\kappa+1}\right)^{\frac{1}{\kappa-1}} \cdot \sqrt{\frac{2\kappa}{\kappa+1} \cdot p_{abs} \cdot \rho_{int}}$	Above ground leaks detected by survey[3,4], incidents reported after third-party damage[10,11] and other incidents[5,6], incident emissions of facilities[12]
	References in the report: (1) Section 3.2.1, p. 26, (2) Section 3.3.1, p. 42, (3) Section 3.2.3, p. 32, (4) Section 3.4.1, p. 46 , (5) Section 3.2.6, p. 37, (6) Section 3.3.5, p. 45, (7) Section 3.2.5.1, p. 34, (8) Section 3.2.2.,p. 31, (9) Section 3.3.2, p. 43, (10) Section 3.2.5, p. 34, (11),Section 3.3.4, p. 45 (12) Section 3.4.2, p. 48	

Table 16: Options for Determining the Duration of Gas Escape t of Intrinsic and Incident Emissions

Nr.	Option	Application
1	**Duration is exactly known**, since the operator knows when the gas escape started	Incidents reported after third-party damage[1,2] and other incidents[3,4]
2	**Continuous** leakage (=8,760 h/yr)	Emissions of gate valves on pipelines[5], intrinsic emissions of facilities[6]
3	A maximum duration of **48 h is assumed**	Emissions after gas smell in urban areas[3,4]
4	**Recent events** (e.g. ground movements or recent works near the incident) can be taken into account: $t = \frac{date\ of\ the\ detection - date\ of\ recent\ events}{2}$	Other incidents (e.g. gas smell in rural areas)[3,4]
5	**The last survey/monitoring** can be considered: $t = \frac{date\ of\ the\ detection - date\ of\ the\ last\ survey}{2}$	Other incidents[3,4]
6	Duration is determined with the **monitoring period and with the permitted repair time**: $t = \frac{t_{mon} + t_{rep}}{2}$	Leaks detected by survey[7,8,9,10]
7	Duration is not exactly known but can be estimated by **verified expert assumptions** (depending on the size of the leak/incident, pipeline pressure, location, etc.)	Leaks detected by survey and all incidents[1,2,3,4,7,8,9,10]

References in the report:

(1) Section 3.2.5, p. 34, (2),Section 3.3.4, p. 45, (3) Section 3.2.6, p. 37, (4) Section 3.3.5, p. 45, (5) Section 3.2.3, p. 32, (6) Section 3.4.1, p. 46 ,(7) Section 3.2.1, p. 26, (8) Section 3.3.1, p. 42, (9) Section 3.2.2.,p. 31, (10) Section 3.3.2, p. 43

3.6 Summary of Identified Need for Research

The project work identified need for further research for several emission types or input parameters of the equations.

1.) Measurement of emission rates of leaks detected by survey

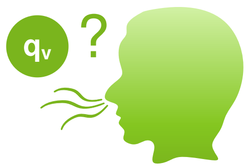
At the moment there is no measurement data available providing full information on all identified influencing parameters. Preliminary investigations should be made either in field or in laboratory measurements which can identify the attributes that have to be taken into account for the sampling in large measurement programmes to avoid biased sampling and to get representative EF (Section 3.2.1.1.1, p.27). Possible influencing factors are identified in Annex 5, p. 70 and should be investigated in further research.

2.) Duration of gas escape for leaks detected by survey

The lifetime of leaks detected by survey ranges between the beginning and the end of a monitoring period plus the permitted repair time and is therefore currently assumed with $t = \frac{t_{mon}+t_{rep}}{2}$. Experts assume that leaks do not exist longer than one year without being detected as an incident. At the reporting time, no scientific investigation is known, which states that leaks grow within their lifetime. However, this is considered possible. There is need for research to evaluate this phenomenon and its relation for certain pipeline materials or causes of leaks (ref. Section 3.2.1.2, p. 29).

3.) Emission rate of incidents reported after gas smell outside houses

No measurement data is available for emissions rates of incidents which were recognized by a gas smell outside. To estimate the contribution of emissions in case of gas smells, assumptions are made based on the emission rates of leaks detected by survey (3.2.6.1.1, p. 38). These assumptions have been developed within the experts of the project group but there is further need for research, since many influencing factors exist which cannot be rewarded at the moment.

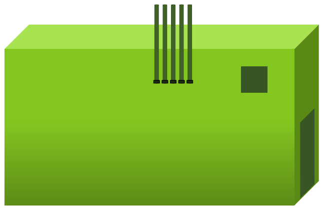


4.) Duration of gas escape for incidents reported after gas smell outside houses

In most areas, in particular <u>in cities</u>, a daily detection by passing people can be presumed. The gas flow is stopped (at least by provisional measures) as soon as possible people call the DSO. For this reason, a t of 2 days (margin factor 2) is assumed which should be validated by further research (ref. section 3.2.6.1.2, p. 39). Moreover, it should be evaluated, if a distinction is possible between above ground and underground emission sources. Currently, the same value is taken for both.

5.) **Intrinsic emissions of PR(M)S and necessary classification**

Currently, a classification of pressure regulating (and meter) stations according to the inlet pressure is existing. For this reason, emission factors are available for different pressure levels. It might be possible that facilities with a low inlet pressure produce higher emissions if the flow rate is high. In contrast, facilities with higher inlet pressure might have lower emissions if the flow rate is low. However, no study or project in known by now, which investigated, if there is a correlation, so this should be subject of further research (ref. section 3.4.1, p. 46).



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Annex 1: Classification of Emissions

Many different names exist for the same categories of emissions occurring from the different sources. Table A.1 gives an overview.

Table A.1: Comparison of Categories of Emissions of MEEM and other Data Sources

<table>
<tr><th>Cat.</th><th>MEEM</th><th>Marcogaz</th><th>Battelle</th><th>EPA</th></tr>
<tr><td rowspan="2">A</td><td rowspan="2">intrinsic emissions (permeation, leaks detected by survey, continous leakage of facilities)</td><td>fugitive emissions</td><td rowspan="2">permanent gas loss[13]</td><td rowspan="2">leakages</td></tr>
<tr><td>pneumatic emissions[14]</td></tr>
<tr><td rowspan="2">B</td><td rowspan="2">operational emissions
(venting and purging of pipelines and facilities)</td><td rowspan="2">maintenance vents</td><td rowspan="2">gas loss due to commissioning or renewal[15]</td><td>routine maintenance
(pipeline blowdown)</td></tr>
<tr><td>routine maintenance
(pressure relief valves)</td></tr>
<tr><td rowspan="2">C</td><td rowspan="2">incident emissions (incidents reported by third parties after third-party-damage, gas smell, etc.)</td><td rowspan="2">incident vents</td><td>gas loss due to third-party damage[16]</td><td rowspan="2">upsets (mishaps)</td></tr>
<tr><td>gas loss due to ruptures or landslide[17]</td></tr>
</table>

Source: Own illustration DBI Gas- und Umwelttechnik based on [14], [23], [24]

13 This is a translation, the original term is “ständige Gasverluste”.
14 Caused by valves with pneumatic operation.
15 This is a translation, the original term is “Gasverluste bei Neuverlegung oder Erneuerung“.
16 This is a translation, the original term is “Gasverluste infolge von Fremdschäden”
17 This is a translation, the original term is “Gasverluste infolge von Rohrbrüchen bzw. Bodenbewegungen”

Annex 2: Permeation Coefficients

The various permeation coefficients given in the literature are difficult to compare because of their different units (Table A.2). However, all coefficients can be converted to a uniform unit and can be applied with the same equation for estimating permeation emissions (ref. equation (3.16)).

Table A.2: Permeation Coefficients from Different Studies

Permeation Coefficient (original)		**Valid for**	**Source**	**Permeation Coefficient** (converted)	
Value	**Unit**			**Value**	**Unit**
0.019	PE100, 20°C	$cm^3_{CH4}/(m \cdot bar \cdot d)$	[5, p. 60]	1.90E-08	$m^3_{CH4}/m \cdot bar \cdot d$
0.056	HDPE, 20°C	$cm^3_{CH4}/(m \cdot bar \cdot d)$	[25]	5.60E-08	$m^3_{CH4}/m \cdot bar \cdot d$
34.1	PE100, 20°C	$(ml \cdot mm)/(m^2 \cdot bar \cdot d)$	[26, p. 18]	3.41E-08	$m^3_{CH4}/m \cdot bar \cdot d$
1.11E-09	PE80, 8°C	$cm^2_{CH4}/(bar \cdot s)$	[27, p. 6]	9.59E-09	$m^3_{CH4}/m \cdot bar \cdot d$
0.006	PE100, 8°C	$cm^3_{CH4}/(m \cdot bar \cdot d)$	[5, p. 60]	6.00E-09	$m^3_{CH4}/m \cdot bar \cdot d$
0.29	Plastic, 8°C	$m^3_{CH4}/(km \cdot bar \cdot yr)$	[28, pp. 2-16]	2.30E-08	$m^3_{CH4}/m \cdot bar \cdot d$

Annex 3: Permeation – Influence of the Soil Temperature

Summary of a research project of DBI Gas- und Umwelttechnik GmbH Leipzig on behalf of E.ON Metering GmbH Essen (Source: [29], [30])

The currently used permeation coefficients for the examination of permeation from gases through plastic pipes are usually valid for an ambient temperature of 20 °C. The monthly mean temperature of the soil is often lower. Due to the fact, that the quantity of plastic pipes and the future feed-in of hydrogen are increasing in the German distribution grid, the permeation and its reliable examination are of high importance for grid operators.

The project analysed four different modern pipe materials (polymer pipe, multi-layer composite pipe and two polymer pipes with aluminium barrier layer). The samples were filled with three different gas compositions (Table A.3) and this summary focuses on the results for 100 vol-% methane.

Table A.3: Technical Facts about the Project

Technical facts about the project	
Pipe materials	PE100 RC, HexelOne®, HexelOne® + barrier layer of aluminium, SLA Barrier® Pipe
Pipe dimension	DN110 and SDR11
Test gas composition	100 vol-% CH_4, 70 vol-% CH_4, and 30 vol-% H_2, 100 vol-% H_2
Test temperatures	20 °C and 8 °C
Duration	1 year
Pressure	10 bar (11 bar absolute) and 16 bar (17 bar absolute)

Source: [29] (translated)

As the measurement results show, the amount of permeating gas depends very much on the temperature. For practical applications, the permeating volume per year is related to real soil temperatures. Since the selected examination temperatures (8 °C and 20 °C) do not reflect the real soil temperatures in Germany over one year, an average soil temperature for Germany of the last 120 years in one meter depth was taken into account. From the determined specific permeation coefficients for 8 °C and 20 °C a compensation function was generated based on experience from investigations (Table A.4). This compensation function represents an assumption but was confirmed by a control measurement (at 14 °C for PE100 RC, 100 vol-% CH_4).

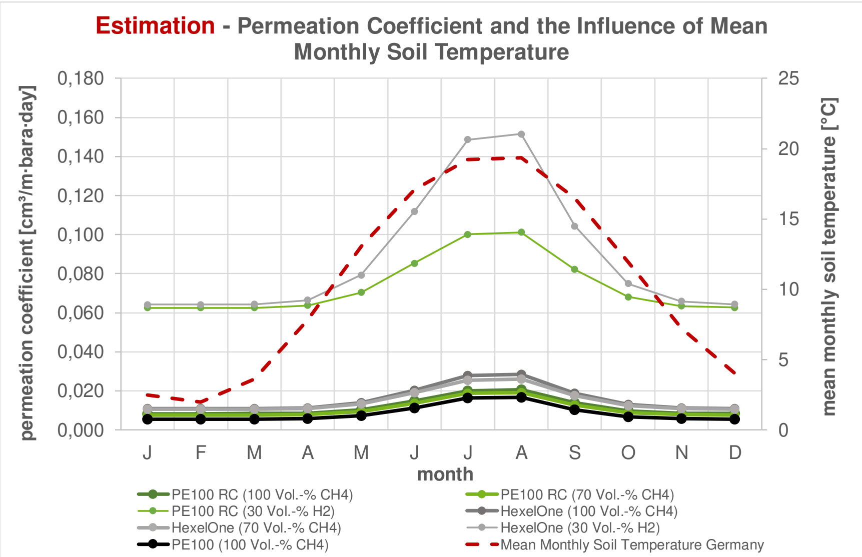
Table A.4: Compensation Function for the Test Materials

Material (test gas)	Compensation function[1,2]
HexelOne (100 vol.% CH_4)	$f(x) = 0{,}010866 \cdot e^{0{,}00003x^{3{,}549}}$
PE100 RC (100 vol-% CH_4)	$f(x) = 0{,}008307 \cdot e^{0{,}00002x^{3{,}549}}$
PE100 (100 vol-% CH_4)	$f(x) = 0{,}005550 \cdot e^{0{,}00003x^{3{,}549}}$
Explanation [1] „x“ refers to the temperature in [°C] [2] The respective compensation function was determined based on expert experience with the permeation rates for 8 °C and 20 °C and confirmed with a control measurement at 14 °C. It is only valid for the tested specimens but has a similar structure for other specimens/materials.	

Source: [30, p. 21] (translated)

With the compensation function from Table A.4, temperature-specific permeation coefficients could be determined. The temperature-specific permeation coefficients related to the monthly average soil temperature for Germany are shown in Figure A.1 and Table A.5. Table A.7 includes two examples for the application of the compensation function.

Figure A.1: Permeation Coefficient and Influence of Mean Monthly Soil Temperature



Source: [29] (translated)

Table A.5: Permeation Coefficients for different Temperatures

Gas Composition	Temperature	Specific Permeation Coefficient $[\frac{cm^3}{m \cdot bar \cdot d}]$
100 vol-% CH_4	20 °C	0.019 – 0.032*
100 vol-% CH_4	8 °C	0.006 – 0.011*
* Span results from the different materials taken into account		

Source: [29] (translated)

It is possible, to determine a yearly average soil temperature and to calculate the permeation coefficient for this temperature and the resulting methane emissions. However, this does not reward the exponential function of the permeation coefficient, which is especially important for higher temperatures and leads to a significant underestimation of emissions (about 25 %). For this reason, monthly average temperatures should be considered.

Conclusions

The investigations of the different pipe materials under different conditions gave specific permeation rates that lead to specific permeation coefficients. Compared to previous permeation investigations (usually carried out at about 20 °C) additional measurements were made at 8 °C and significant influence of the temperature on the permeation coefficient could be observed. However, in addition to the temperature, the pipe structure and the pipe material with the associated specific density and the crystallinity influence the permeation rates. It is, therefore, not necessarily possible to generalize the results of the study. This accounts in particular for the multilayer composite pipes.

Annex 4: Determination of the Emission Rate after Third-Party Damages

Different equations for calculating emission rates in case of third-party damages are in place. They include the same parameters and lead to the same result. However, due to transformations and the usage of different symbols, the equations look different from each other, which makes it difficult to compare different emission estimates. Table A.6 gives an overview about the allocation of different symbols to the same parameter. The different equations are given in Table A.7 and Table A.8.

Table A.6: Allocation of Different Symbols to the Same Parameter

Parameter	Symbols currently used	MEEM
Ideal gas constant (universal gas constant)	r, R, R_0	R_0
Specific gas constant	r, R	R_i
Atmospheric pressure	P_a, p_a, p_2	p_{atm}
Absolute pressure of gas in the pipeline	P_i , p_i, p_1, P_0, p_{abs}	p_{int}
Overpressure of gas in the pipeline	p_p	-
Temperature of the gas in the pipeline	T_i, T_0	T_{int}
Adiabatic index (heat capacity ratio)[18]	γ , κ	κ
Mass flow rate	$Q_M, \dot{m}$	q_m
Volume flow rate	$Q, \dot{Q}$	q_V
Density of the gas	ρ_i, ρ_1	ρ_{int}
Standard density	$\rho_{St}, \rho_0, \rho_n$	ρ_n
Area of the damage	A, S	A
Internal diameter of the pipeline	D, d_{int}	d_{int}
Distance between the damage and the next pressure regulating station	L	-
Velocity of the gas in the pipeline	v	-
Discharge coefficient[19]	C_D, C_e, C, μ	C_D

18 According to ISO 5167, γ is the ratio of the specific heat capacities and κ is the isentropic index [13]. γ should only be used if κ is not known and for ideal gases γ and κ are the same. However, the meaning can be different, especially in different linguistic areas. This report follows the definition of ISO 5167.

19 For the discharge coefficient, ISO 5167 suggests C [13]. Since this can be misinterpreted as the heat capacity, C_D is used.

The MEEM symbols were chosen in accordance with ISO 5167: Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full - Part 1: General principles and requirements [1]).

Table A.7. Equations for Incident Emissions after Third-Party Damages (subsonic flow)

Equation	Note
$\dot{m} = \mu \cdot A \cdot \sqrt{\frac{\kappa}{\kappa-1} \cdot \left(\frac{p_a}{p_i}^{\frac{2}{\kappa}} - \frac{p_a}{p_i}^{\frac{\kappa+1}{\kappa}} \right)} \cdot \sqrt{2 \cdot p_i \cdot \rho_i}$	
$Q = 3600 \cdot \frac{S}{\rho_0} C_D \cdot P_i \cdot \left(\frac{P_a}{P_i}\right)^{\frac{1}{\gamma}} \cdot \sqrt{2 \cdot \frac{\gamma}{\gamma - 1} \cdot \frac{1}{r \cdot T_i} \cdot \left(1 - \left(\frac{P_a}{P_i}\right)^{\frac{\gamma-1}{\gamma}} \right)}$	
$Q_M = S \cdot \sqrt{\frac{2\gamma}{\gamma-1} \cdot P_1 \cdot \rho_1} \cdot y$ and $y = \left(\frac{P_2}{P_1}\right)^{\frac{1}{\gamma}} \cdot \sqrt{1 - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}}$	20
$\dot{Q}_{St} = \frac{C_e \cdot \psi \cdot P_0 \cdot A}{\rho_{St}} \cdot \left[\frac{\gamma}{R \cdot T_0} \cdot \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}} \right]^{\frac{1}{2}}$ and $\psi = \left\{ \frac{2}{\gamma-1} \cdot \left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{\gamma-1}} \cdot \left(\frac{P_a}{P_0}\right)^{\frac{2}{\gamma}} \cdot \left[1 - \left(\frac{P_a}{P_0}\right)^{\frac{\gamma-1}{\gamma}} \right] \right\}^{\frac{1}{2}}$	
$Q = C_D \cdot S \cdot v$ and $v = 540 \cdot \sqrt{\frac{p_p}{p_{abs}} \cdot \frac{D}{0.02L+D}}$	
Explanation in Table A.6	

[20] The equation does not include the discharge coefficient, and therefore, shows the most conservative case ($C_D = 1$).

Table A.8: Equations for Incident Emissions after Third-Party Damages (Supersonic Flow)

Equation	Note
$\dot{m} = \mu \cdot A \cdot \left(\frac{2}{\kappa + 1}\right)^{\frac{1}{\kappa - 1}} \cdot \sqrt{\frac{\kappa}{\kappa + 1}} \cdot \sqrt{2 \cdot p_i \cdot \rho_i}$	
$\dot{Q} = 3600 \cdot \frac{S}{\rho} \cdot p_i \cdot C_D \cdot \sqrt{\frac{\gamma}{r \cdot T_i} \cdot \left(\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{\gamma-1}}\right)}$	
$\dot{m} = S \cdot \left(\frac{2}{\gamma + 1}\right)^{\frac{1}{\gamma - 1}} \cdot \sqrt{\frac{2\gamma}{\gamma + 1} \cdot p_1 \cdot \rho_1}$	20
$\dot{Q} = \frac{C_e \cdot \psi \cdot p_0 \cdot A}{\rho_{St}} \cdot \left[\frac{\gamma}{R \cdot T_0} \cdot \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{\gamma-1}}\right]^{\frac{1}{2}}$	
$Q = C_D \cdot S \cdot v$ and	
$Q = 0.67 \cdot p_{abs} \cdot d_{int}^2$	
Explanation in Table A.6	

Annex 5: Planning of a Measurement Programme

The MEEM project showed that data for emission rates (in particular of underground leaks) is lacking in many countries. The values applied are based on a very limited database and are presumably outdated. Consequently, there is a need for getting more and actual data.

The following sections provide considerations for the planning of measurement programmes, necessary for the application of the approach described in section 3.2.1.1.1, p. 27.

Technologies for Measurements on Pipelines

Three measurement principles are considered for direct measurements on underground pipelines:

- Tracer Method
- Suction Method
- High Flow Sampler (HFS)

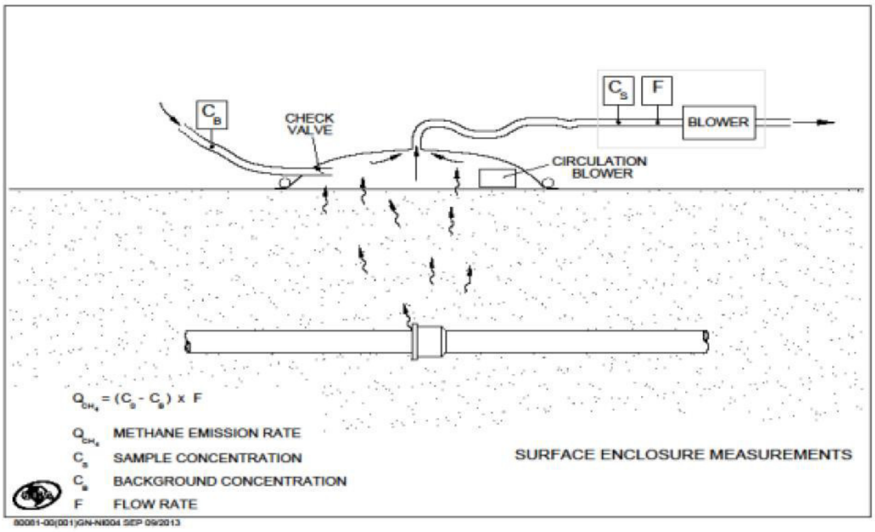
The tracer method is more often applied for measurements on facilities and is therefore described in greater detail in the section about technologies for measurements on facilities. However, it is used in [31, p. S47] for underground pipeline leak measurements as quality assurance.

The suction method and the HFS are both based on a similar principle. The suction method uses probes in the area surrounding a pipe leak, which aspirate the gas from the soil (Figure A.2). After a certain volume has been extracted and discarded, the concentration of CH_4 is measured in the sucked gas flow. This ensures that only emissions that have not accumulated earlier in the soil surrounding the leak are measured. The high flow sampler uses a surface enclosure to capture the leakage (Figure A.3) with a high flow rate. Both measurement principles are suitable for determining emission rates but require a previous detection of the leaks, e.g. by carpet probe.

Figure A.2: Emission Rate Measurement with Suction Method in Amsterdam

Source: Kiwa Technology B.V. [32, p. 10]

Figure A.3: Scheme of High Flow Sampler Measurement on Underground Pipelines



Source: Lamb et al. [31, p. 26]

Technologies for Measurements on Facilities

Five measurement principles are considered for direct measurements on facilities:

- Tracer Method
- Method of EN 15466
- Air Flow Measurements
  - Bagging
  - High Flow Sampler (HFS)
  - Combination of blower with flow measurement and FID measurement

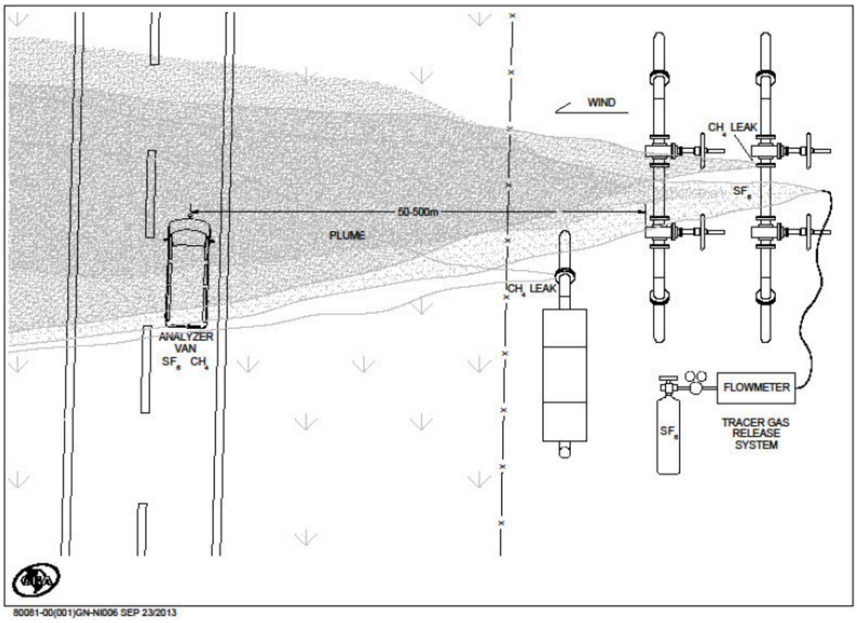
The tracer method is based on the release of an inert gas (e.g. sulphur hexafluoride SF_6) with a controlled emission rate near the leak (Figure A.4). The concentrations of CH_4 and the tracer are both measured downwind and the emission rate of the leak is determined by equation (0.1)

$$q_{m,i} = \frac{(c_i - c_{i,background})}{c_{tracer}} \cdot q_{m,tracer} \qquad (0.1)$$

Where

$q_{m,i}$	is the emission rate (mass flow) of the substance i (e.g. CH_4),
c_i	is the concentration of the substance i (e.g. CH_4),
$c_{i,background}$	is the background concentration of the substance i (e.g. CH_4),
c_{tracer}	is the concentration of the tracer gas and
$q_{m,tracer}$	is the emission rate (mass flow) of the tracer gas (e.g. SF_6).

Figure A.4: Scheme of Tracer Measurement



Source: Lamb et al. [31, p. S29]

The tracer method can measure various sources of emissions on a facility at the same time and can deliver one emission rate for the whole facility but is rather unsuitable for the measurement of single emission sources (e.g. one flange) on a facility. The "method works best when a facility is relatively isolated from other interfering sources and when there are suitable roads or areas upwind and downwind for making cross-plume measurements" [31, p. S33]. The environmental impact of the measurements should be considered, since SF_6 is a potent greenhouse gas.,

All other measurement principles are suitable for the determination of emission rates, as is the tracer method, but require the previous detection of the leak, e.g. by infrared camera or sniffing method.

The method of EN 15466 is based on gas concentration values which are obtained with portable screening instruments. The emission rate is calculated with the help of correlation factors available from the US EPA for the oil industry and the synthetic organic chemical manufacturing industry (SOCMI) [33]. However, in 2010 the GERG project „Inventory of Natural Gas Emissions Measurement Method" concluded that there is no correlation of the values suggested in the standard and of reference values obtained by measurements on open ended pipes, threaded connections, flanges and valves [34, p. 1]. For this reason, the method of EN 15466 seems not well suitable for the natural gas industry. In contrast to that, the measurements with the HFS had a "good correlation with reference values." [34, p. 9].

In general, air flow measurements are considered the most useful direct methods for the natural gas industry. This includes bagging, HFS and also the combination of blower with flow and FID measurement. All of them are based on the measurement of a controlled air flow rate as well as of the concentration of CH_4 in this flow rate (Figure 5 as example for the HFS).

Figure 5: High Flow Sampler Measurement on a Facility

Source: Heath Consultants Incorporated [35]

Leak Selection

There are no specific requirements on how many measurements are needed for obtaining representative emission factors for one operator or a whole country.

Generally, a representative sample of a given population is obtained from random sampling. Since several studies showed that most of the emission sources are small and only a few have large emission rates, a stratified sampling[21] seems accurate. For instance, the study of Lamb, et al. "focused on the top eight emitting categories from the current EPA methane inventory" and selected randomly the leaks from a list of leaks provided by the distribution companies [36, p. 4].

Another large measurement campaign conducted at natural gas production facilities [37, pp. S-67] believed to ensure representative sampling by

- selecting a large number of participant companies,
- selecting a range of geographic areas to sample,
- setting minimum number of sampling targets in each area.

The following parameters (Table A.9) might have an influence on the emission rate. At the moment there is no measurement data available providing full information on all identified parameters. The available data shows possible tendencies, but they could be caused by underlying parameters. For instance, the operating pressure of a pipeline was found to have an influence on the emission rate but it could be, that the pressure influence is not observed, if there is a very dense soil above the leak.

Preliminary investigations should be made either in field or in laboratory measurements which can identify the attributes that have to be taken into account for the sampling in large measurement programmes to avoid biased sampling.

[21] A stratified sampling is "A sampling strategy based on known information about the distribution of emissions designed to yield a data base that minimized any bias and addressed the most significant source categories while accounting for current emission factors (EF) with large uncertainties." [26, p. S108]

Table A.9: Parameters which might have an Influence on Emission Rates

Parameter	Possible Influences on Emission Rate
Diameter of a pipeline/ joint type	An increasing diameter leads to a larger joint perimeter and thus increasing probability of leakages (and accordingly to a higher emission rate). Furthermore, the type of joint sometimes depends on the diameter of the pipeline. Smaller diameter pipes are often threaded and larger often welded. Welded joints are often tighter and presumed to show lower emission rates than threaded joints.
Material	Different pipeline materials show different failure types, which may lead to different damage sizes and accordingly to different emission rates.
Soil type (e.g. sandy or cohesive)	Cohesive soils are presumed to reduce emission rates [14, pp. 4.4-28], [13, p. 6]. However, it is questionable whether the soil can seal a damage or if it just distributes the gas loss, so that the gas escapes at another point. Another aspect are frozen soils. It is not possible to measure emission rates when the soil is frozen. However, this does not necessarily mean that leaks are sealed. Gas could also accumulate and escape as soon as the soil thaws.
Location (above ground or below ground)	In previous measurements, vaulted facilities showed much lower emission rates compared to above ground sites (ref. [21, p. 5164]). One reason for this might be that facilities in vaults don´t have regulators that bleed to the atmosphere.
Pressure level	In case of free flow (no covering soil) the emission rate increases with the pressure. For underground pipelines, this might be different since the covering soil could suppress the pressure influence. For facilities, higher emissions rates were found with higher inlet pressures [21, p. 5164], [13, p. 9] but there could be a cross-correlation with the flow rate.
Size (area) of a damage	In case of free flow (no covering soil) the emission rate increases linear to the damage size. For underground pipelines, this might be different, since the covering soil might seal the damage, leading to a smaller emission rate than expected for the damage size.
Size of a facility	It is expected that emission rates increase with a larger number of regulators, joints, seals, etc.
Weather data	Temperature, wind, and moisture affect the air sampling and soil conditions.

After clarification of the actual influencing parameters, the attributes which are present in an operators or countries grid should be selected for the sampling process. The sampling process should also be influenced by the availability of parameters (stratified sampling). For instance, if the grid consists mainly of low pressure pipelines, more measurements should be made on leaks on low pressure pipelines.

Recording of Data while Doing Measurements

When measurements on pipelines or facilities are conducted, at least the following relevant additional data (Table A.10) should be recorded to enable a subsequent evaluation of the accuracy and uncertainties in the measurement data and to allow comparisons.

Table A.10: Data Recording During Measurements

Criterion	Examples
Material	Steel/ductile iron, PE, (HI) PVC, grey cast iron, other
Year of installation	1981,1990, 2003
Nominal Pressure (Overpressure)	PN1, PN4, PN10
Operating Pressure (Overpressure)	p = 40 mbar, p = 100 mbar, p = 1 bar
Soil classification and moisture	- Minimum classification of cohesive or sandy soil, if possible more detailed description of particle size distribution, e.g. by Sieve analysis - Determination of the soil moisture, e.g. by weighing and heating/ damping of the moisture
Depth	80 cm
Coverage	Bitumen, bricks, cultivated
Diameter of the pipelines	DN50, DN100, DN150
Location	Above ground, underground, vaulted
Date	DD-MM-YY
Geographical location	Address or coordinates
Surroundings	Distances from buildings/structures and underground infrastructures/pipes/cables.

Moreover, the following factors might influence the measurement itself and/ or the emission rate of leaks and should be part of further research projects for measurements:

- Weather parameters:
    - Windspeed during testing
    - Temperature average of the last 72 hours
    - Total amount of rain in the last 72 hours
- Level of ground water
- Soil compaction (tested, for instance, by cone penetration test)

Evaluation of Measurement Results

To create a representative EF for several leaks, the distribution of the leak rates needs to be considered. A huge measurement campaign (230 underground pipeline leaks) in the US in 2013 stated that leak rates show a highly skewed distribution [21, p. 5161], [31, p. S46]. Thus, probabilistic modelling with accounting for the skewness is necessary to get representative emission factors (ref. [31, pp. S38-S44] for further information).

Moreover, correlation factors might be necessary to reward emission reduction measures like dynamic pressure control.

Annex 6: Data Recording for Estimating Operational Emissions

The following data (Table A.11) should be recorded by an operator during maintenance/ commissioning or decommissioning activities to enable the estimation of emissions.

Table A.11: Data Recording during Maintenance/Commissioning or Decommissioning Activities

Parameter	Examples
Nominal diameter of the pipelines	DN50, DN100, DN150
Pressure of the pipeline for venting (overpressure)	$p_{int,vent}$ = 2 bar
Pressure of the pipeline for purging	$p_{int,purge}$ = 0.1 bar
Length of pipeline section, which is vented/purged	l = 100 m
Additionally (if known)	
Temperature of gas inside the pipeline[22]	T_{int} = 283 K
Purge Factor[23]	f_{purge} = 1.5

[22] If temperature is not known, assumptions can be made in accordance to the average soil temperatures of the country.
[23] Explained in detail in section 2.1.12. If the actual purge factor is not known for an operation, country specifications should be taken into account.

Annex 7: Validation of the Method (Sample Calculations)

The following figures show sample calculations made for the report with the excel workbook, which was developed for the MEEM project (ref. file 180622_MEEM DSO_Validation and Sample Calculations.xlsx)

Figure A.5: Sample Calculation for Underground Leaks Detected by Survey

Underground leaks detected by survey			Class 1		Class 2		Class 3	
Parameter	**Symbol**	**Equation**	**Value**	**Unit**	**Value**	**Unit**	**Value**	**Unit**
Emission rate per leak	q_v		0.140	m³/leak·h	0.140	m³/leak·h	0.140	m³/leak·h
Monitoring period	t_{mon}		6	yr	6	yr	6	yr
Maximum repair time	t_{rep}		0.003	yr	0.08	yr	0.50	yr
Duration of gas escape	t	$t = \frac{t_{mon} + t_{rep}}{2}$	3.00	yr	3.04	yr	3.25	yr
			26,292	h	26,640	h	28,470	h
Emission Factor	EF		3,681	m³/leak	3,730	m³/leak	3,986	m³/leak
Number of leaks	n = AD		384	leaks	48	leaks	48	leaks
Methane emission	E_{CH4}	$E_{CH4} = q_v \cdot t \cdot n \cdot x_{CH4}$	1,266,458	m³/yr	160,403	m³/yr	171,421	m³/yr
Total methane emission	$\mathbf{E_{CH4}}$		**1,598,282**	**m³/yr**				

Source: Own Calculation DBI Gas- und Umwelttechnik

Figure A.6: Sample Calculation for Calculation of Emissions Rate for Underground Leaks Detected by Survey

Parameter	Symbol	Equation	Value	Unit
Appearance of the hole			Circular	-
diameter of the hole	d		25	mm
Area of the hole	A		0.0005	m²
Equivalent radius	r_{eq}	$r_{eq} = \sqrt{\frac{A}{4\pi}}$	0.0063	m
Operating Pressure (Overpressure)	p_{int}		0.05	bar
Absolute Pressure of the pipeline	p_{abs}		106,325	Pa
Atmospheric Pressure	p_{atm}		101,325	Pa
Temperature of the Gas in the Pipeline	T_{int}		283.15	K
Specific Gas Constant	Ri	$R_i = \frac{R_0}{M_i}$	475.09	J/kg·K
Density of the gas at reference conditions	ρ		0.78	kg/m³
Ground Environment Coefficient	K	$K_{sol} = \frac{0.3}{\sqrt{k}}$	300,000	1/m
Permeability of the Ground	k		1E-12	m²
Emission rate per leak	q_v	$q_V(T,p) = 3600 \cdot \frac{6\pi\mu r_{eq}^2}{\rho(T,p)k\beta} \cdot \left[-1 + \sqrt{1 + \frac{k^2}{\mu^2} \cdot \frac{2\beta}{3r_{eq}R_i T_{int}} \cdot (p_{int}^2 - p_a^2)}\right]$	**0.132**	**m³/leak·h**

Source: Own Calculation DBI Gas- und Umwelttechnik

Figure A.7: Sample Calculation for Permeation

Parameter	Symbol	Equation	Value	Unit
Standard dimension ratio	SDR		17	-
Temperature			20	°C
Permeation coefficient	PC_{CH4}		1.90E-08	m³/m·bar·d
CH4 content of the system	x_{CH4}		89.6	mol-%
Absolute pressure of the pipeline	p_{abs}		1.063	bar
Partial pressure of CH4	p_{CH4}	$p_{CH4} = x_{CH4} \cdot p_{abs}$	0.953	bar
Length of pipelines	l		24,000	km
Duration of gas escape	t		365	d/yr
Methane emissions	$\mathbf{E_{CH4}}$	$E_{CH4} = P_{CH4} \cdot \pi \cdot SDR \cdot p_{CH4} \cdot l \cdot t$	**8,468**	**m³/yr**

Source: Own Calculation DBI Gas- und Umwelttechnik

Figure A.8: Emissions Rate of a Leaking House Connection

Parameter	Symbol	Equation	Value	Unit
Appearance of the damage	-		Annular Gap	-
Dimensions of damage	a		17.0	mm
	b		16.9	mm
	c		0.1	mm
	d		-	-
Area of the damage	A		0.00001	m²
Perimeter of the damage	P		0.2124	m
Hydraulic diameter of the damage	d_h		0.0002	m
Area based on hydraulic diameter	A		0.00000003	m²
Operating Pressure (Overpressure)	p_{int}		0.05	bar
Absolute Pressure of the pipeline	p_{abs}		106,325	Pa
Atmospheric Pressure	p_{atm}		101,325	Pa
Temperature of the Gas in the Pipeline	T_{int}		283.15	K
Specific Gas Constant	Ri	$R_i = \frac{R_0}{M_i}$	475.09	J/kg·K
Density of the gas at reference conditions	ρ		0.78	kg/m³
Density of the gas at operational conditions	ρ		0.79	kg/m³
Discharge Coefficient	C_D		1.00	-
Adiabatic Index	κ		1.30	-
Critical pressure ratio	$(p_{atm}/p_{abs})_{crit}$		0.55	-
Actual pressure ratio	p_{atm}/p_{abs}		0.953	-
Type of flow			subsonic	-
Emission Rate (subsonic)	q_v	$q_V(T,p) = 3600 \cdot \frac{C_D \cdot A}{\rho_{(T,p)}} \cdot \left(\frac{p_a}{p_{int}}\right)^{\frac{1}{\kappa}} \cdot \sqrt{2 \cdot \frac{\kappa}{\kappa - 1} \cdot p_{int} \cdot \rho_{int} \cdot \left(1 - \left(\frac{p_a}{p_{int}}\right)^{\frac{\kappa-1}{\kappa}}\right)}$	**0.01**	**m³/h**

Source: Own Calculation DBI Gas- und Umwelttechnik

Figure A.9: Operational Emissions of Pressure Regulating (and Meter) Stations

Element	Inlet/Outlet Pressure	Nominal Diameter Piping	Length Piping [mm]	Internal Diameter [mm]	Volume Piping [mm³]	Volume Piping [m³]	Venting Volume [m³]	EF_{vent} [m³/event]	Purging Volume [m³]	EF_{purge} [m³/event]
PRS small (gas cabinet)	PN 2.5	DN 25	668	29.7	462,785	0.0005	0.002	0.004	0.001	0.003
	PN 0.5	DN 50	568	55.7	1,384,040	0.0014	0.002		0.002	
PRS Medium	PN 4	DN 50	4,651	55.7	11,333,045	0.0113	0.055	0.150	0.018	0.097
	PN 1	DN 100	5,437	107.9	49,719,191	0.0497	0.095		0.079	
PRS Medium	PN 4	DN 80	4,651	83.1	25,225,412	0.0252	0.122	0.332	0.040	0.215
	PN 1	DN 150	5,437	160.3	109,735,768	0.1097	0.210		0.174	
PR(M)S Large	PN 16	DN 80	4,651	83.1	25,225,412	0.0252	0.426	0.636	0.040	0.215
	PN 1	DN 150	5,437	160.3	109,735,768	0.1097	0.210		0.174	
PR(M)S Large with Preheating	PN 16	DN 100	6,706	107.9	61,319,177	0.0613	1.035	3.065	0.097	1.270
	PN 4	DN 200	6,121	210.1	212,209,277	0.2122	1.023		0.337	
	PN 1	DN 300	6,844	312.7	525,600,349	0.5256	1.007		0.836	

Additional Parameters for Calculation						
p_{int} in bar	0.1	0.5	1	2.5	4	16
T_{int} in K	283.15	283.15	283.15	283.15	283.15	283.15
T_n in K	273.15	273.15	273.15	273.15	273.15	273.15
p_n in bar	1.01325	1.01325	1.01325	1.01325	1.01325	1.01325
$Z(T_{int}, p_{abs})$	1.00	1.00	1.00	1.00	0.99	0.96
f_{purge}	1.5					
$p_{int,purge}$	0.1					

Source: Own Calculation DBI Gas- und Umwelttechnik for selected German Pressure Regulating (and Meter) Stations