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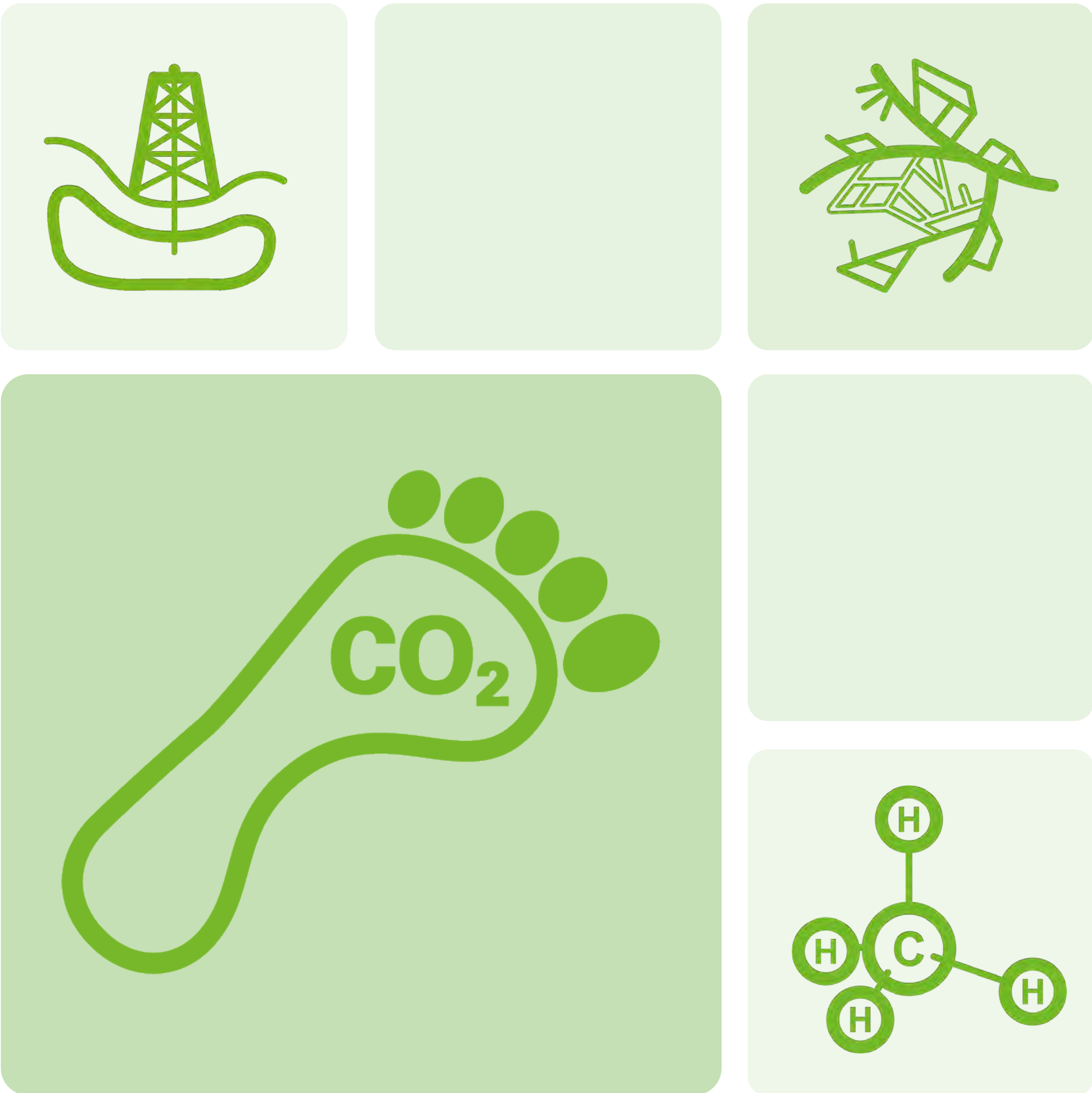
Carbon Footprint of Natural Gas 1.1

Final Report



Imprint

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Carbon Footprint of Natural Gas 1.1

Client

Timm Kehler, Dieter Rütten, Verena Friedl

Zukunft Gas GmbH
Neustädtische Kirchstraße 8
D-10117 Berlin, Germany
office@gas.info
www.gas.info

Project Execution

Project Management

Charlotte Große
charlotte.grosse@dbi-gruppe.de
T +49 341 2457-149

Contact

DBI Gas- und Umwelttechnik GmbH
Karl-Heine-Strasse 109/111
D-04229 Leipzig, Germany

www.dbi-gruppe.de

Authors

DBI Gas- und Umwelttechnik GmbH

Charlotte Große, Melanie Eyßer, Stefanie Lehmann, Marco Behnke

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Executive Summary

The goal of this study was to determine the Carbon Footprint[1] (CF) of natural gas distributed in Central Europe[2] (CE) or Germany (DE) for the years 2015 to 2018. The analysis comprised the steps natural gas production, -processing, -transport and storage outside as well as inside CE (DE) and the natural gas distribution within CE (DE). Usage of gas was not included.

The key findings are:

- The specific methane emissions decreased in all considered production countries[3]. Since proportionally more gas was imported from Russia, which has higher specific methane emissions than Norwegian or Dutch gas, methane emissions in the CE region have remained more or less stable[4].
- At the same time, CO_2 emissions have increased, mainly due to increased energy consumption for gas extraction and gas transport to Central Europe.
- Thus, between 2015 and 2018 the carbon footprint has increased but is still slightly below the value calculated for 2014 in the previous study[5].

The study collected reliable and up-to-date data on the life cycle greenhouse gas emissions released during the different stages of the natural gas value chain in Central Europe and Germany. It was conducted in accordance with DIN EN ISO 14040, 14044 and 14067 regarding data quality, completeness, and consistency. The present study was calculated using the LCA model GaBi from Sphera.

The impacts of all greenhouse gases were assessed using the GWP100 values from the IPCC 4th Assessment Report, which is currently the basis for national greenhouse gas inventories. The following main results were identified:

- The carbon footprint of natural gas distributed in Central Europe was calculated to be **7,722 gCO_2e/GJ (NCV)** or **28 gCO_2e/kWh (NCV)** in 2018.
- The carbon footprint of natural gas distributed in Germany was calculated to be **6,592 gCO_2e/GJ (NCV)** or **24 gCO_2e/kWh (NCV)** in 2018.
- **Methane losses amount to 0.5 % (0.3 %)** related to the gas distributed in CE (DE) in 2018.

The difference of the values for Central Europe and DE mainly results from different natural gas supply structures but also from deviating characteristic values for energy demand and gas losses from transport, storage and distribution.

The increase between 2015 and 2018 is mainly due to the increasing share of natural gas from Russia with its long transport distances, but also because of increasing carbon footprints of the individual producer countries (e.g. Germany and the Netherlands show an increase in energy intensity of their gas production over the years).

Nevertheless, methane emissions have decreased in all natural gas producing countries and production steps. This is probably a result of measures to reduce methane emissions. Norway and Russia, for example, have

1 "Sum of greenhouse gas emissions (…) in a product system, expressed as CO_2 equivalents and based on a life cycle assessment using the single impact category of climate change" [1].

2 The region "Central-Europe" comprises: Austria, Belgium, Czech Republic, Estonia, Germany, Hungary, Latvia, Lithuania, Luxemburg, the Netherlands, Poland, Slovakia [2].

3 The methane emissions of natural gas distributed in CE decreased by the following percentages in 2018 compared to 2015: Germany: 3.5 %, The Netherlands: 1.3 %, Norway: 1.1 %, Russia: 6.3 %.

4 The methane emissions of natural gas distributed in CE decreased by 0.7 % in 2018 compared to 2015.

5 "Previous study" refers to the study "Critical Evaluation of Default Values for the GHG Emissions of the Natural Gas Supply Chain" published in 2016. [3] The following values were calculated for 2014 in the previous study: 7,939 gCO_2e/GJ (NCV) or 29 gCO_2e/kWh (NCV) for natural gas, distributed in Central Europe and 7,050 gCO_2e/GJ (NCV) or 25 gCO_2e/kWh (NCV) for natural gas, distributed in Germany.

tax systems for methane emissions that led to emission reductions. At the same time, however, energy demand has increased, leading to higher CO_2 emissions.

Content

List of Abbreviations

AR	Assessment Report
BGR	Federal Institute for Geosciences and Natural Resources (Germany)
BVEG	German Federal Association of Natural Gas, Petroleum and Geoenergy (Germany)
CCFB	Climate Carbon Feedback
CE	Central Europe: Region considered in this report. Consisting of Austria, Belgium, Czech Republic, Estonia, Germany, Hungary, Latvia, Lithuania, Luxemburg, the Netherlands, Poland, Slovakia
CF	Carbon Footprint: All greenhouse gas emissions of a product expressed as CO2e
CH_4	Methane
CO_2	Carbon Dioxide
CO_2e	CO_2 equivalent
EF	Emission Factor
GER	Germany
GHG	Greenhouse Gas
GPR(M)S	Gas Pressure Regulating (and Metering) Station
GTP	Global Temperature Change Potential
GWP	Global Warming Potential
IEA	International Energy Agency
IfEU	Institute for Energy and Environmental Research
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standard Organisation
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle Impact Assessment
LNG	Liquefied Natural Gas
NGO	Non-governmental organization
NCV	Net Calorific Value
NGVA	Natural & bio Gas Vehicle Association
NIR	National Inventory Report
OECD	Organization for Economic Cooperation and Development
TSO	Transmission System Operator
UBA	Federal Environmental Agency (Germany)
UGS	Underground gas storage
UNFCCC	United Nations Framework Convention on Climate Change
VOC	Volatile Organic Compounds

If not stated different, standard conditions in this report refer to 273.15 K, and 101.325 kPa.

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1 Introduction

In 2019/20 climate change and greenhouse gas emissions (GHG) are more than ever in the focus of the public debate, with topics ranging from "Fridays for Future", the Green Deal of the European Commission (EC) and ultimately the EU Methane Strategy. Recently, the European Parliament requested stricter GHG reduction goals of 60 % until 2030 [4]. For reaching this goal and for observing the reductions, it is important to determine the effects of human activities on the climate.

An appropriate measure to assess these effects is the Carbon Footprint (CF) of products, which is the "Sum of greenhouse gas emissions (…) in a product system, expressed as CO_2 equivalents and based on a life cycle assessment using the single impact category of climate change" [1, p. 16].

The study at hand was commissioned as an update of the study "Critical Evaluation of Default Values for the GHG Emissions of the Natural Gas Supply Chain" published in 2016 [3], hereinafter referred to as "previous study".

The goal of this study is to determine the CF of natural gas from the upstream production phase down to its distribution in the natural gas grid of the countries in Central Europe (CE)[6] for the years 2015 to 2018. The results are intended to be used as a transparent database in the (political) communication with decision makers, non-governmental organizations (NGO) and other interested parties. Furthermore, the results shall facilitate the comparison of the CF that is associated with different fuels.

The study is based on best available industry data in addition to publicly available statistical data and considered the requirements of the life cycle assessment (LCA) as set out by DIN EN ISO 14040 [5], DIN EN ISO 14044 [6], and DIN EN ISO 14067 [1]. It includes the four steps of a life cycle assessment: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation.

Research of best available data was focused on the major supplying countries to CE: the Netherlands, Norway and Russia. Moreover, Germany with its declining domestic production but as the main consumer and important transit country of natural gas was also considered in the collection of recent records. The input data relevant for these countries and necessary for the calculation of the CF, is described in Chapter 3. Furthermore, Chapter 3 quantifies greenhouse gas (GHG) emissions, that are released from the life cycle stages production, processing, transport, storage and distribution of natural gas. Chapter 4 presents the results of the impact assessment with the effect on climate change as the only impact category. The results are interpreted and evaluated in Chapter 5 and significant issues (i.e. the contributions of different GHG to and the effect of the metric on the CF) are identified. Subsequently, Chapter 6 describes conclusions that can be drawn from the results as well as the existing limitations and recommendations.

The project has been commissioned and coordinated by Zukunft GAS GmbH and carried out by DBI Gas- und Umwelttechnik GmbH Leipzig.

6 The region "CE" comprises: Austria, Belgium, Czech Republic, Estonia, Germany, Hungary, Latvia, Lithuania, Luxemburg, the Netherlands, Poland, Slovakia [2].

2 Goal and Scope of the Study

2.1 Reasons for Conducting the Study, Intended Application, Intended Audience

The main objective of this study is to provide transparent information about the life cycle emissions of natural gas in Central Europe and Germany, based on reliable and up-to-date data. It is conducted in continuation of the preceding study "Critical Evaluation of Default Values for the GHG Emissions of the Natural Gas Supply Chain" published in 2016 [3], pursuing the path of an open communication of the of the natural gas value chain's carbon intensity over the recent years.

The goal of a CF study is "to calculate the potential contribution of a product to global warming expressed as CO_2 equivalent (CO_2e) by quantifying all significant GHG emissions and removals over the product's life cycle." [1].

The study determines the Carbon Footprint of natural gas which is distributed in Central Europe and Germany for the years 2015-2018. The assessment of the carbon footprint was carried out according to the requirements of DIN EN ISO 14040 [5], DIN EN ISO 14044 [6], and DIN EN ISO 14067 [1].

The results enable a comparative evaluation of carbon footprint research with other similar studies and contribute to an improvement of the available database.

The study was commissioned by Zukunft GAS. Its findings will be used as a sound scientific basis in the communication with the association´s members, stakeholders, and politics about greenhouse gas emissions of natural gas.

2.2 Product System, System Boundaries and Functional Unit

This study considers the products "Natural gas distributed in Central Europe" and "Natural gas distributed in Germany".

The product system comprises the individual stages of the natural gas value chain. The following description was extracted from [3]:

Natural Gas Production

Natural gas can occur in connection with oil fields or in separate gas fields. If natural gas reserves are discovered during exploratory drilling, production wells are drilled to enable the natural gas to be extracted. The energy effort for the extraction of natural gas depends on the type of natural gas (conventional or unconventional such as shale gas) and on the location of the field (onshore or offshore).

Natural Gas Processing

Natural gas consists of different components (methane, propane, carbon dioxide, hydrogen sulphide, water, etc.). Some of these components (especially hydrogen sulphide and water) need to be separated to avoid operational problems (e.g. the degradation of pipelines). Other components (e.g. CO_2) are separated to create a certain calorific value of the gas. The calorific value is important for the functioning of end user appliances. Different processes, for instance dehydration or separation of condensates, are applied for gas processing.

Natural Gas Transport

The transport of natural gas from production and processing sites is normally carried out with high-pressure pipelines, or as liquefied natural gas (LNG). As a result of friction, the pressure of the gas within the pipeline will gradually decrease. To reverse this decrease, compressor stations are placed along the pipeline (onshore at intervals of approximately 100 to 150 km).

Natural Gas Storage

In order to balance seasonal or peak-load fluctuations, natural gas can be stored in underground storage facilities. These facilities can be divided into two categories: porous storage and salt cavern storage. In porous storage the natural gas is stored within a porous rock formation. Surrounding impermeable rock stops the stored gas from escaping. Depleted gas reservoirs and natural aquifers are often utilised for this purpose. In cavern storage an impermeable space is created within the salt rock and filled with natural gas. In addition to underground storage, there is also above ground storage.

Natural Gas Distribution

In contrast to compressors, gas pressure regulating (and metering) stations (GPR(M)S) reduce pressure in the pipeline. This is necessary for the withdrawal of the gas by the end-user. Further functions of GPR(M)S are volume measurement, preheating and odourisation of natural gas. When pressure of natural gas is reduced, the gas temperature decreases (Joule-Thompson Effect), therefore preheating units have to increase the temperature of the gas. Odourisation is needed since natural gas is odourless and by adding an odorant it enables to detect leaks. At a municipal level, natural gas is distributed via high-, medium- and low-pressure pipelines. It is primarily used in the heating market (heat generation for domestic use and process heating for industry), in the industry, for electricity generation, in the chemical industry and (to a minor degree) in the transport sector. In addition to power plants, industry, and domestic customers, it is therefore necessary to supply filling stations with natural gas as well.

Figure 1: Product System, own illustration based on [7] summarizes the product system with its included elements. Application technologies are not within the scope of this study.

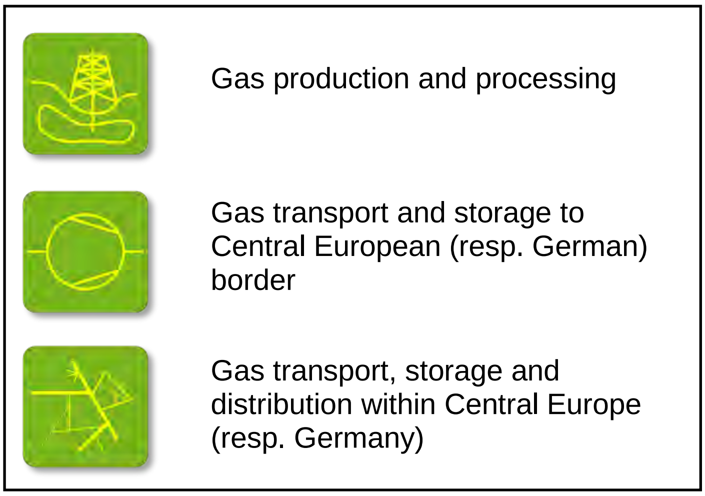

Figure 1: Product System, own illustration based on [7]

The study focuses on pipeline gas. Liquefied Natural Gas (LNG) is included in the gas supply structure, however, is not considered as a product. Data on emissions of the production, processing and transport of LNG were taken from [8][7].

7 There is more current data available for LNG in the Thinkstep Study from 2019 [9]. As opposed to [8], the latter does not include values for LNG supplied to CE. The impact of taking values for CE instead of EU-28 was considered more important than taking values for 2017 instead of 2015.

Geographically, the study focuses on the region Central Europe (CE), including the following countries (for an overview, refer to Figure 2: System "Natural gas Distributed in CE", own illustration based on [10]):

- Belgium
- Germany
- Estonia
- Latvia
- Lithuania
- Luxembourg
- The Netherlands
- Austria
- Poland
- Slovakia
- Czech Republic
- Hungary

Moreover, countries producing gas for CE or transporting gas to the CE border are regarded. These are:

- Russia
- Belarus
- Ukraine
- Norway
- United Kingdom (UK)

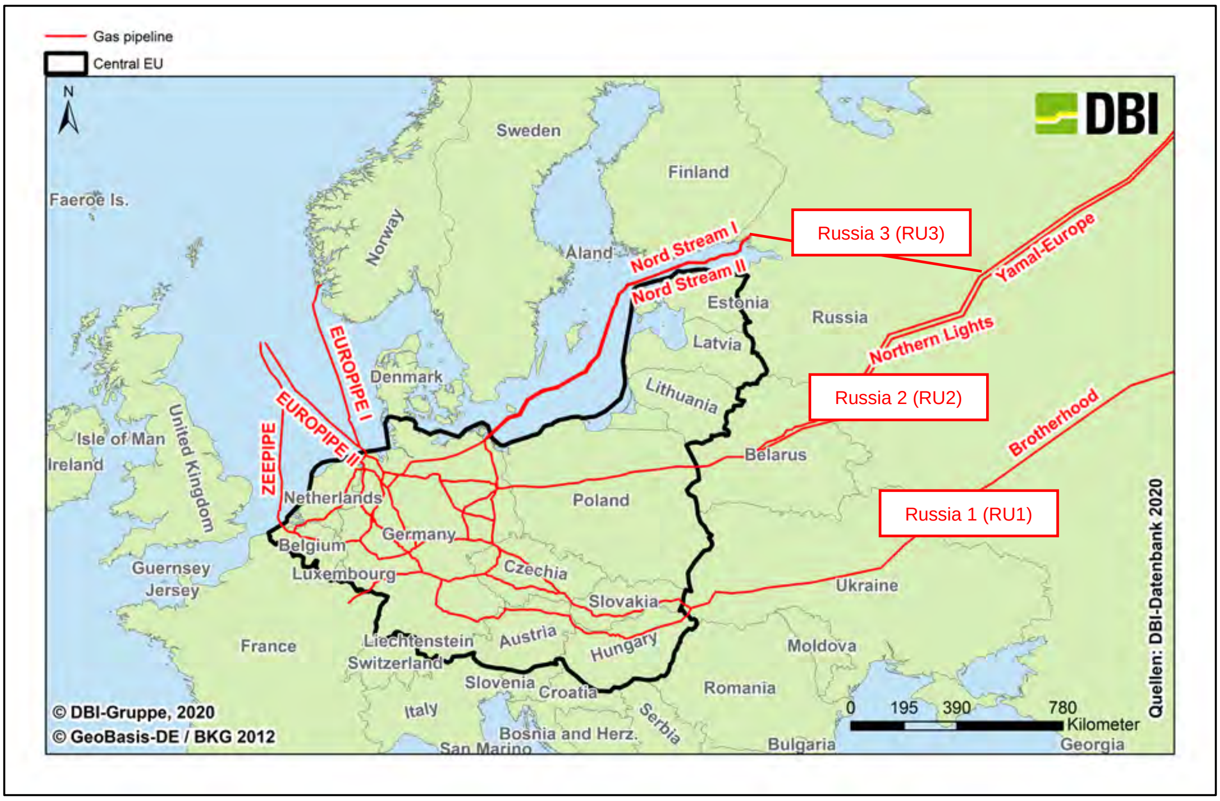

Figure 2: System "Natural gas Distributed in CE", own illustration based on [10]

Table 1 gives an overview on the system boundaries applied in this study. Some aspects were excluded from the calculations because no data were available. However, the contribution of these excluded aspects to the total CF was presumed to be negligible.

Table 1: System Boundaries

	Included elements	Excluded elements (no sufficient data available)
Exploration	Out of scope	
Production	- Gas losses (leakage, repair, incidents) - Flaring - Energy consumption - Infrastructure emissions (building of platforms)	
Processing	- Gas losses (leakage, repair, incidents) - Infrastructure emissions (building of platforms and process plants) - Energy consumption - CO_2 removal, water removal, H_2S removal	
Gas transport to Central European border and storage outside Central Europe	- Gas losses (leakage, repair, incidents) - Energy consumption of gas transport - Flaring - Infrastructure emissions (building of pipelines)	- Energy consumption of gas storage
Gas transport within Central Europe and storage inside Central Europe	- Gas losses (leakage, repair, incidents) - Energy consumption - Infrastructure emissions (building of pipelines)	- Flaring - Energy consumption of gas storage
Distribution within Central Europe	- Gas losses (leakage, repair, incidents)	- Biogas injection plants - Infrastructure emissions (building of pipelines) - Energy consumption of distribution (e.g. for preheating)
Gas utilisation	Out of scope	

The functional unit is one gigajoule (GJ) natural gas (net calorific value, NCV) distributed at regional level.

2.3 Assumptions and Limitations

The assumptions made for the calculation of the carbon footprint are described in detail in the relevant sections.

The following limitations exist:

- The study considers climate change to be the single impact category. Further environmental impacts are not evaluated in this study.

- Energy demands of gas pressure regulating and measuring stations as well as of gas storage outside and inside CE are not considered by this study because sufficient data was not available. This information was presumed to be of limited relevance to the results.
- Electricity grid mixes were taken from the GaBi database [11]. GaBi includes an average electricity grid mix, which is valid from 2016 until 2022. For this reason, the electricity grid mixes are the same for each year over the considered time frame in this study. Changes in the electricity mix (and effects of rising shares of renewables) between 2015 and 2018 were not considered.
- Many data on energy demands and emissions is not given separately for gas production in the original data sources, but as a summary of oil and gas production. To obtain specific data for gas production, an allocation according to energy content is made if necessary.

2.4 Software and Database

The calculations in this study were performed using the LCA software GaBi ts Version 9.2.1 [11]. Data were taken from the GaBi professional database 8.7 (2020), the Extension Database II (Energy), as well as from literature or industry sources.

For the previous study, the LCA model GHGenius version 4.03 [12] was used. An exemplary comparison of the results obtained with both models was made, the results are described in section 3.2.1.

2.5 Impact Categories, Impact Assessment and Evaluation Method

According to DIN EN ISO 14067, the relevant impact category for the creation of a carbon footprint analysis is climate change [1]. Thus, the following environmental impact models were considered: Global Warming Potential (GWP) and Global Temperature change Potential (GTP) in accordance with the 5th Assessment Report [13] and the 4th Assessment Report [14] of the Intergovernmental Panel on Climate Change (IPCC). The applied impact categories, impact assessment method, models and indicator are summarized in Table 2.

Table 2: Impact Category, Impact Assessment Model, and Impact Category Indicator

Impact Categories	**Impact Assessment Method**	**Source of Impact Assessment Model**	**Impact Category Indicator**
Climate Change, incl. biogenic carbon and Land Use Change	TRACI 2.1, incl. biogenic carbon	GWP_{100}-values from the 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) [14]	g CO_2 equivalent (gCO_2e)
Climate Change, incl. biogenic carbon and Land Use Change	IPCC AR5 and ReCiPe 2016 v1.1	GWP_{100}-values from the 5th Assessment Report of IPCC [13]	g CO_2 equivalent (gCO_2e)
Climate Change, incl. biogenic carbon, and Land Use Change	IPCC AR5	GTP_{100}-values from the 5th Assessment Report of IPCC [13]	g CO_2 equivalent (gCO_2e)

The evaluation took place according to the requirements of DIN EN ISO 14067 [1]. This included:

- Identification of significant issues based on the results of the quantification of the CF according to life cycle inventory analysis (LCI) and the life cycle impact assessment (LCIA) phases
- An evaluation that considers completeness, sensitivity and consistency checks
- Conclusions, limitations, and recommendations.

2.5.1 Global Warming Potential (GWP)

To enable the combination of the effect of several greenhouse gases in one value, the effect of non-CO_2 GHG is assessed relative to the effect of CO_2. Therefore, the common metric “CO_2 equivalent” is generally used to calculate a CF. The CO_2 equivalent values of greenhouse gases are determined by applying a factor for the “Global Warming Potential” (GWP) to the individual greenhouse gas emissions. As it is called for in DIN EN ISO 14067 [1] the GWP over a time span of 100 years (GWP_{100}) was applied in this study. The GWP values have been changing considerably over the last decades due to the development of scientific knowledge and the probable effect of the greenhouse gases on radiative forcing and hence, the expected global warming.

The GWP values utilised in this study were taken from the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change [14, p. 212]. This report has been fixed as a binding source for the National Inventory Reports since the United Nations Climate Change Conference in Warsaw in 2013 [15].

The latest GWP_{100} values were, however, released in the Fifth Assessment Report (AR5) of the IPCC [13, p. 714]. For example, the GWP_{100} for methane is listed in this current report as 30 (36 including climate carbon feedback) in contrast to 25 in the Fourth Assessment Report. In order to consider these latest developments, a sensitivity analysis, including the latest GWP_{100} values, as well as the GTP metric described in section 2.5.2, from the Fifth Assessment Report of the IPCC, was carried out.

The GWP values used by the LCA-models that were applied in this study are displayed in Table 3.

Table 3: Overview of GWP Values Applied in This Study

Metric	GWP (100 Years)	GWP (100 Years), excl. ccfb[8]	GWP (100 Years), incl. ccfb[8]
Source	AR4 [14, p. 212]	AR5 [13, p. 714; 731]	AR5 [13, p. 714; 731]
CO_2	1	1	1
CH_4	25	30	36
N_2O	298	265	298
CF_4	7,390	6,630	7,350
PFC-116	12,200	11,100	11,100
SF_6	22,800	23,500	23,500

2.5.2 Global Temperature Change Potential (GTP)

Another metric for assessing the potential of a greenhouse gas on the climate system relative to CO_2 besides the GWP is the Global Temperature change Potential (GTP). It has been introduced in the Fifth IPCC Assessment report [13] and can be applied for three different fixed time horizons (20, 50 and 100 years) with proposed fixed values, or based on a target year with dynamic values based on the time span until that target year. GTP values used in this study are listed in Table 4.

Whereas the GWP assesses the effect of GHG on radiative forcing accumulated over a certain time (here: 100 years), the GTP assesses “the temperature response at a given point in time with no weight on

[8] ccfb = climate carbon feedback

temperature response before or after the chosen point in time" [16, p. 87].

The application of GTP-values is becoming increasingly important in the communication, especially in the field of climate policy. It represents an end-point metric that is based on temperature change for a selected year in the future; giving the absolute change in global mean surface temperature at a chosen point in time in response to an emission pulse, relative to the temperature change due to the emission of equal amounts of CO_2 [17]. The GTP goes further than GWP and integrates not only radiative forcing, but also climate response in describing the effects of emissions, as it estimates the change in global mean temperature for a selected year in the future. In other words, this metric tries to answer the question: What will the temperature change be in a certain year in response to the radiative forcing of certain GHG emissions?

It can be argued, that the GTP is more suitable, to assess mitigation strategies with regard to the zero-emissions goal before global temperature change can be limited to 2 °C. For further information on the significance of the different metrics under different policy scenarios, reference to [18] shall be recommended here.

However, metrics with longer time spans have inevitably an uncertainty range. GTP calculations are more complicated and are less certain than simple radiative forcing calculations. Although uncertainty is increased, it can be argued, that relevance is also increased since it is more useful for policy makers to know what the actual temperature change will be, instead of only the amount of energy that has been added to the system. Since the GTP does not only include effects on radiative forcing like the GWP does, but also on the climate response which is located further down the cause-effect-chain of the climate change potential, it is consequently associated with higher uncertainties than the GWP [13, p. 58].

Table 4: Overview of GTP Values Applied in This Study

Metric	GTP (100 Years)
Source	AR5 [13, p. 714; 731]
CO_2	1
CH_4	6
N_2O	234
CF_4	8,040
PFC-116	13,500
SF_6	28,200

2.6 Critical Review

A critical review is not part of this study. However, the report was prepared in a manner that enables it to be reviewed after the end of the project.

3 Inventory Analysis

3.1 Data Collection and Validation

3.1.1 Relevant Studies

In the following, the studies that were mainly used for data collection are shortly described. Nevertheless, further studies were used for country-specific information and are mentioned as sources in the sections 3.1.3 to 3.1.9.

European Commission/EXERGIA 2015 [19]

The "Study on actual GHG data for diesel, petrol, kerosene and natural gas" (hereinafter referred to as "EXERGIA study") was carried out by the Greek institute EXERGIA on behalf of the European Commission and published in July 2015. The subject of the EXERGIA study were greenhouse gas emissions occurring during the life cycle steps production, processing, transport, distribution and dispensing on filling stations for natural gas mobility in Europe. However, the EXERGIA study reported considerably higher upstream emissions than those published by other studies, such as the JEC-study in 2013 [20]. Critical analysis by third-parties (e.g. BDEW [21], DNV-GL [22], ifeu [23]) showed that EXERGIA relied partly on obsolete data or estimations, and that weaknesses were present in the methodology of the research.

Zukunft ERDGAS/DBI 2016 [3]

Zukunft ERDGAS commissioned the DBI study in 2016 to collect updated data and solve methodological issues of the EXERGIA study. The study used the same GHG model as the EXERGIA-study (GHGenius), but its focus was solely on the region Central Europe. The Zukunft ERDGAS/DBI 2016 study is the predecessor for the study at hand.

The study Zukunft ERDGAS/DBI 2016 was reviewed by the German Federal Environmental Agency (UBA) in 2018 [24] and was considered plausible and reliable.

NGVA/Thinkstep 2017 [8]

This study was conducted in parallel with the Zukunft ERDGAS/DBI 2016 study and is focused not only on Central Europe, but on Europe in total. Data for Central Europe was mostly taken from the Zukunft ERDGAS/DBI 2016 study, except for the Norwegian gas processing and transport where updated data was collected. Moreover, the study collected data for the LNG supply chain.

Nord Stream 2/Thinkstep 2017 [25]

This study was commissioned in 2017 by the Nord Stream 2 AG to compare future gas imports on the Nord Stream 2 with imports from other routes (e.g. US-American LNG). Detailed considerations were made for infrastructure emissions of the transport pipelines and compressor stations.

BGR 2020 [26]

In 2020, the Federal Institute for Geosciences and Natural Resources in Germany (BGR) published a survey on the climate impact of natural gas from production to shipping via pipeline and LNG. It relied mainly on the data basis of the studies by DBI and Thinkstep mentioned before.

3.1.2 Overview of Collected Data

The study at hand is an update of the study "Critical Evaluation of Default Values for the GHG Emissions of the Natural Gas Supply Chain" published in 2016 [3].Thus, the study refers to the same data base as the previous study, but updated data were collected for those countries that contribute significantly to the final result (The Netherlands, Norway, Russia) as well as for Germany. Table 5 shows for which process steps in the natural gas supply chain updated data was available and used in this study.

Table 5: Overview of Data Collection

Country	Production	Processing	Transport to CE	Transmission in CE	Distribution in CE
Austria	not existing	not existing	not existing	previous study	previous study
Belarus	not existing	not existing	updated	not existing	not existing
Belgium	not existing	not existing	not existing	previous study	previous study
Czech Republic	not existing	not existing	not existing	previous study	previous study
Germany	updated / previous study	updated / previous study	not existing	previous study	updated
Estonia	not existing	not existing	not existing	previous study	previous study
Latvia	not existing	not existing	not existing	previous study	previous study
Lithuania	not existing	not existing	not existing	previous study	previous study
Luxembourg	not existing	not existing	not existing	previous study	previous study
Hungary	not existing	not existing	not existing	previous study	previous study
The Netherlands	updated	updated	not existing	updated	updated
Norway	updated	updated	updated	not existing	not existing
Poland	previous study	previous study	not existing	previous study	previous study
Russia	updated	updated	updated	not existing	not existing
Slovakia	not existing	not existing	not existing	previous study	previous study
UK	previous study	previous study	previous study	not existing	not existing
Ukraine	not existing	not existing	updated	not existing	not existing

updated (green)	Updated data available and used for this study
previous study (light grey)	No updated data available - data from the previous study was used
not existing (dark grey)	Process step not existing

Data was collected from internet research, literature review and operators' information[9]. Data sources are specified in the respective input data tables in this chapter. To be compatible with the GaBi model, some data was converted using the gas characteristics shown in Annex 1.

3.1.3 Default Values

<u>Infrastructure</u>

Various data on material and energy demand of infrastructure for natural gas production, processing and transmission was taken into account. Detailed information about on- and offshore production plants as well as natural gas treatment plants used in the study at hand can be found in the study "Life Cycle Inventory of Natural

9 A data collection sheet was prepared and sent to the operators to collect primary data. The operators filled the sheet and sent it back.

Gas Supply“ [27, p. 26-28]. The input data for on- and offshore pipelines and compressor stations is provided in the Thinkstep Nord Stream 2 study [25].

Where the number of compressor stations was not available, it was assumed that one compressor station is installed at the beginning of a gas transport pipeline and on every 100 km onshore pipeline.

Equipment Emission Factors

The combustion of natural gas in natural gas upstream process steps occurs in gas turbines and gas engines. If not stated otherwise, a share of 20 % of natural gas consumption (NCV) was assumed to be combusted in gas engines and 80 % of natural gas consumption in gas turbines in the steps “production” and “processing”. For gas transport, a share of 95 % gas turbines and 5 % gas engines was assumed in the calculations, except for the Russian transport routes. Gazprom reported a share of 100 % gas turbines for the own consumption equipment along their transport routes [28]. The emission factors for the natural gas and diesel combustion are stated in Table 6: Equipment Emission Factors [g/GJ fuel input] [29]. They are the default values used in the GaBi database for the respective processes in all countries.

Table 6: Equipment Emission Factors [g/GJ fuel input] [29]

	Natural gas CHP	Natural gas engine	Diesel CHP
CO_2	56,100.0	54,394.0	74,066.0
CO	31.8	215.5	346.9
CH_4	3.3	483.7	3.3
NOx	125.0	327.7	104.7
N_2O	1.2	1.16	0.4
NMVOC	0.8	45.7	33.4
PM2,5	2.9	0.03	19.6
SO_2	1.3	1.4	139.7

As background system for the provision of Diesel fuel in all countries the aggregated GaBi process “EU-28: Diesel mix at refinery ts” [29] was applied. Country-specific electricity mixes were selected in the GaBi Database for specific countries, for example “NO: Electricity grid mix (consumption mix) ts”. For electricity consumption in CE, an electricity mix had been modelled representing the weighted average of the countries in CE, applying national natural gas consumption as the weighing factor.

For the flaring of natural gas, the emission factor of 55.9 tCO_2/MJ published by UBA [30, p. 44] was used for the incineration of natural gas.

3.1.4 Natural Gas Supply Structure of Central Europe and Germany

Natural gas that is consumed in Central Europe originates from a diverse range of origins. In order to allocate the different carbon footprints of the producing countries to their share in the consumption mix of Central Europe, these proportions were calculated using different data sources and validations.

The starting point for this calculation was the IEA database “Gas Trade Flows” [31]. This database covers the physical amounts of natural gas flowing across the border points for 31 participating countries in Europe monthly. In the analysis, the natural gas flows into Central Europe at the border points were added and with help of a map containing the major transport pipelines [32] allocated to the corresponding producing countries. Domestically produced quantities of natural gas in the countries of Central Europe were added to this "gas pool", according to data provided by the IEA [33, p. III.28-III.157].

Countries producing less than 2 % of natural gas for the pipeline gas supply in CE and in Germany have been neglected for the calculation.

Moreover, flows that are consumed in countries outside of Central Europe (transit flows), sometimes reach Central Europe across the border points. These transit flows have been subtracted from the natural "gas pool" of CE according to data on natural gas imports by origin provided by IEA [33, p. II.22-II.45], [34] for the countries outside of CE. Additionally, natural gas flows entering Ukraine from border points in Slovakia and Hungary, have been subtracted as Russian transit flows.

Figure 3: Natural Gas Supply Mix in Central Europe, Years 2015-2018, own calculation based on [31, 33, 34] shows the natural gas supply mix in Central Europe for the years 2015 to 2018. Detailed data tables can be found in Annex 6.

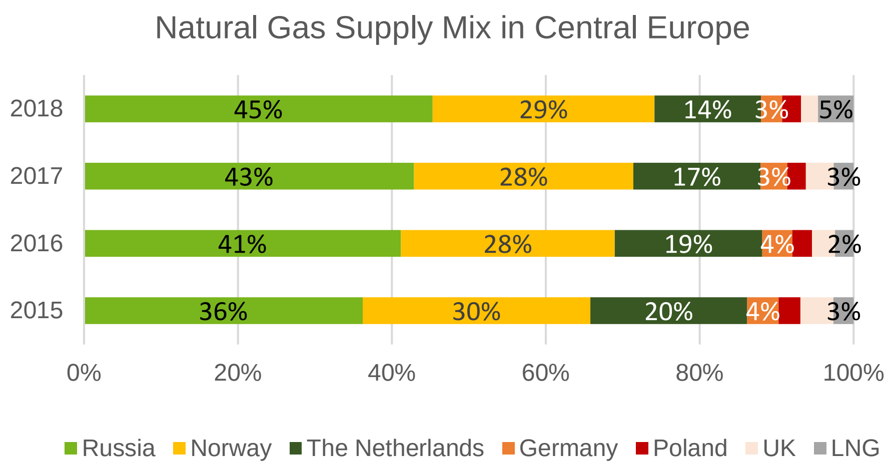

Figure 3: Natural Gas Supply Mix in Central Europe, Years 2015-2018, own calculation based on [31, 33, 34]

For the analysis of the carbon footprint of natural gas consumed in Germany, a gas supply mix was determined similarly using data sources of the IEA [31, 33, 34] and data published by supplying companies [35, 36]. The specific gas supply structure applied in the previous study published by the German Ministry of Economics and Energy has not been published anymore for reasons of data protection since 2016 [37, p. 10]. The data published for 2015 show good consistency with the data obtained with the named sources.

Figure 4: Natural Gas Supply Mix in Germany, Years 2015-2018, own calculation based on [31, 33–36] shows the natural gas supply mix in Germany for the years 2015 to 2018. Detailed data tables can be found in Annex 7.

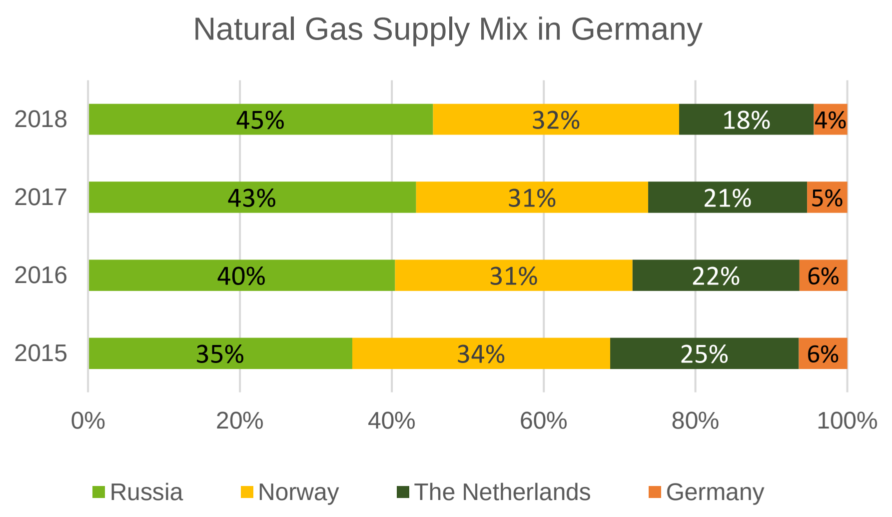

Figure 4: Natural Gas Supply Mix in Germany, Years 2015-2018, own calculation based on [31, 33–36]

Countries of origin of LNG flows into Central Europe cannot be allocated using the IEA "Gas Trade Flows" [31]. Whilst the amounts of LNG in the Central European gas mix is obtained from the "Gas Trade Flows" [31], the allocation to the different countries of origin is performed with the help of the dataset by IEA "World LNG imports by origin" [33, p. II.46-II.51]. Figure 5: Natural Gas Mix, Origins of LNG imports, Years 2015 (left) and 2018 (right), own calculation based on [31, 33, 34] shows the proportions of LNG origin countries in the natural gas mix in CE of the years 2015 and 2018.

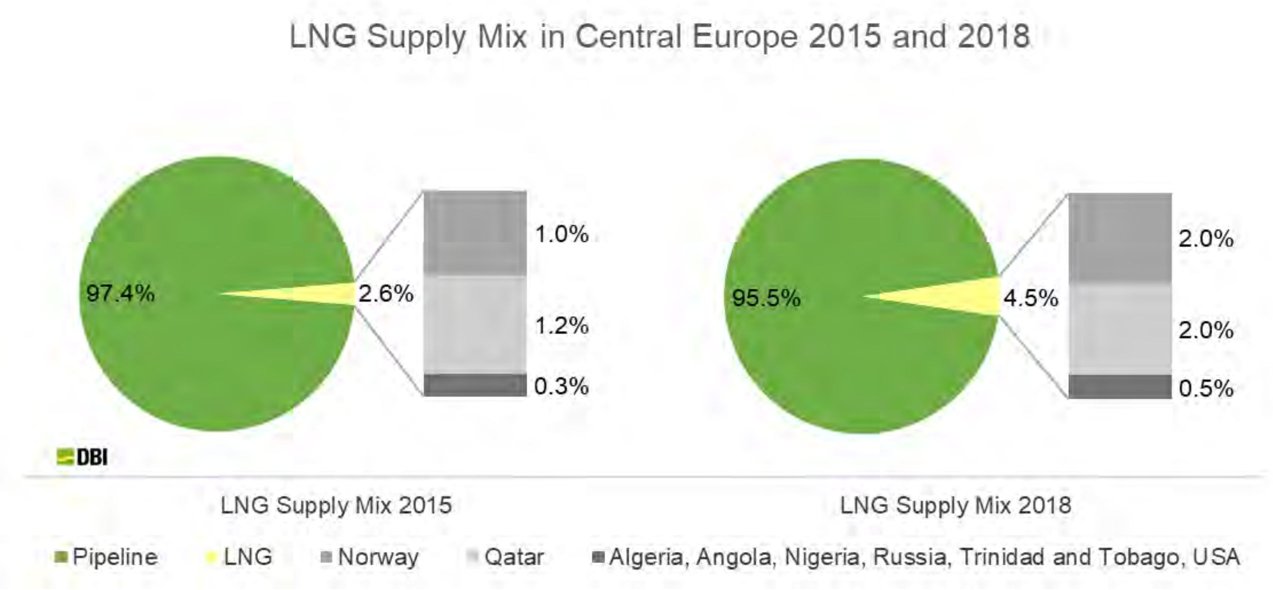

Figure 5: Natural Gas Mix, Origins of LNG imports, Years 2015 (left) and 2018 (right), own calculation based on [31, 33, 34]

Since the IEA is an international organisation of the OECD countries with extensive experience in the field of energy statistics, their data sets are generally considered reliable and are plausible in relation to each other since the energy balances (import + production = consumption + export) are largely comparable with only slight statistical deviation.

The IEA data on "imports by origin" [34] and [33] show some inconsistencies, especially concerning the imports from the Netherlands and Norway, and data gaps for relevant importing countries. For these reasons, the approach described above was chosen.

Gas flows from Norway were validated using data published by the Norwegian Petroleum Directorate (NPD) [36]. These numbers are within 13 % deviation from the data reported by [31]. Data obtained for the flows of natural gas produced from Russia reported by [31], were validated using data published by Gazprom [35]. The numbers reported by Gazprom are within 10 % variation to the data reported in [31]. LNG quantities reported by the IEA “LNG imports by origin” [33] are not well aligned with the data reported by the IEA “Gas Trade Flows” [31], as they deviate up to 31 % from each other. In order to stay within a consistent data source, LNG quantities were taken from [31]. However, due to missing allocation of LNG imports to origin countries, shares were calculated based on data provided in [33] and multiplied to the total quantities provided in [31].

Because the actual origins of natural gas in the European gas market are not only dependent on long-term supply contracts that were not publicly available, but also on short-term market mechanisms such as barter agreements between natural gas traders, the shares of the gas supply structure are naturally associated with moderate uncertainty.

3.1.5 Central Europe

For the transport and distribution within CE, average values were calculated for energy demand and gas losses (Table 7). The average was weighted according to yearly national natural gas consumption of the countries in CE taken from [33]. Except for Germany and the Netherlands where current data was collected (ref. section 3.1.6 and 3.1.7), values used for the average building originate from the previous study.

For gas storage, data was only available for Germany. For this reason, the value has also been applied for CE.

Table 7: Input Data for Central Europe

Parameter	**Value**				**Unit**	**Source/ Remark**
	2015	**2016**	**2017**	**2018**		
Gas transport and storage in CE						
Natural gas	1.63E-02	1.62E-02	1.63E-02	1.65E-02	kJ/(MJ*km)	[3, 19, 38]
Electricity	3.93E-04	3.73E-04	3.70E-04	3.79E-04	kJ/(MJ*km)	[3, 19, 38]
Diesel fuel	0	0	0	0	kJ/(MJ*km)	[3, 19, 38]
Total	1.67E-02	1.66E-02	1.66E-02	1.68E-02	kJ/(MJ*km)	-
Gas losses	0.576	0.566	0.555	0.562	kJ/MJ	[3, 17, 36][(10)]
Pipeline transport length in CE	271	271	272	272	km	[19]
Gas distribution						
Gas losses	3.079	3.010	2.980	3.054	kJ/MJ	[19, 39, 40]

10 German value is assumed for losses of gas storage because other values were not available.

3.1.6 Germany

Data for natural gas production in Germany was taken from the annual national energy balances from 2015 to 2018 [41]. The energy balances include information on the domestic production of natural gas, flaring, and energy consumption for oil and gas extraction. Since the study at hand focuses solely on natural gas production, it was necessary to make an allocation based on energy content to determine the share of energy consumed in the natural gas production process.

$$Specific\ Energy\ Consumption\ Gas\ Production = \frac{Energy\ Consumption\ Gas\ and\ Oil\ Production}{Amount\ of\ Gas\ Produced} \cdot Share\ of\ Gas\ Production$$

Specific methane emissions for production as well as data for vented CO_2[11] were taken from the annual reports of the German Federal Association of Natural Gas, Petroleum and Geoenergy (BVEG)[12] [43] and were converted using the values from Annex 1.

For the energy demand of gas production and gas processing, values were provided by the BVEG for the previous study. Since then, no updated data has been available, therefore the values of 2014 were used for all years.

The same accounts for gas transmission: data from the German transmission system operators (TSO) was provided for the previous study but no updated data has been available. The values of 2014 were used for all years. Data for gas storage was taken from the NIR 2020 but was only available for gas losses. The energy demand of gas storage is not considered in this study, but is expected to have a minor impact on the total CF. The NIR includes an Emission Factor of 0.04 $kgCH_4$/1,000 m^3 which is related to the working gas volume (standard conditions).

Data for gas distribution was taken from the NIR 2020 for the years 2015-2018 [40].

All input data for the LCI model is summarized in Table 8.

[11] Main source of vented CO_2 is the sour gas conditioning.

[12] The BVEG recommends that only 5/6 of the emissions from acid gas processing shall be attributed to natural gas, since 1/6 of the energy demand for gas processing should be assigned to sulphur production [42].

Table 8: Input Data for Germany

Parameter	Value				Unit	Source/ Remark
	2015	2016	2017	2018		
Gas production						
Natural gas	30.877	28.195	33.552	35.051	kJ/MJ	[41]
Electricity	8.071	8.458	8.846	9.599	kJ/MJ	[41]
Diesel fuel	0.007	0.030	0.016	0	kJ/MJ	[41]
Total	38.955	36.683	42.414	44.650	kJ/MJ	-
Gas losses	0.150	0.090	0.090	0.050	kJ/MJ	[43]
Flaring	1.180	1.021	1.397	1.660	kJ/MJ	[41]
Gas processing						
Natural gas	14.370	14.370	14.370	14.370	kJ/MJ	[43]
Electricity	0.657	0.657	0.657	0.657	kJ/MJ	[43]
Diesel fuel	0	0	0	0	kJ/MJ	[43]
Total	15.028	15.028	15.028	15.028	kJ/MJ	-
Gas losses	0.071	0.080	0.025	0.026	kJ/MJ	[40]
CO_2 vented	0.003	0.003	0.003	0.003	$kgCO_2/MJ$	[43]
Gas transport and storage in DE						
Natural gas	8.56E-03	8.56E-03	8.56E-03	8.56E-03	kJ/(MJ*km)	[3]
Electricity	1.06E-04	1.06E-04	1.06E-04	1.06E-04	kJ/(MJ*km)	[3]
Diesel fuel	0	0	0	0	kJ/(MJ*km)	[3]
Total	8.66E-03	8.66E-03	8.66E-03	8.66E-03	kJ/(MJ*km)	-
Gas losses	1.20E-01	1.20E-01	1.20E-01	1.20E-01	kJ/MJ	[3], [40]
Pipeline transport length in DE	300	300	300	300	km	[19]
Gas distribution in DE						
Gas losses	1.590	1.459	1.421	1.466	kJ/MJ	[40]

3.1.7 The Netherlands

Data for natural gas production in the Netherlands was taken from the annual national energy balances from 2015 to 2018 [44]. Data on gas transport and processing were extracted from the Annual Reports of the Dutch TSO Gasunie [38] and data for gas distribution was taken from the NIR [39]. Table 9 shows all input data for the Netherlands.

Table 9: Input Data for the Netherlands

Parameter	Value				Unit	Source/ Remark
	2015	2016	2017	2018		
Gas production						
Natural gas	13.065	13.896	15.730	16.137	kJ/MJ	[44]
Electricity	5.217	5.476	6.364	7.800	kJ/MJ	[44]
Diesel fuel	0.068	0	0	0	kJ/MJ	[44]
Total	18.349	19.373	22.094	23.937	kJ/MJ	-
Gas losses	0.357	0.338	0.370	0.321	kJ/MJ	[39]
Flaring	0.828	0.922	1.035	0.716	kJ/MJ	[44]
Gas processing						
Natural gas	0.000	0.000	0.000	0.000	kJ/MJ	[38]
Electricity	0.695	1.029	1.194	1.653	kJ/MJ	[38]
Diesel fuel	0	0	0	0	kJ/MJ	[38]
Total	0.695	1.029	1.194	1.653	kJ/MJ	-
Gas losses	-	-	-	-	kJ/MJ	-
CO_2 vented	1.29E-06	1.34E-06	1.17E-06	8.05E-07	kgCO_2/MJ	[39]
Gas transport in NL and to CE and storage						
Natural gas	3.57E-03	3.37E-03	3.59E-03	3.44E-03	kJ/(MJ*km)	[38]
Electricity	1.64E-03	1.58E-03	1.60E-03	1.63E-03	kJ/(MJ*km)	[38]
Diesel fuel	0	0	0	0	kJ/(MJ*km)	[38]
Total	5.21E-03	4.95E-03	5.19E-03	5.07E-03	kJ/(MJ*km)	-
Gas losses	1.33E-03	1.19E-03	9.14E-04	9.30E-04	kJ/(MJ*km)	[38]
Pipeline length to CE border	150	150	150	150	km	(13)
Pipeline length to German border	100	100	100	100	km	[45, p. 71]
Gas distribution						
Gas losses	0.553	0.524	0.461	0.457	kJ/MJ	[39]

3.1.8 Norway

Data for the Norwegian gas production is publicly available from the energy balances [46] and the NIR [47](14).

Data for gas processing and gas transport was provided by Gassco via data collection sheet [48]. Data on emissions of some facilities (e.g. Kollsness Processing Plant) are also publicly available on [49]. However, the website just gives emissions for the total facility (including processing of liquids and of natural gas amounts that are not relevant for CE). Gassco delivered data allocated for Germany and these are presumed to be representative for CE as well.

Gas storage was not considered for Norway, since there are no gas storages on the export corridors to Central Europe. Input data into the LCI model is summarized in Table 10.

13 The Netherlands are located in CE, however, it is assumed that gas is exported within CE to another country.
14 Numbers given by Gassco for processing are subtracted from the numbers of the NIR because the NIR numbers include production and processing.

Table 10: Input Data for Norway

Parameter	Value				Unit	Source/ Remark
	2015	2016	2017	2018		
Gas production						
Natural gas	22.187	21.677	21.629	22.109	kJ/MJ	[46]
Electricity	2.931	2.971	3.173	3.559	kJ/MJ	[46]
Diesel fuel	1.796	1.663	1.379	1.652	kJ/MJ	[46]
Total	26.913	26.311	26.182	27.320	kJ/MJ	-
Gas losses	0.031	0.033	0.044	0.044	kJ/MJ	[47](14)
Flaring	2.381	2.357	2.304	2.390	kJ/MJ	[46]
Gas processing						(15)
Natural gas	0.777	0.760	0.763	0.690	kJ/MJ	[48](15)
Electricity	0.852	0.818	0.845	0.917	kJ/MJ	[48] (15)
Diesel fuel	-	-	-	-	kJ/MJ	[48] (15)
Total	1.629	1.578	1.608	1.607	kJ/MJ	-
Gas losses	0.039	0.037	0.026	0.026	kJ/MJ	[48] (15)
CO_2 vented	7.32E-06	7.07E-06	7.03E-06	7.05E-06	$kgCO_2/MJ$	[47]
Gas transport to CE						(15)
Natural gas	3.38E-03	3.35E-03	3.25E-03	3.06E-03	kJ/(MJ*km)	[48] (15)
Electricity	2.79E-03	2.68E-03	2.76E-03	2.99E-03	kJ/(MJ*km)	[48] (15)
Diesel fuel	-	-	-	-	kJ/(MJ*km)	[48] (15)
Total	6.17E-03	6.04E-03	6.01E-03	6.05E-03	kJ/(MJ*km)	-
Gas losses	0	0	0	0	kJ/(MJ*km)	Assumption (16)
Flaring	-	-	-	-	kJ/(MJ*km)	-
Pipeline length to CE border	925	925	925	925	km	[8]
Pipeline length to German border	925	925	925	925	km	[8]

Data for gas production have been validated with other data sources (Table 11). The data for the energy demand (electricity, diesel and natural gas demand) is in the same order of magnitude in the compared data sources. The data for gas losses differs. The number provided by the operator Equinor is much higher than the numbers published in the Norwegian NIR. However, the numbers from Equinor include, among others, methane emissions of incomplete combustion in turbines [50]. These emissions have not been considered in "gas losses" in this study but were modelled from the natural gas consumption (ref. section 3.1.3).

In general, the Norwegian methane emissions are very low compared to other countries which is, among

[15] Data on processing and transport has been provided by Gassco for this study. The data was not provided as energy demand (except from electricity) but as CO_2 emissions from combustion and CH_4 emissions from combustion, fugitives, and flaring. To fit to the model used in this study, a back-calculation of the emission data into energy demand took place with the default factors in section 3.1.3. It was assumed that all emissions came from natural gas, for this reason, no data for diesel is given in the table.

[16] Losses for gas transport are included in the step "processing".

others, due to their tax system. One tonne of methane is currently priced at NOK 8.76 [51] per standard m³ (= 0.79 €/m³ or about 975 €/t).

Table 11: Comparison of Input Data for Norwegian Gas Production

Parameter	Thinkstep 2017 [8]	DBI 2020 (this study)	DBI 2020 (this study)	Equinor 2019 [52, p. 31]	Unit
	2015	2015	2018	2018	
Electricity	2.927	2.713	3.294	-	kJ/MJ
Diesel fuel	1.991	1.662	1.529	-	kJ/MJ
Natural gas	21.795	20.536	20.465	-	kJ/MJ
Methane losses	0.0046 wt.%	-	-	0.04 vol.%	see row
Gas losses	-	0.0031 %	0.0044 %	-	see row

3.1.9 Russia, Belarus and Ukraine

Data for gas production and gas transport in Russia and from Russia to CE were provided by the operator Gazprom [53] with the help of data collection sheets. Data for gas losses and energy demand of gas transport in Belarus were included in the data delivered by Gazprom for the Belarussian corridor.

Data for gas transport in the Ukraine was provided by transmission system operator of Ukraine (TSOUA) by means of data collection sheets [54].

Gas storage facilities in Russia are not used for natural gas that is exported to Central Europe [55], but for internal demand management of consumers in Russia. Therefore, gas storage in Russia was not considered. However, gas storage facilities in the Ukraine are used for transited gas and needed to be included in the consideration. TSOUA is not an operator of gas storages in Ukraine, thus, could not provide any data on these assets. Data available for Russian gas storages were therefore applied as an assumption [17].

Table 12 to Table 14 show all input data.

[17] According to Gazprom, methane emissions of underground storage in 2019 amounted to 0.03 % of the underground gas storage volumes [56].

Table 12: Input Data for Russia 1 (Ukrainian Corridor)

Parameter	**Value**				**Unit**	**Source/ Remark**
	2015	**2016**	**2017**	**2018**		
Gas production						
Natural gas	12.405	12.795	13.477	14.899	kJ/MJ	[53]
Electricity	0.113	0.112	0.106	0.101	kJ/MJ	[53]
Diesel fuel	0	0	0	0	kJ/MJ	[53]
Total	12.519	12.907	13.583	15.000	kJ/MJ	-
Gas losses	0.280	0.254	0.219	0.195	kJ/MJ	[53]
Flaring	2.796	2.200	1.986	1.593	kJ/MJ	[53]
Gas processing						
Natural gas	included in gas production data				kJ/MJ	[53]
Electricity	included in gas production data				kJ/MJ	[53]
Diesel fuel	included in gas production data				kJ/MJ	[53]
Total	included in gas production data				kJ/MJ	-
Gas losses	included in gas production data				kJ/MJ	[53]
CO_2 vented	1.08E-07	1.08E-07	1.08E-07	1.08E-07	kgCO_2/MJ	[57]
Gas transport to CE and storage outside CE						
Natural gas	1.47E-02	1.55E-02	1.78E-02	1.93E-02	kJ/(MJ*km)	[53]
Electricity	1.96E-03	2.64E-03	3.44E-03	3.38E-03	kJ/(MJ*km)	[53]
Diesel fuel	0	0	0	0	kJ/(MJ*km)	[53]
Total	1.67E-02	1.81E-02	2.12E-02	2.27E-02	kJ/(MJ*km)	-
Gas losses	8.44E-04	8.18E-04	8.58E-04	8.63E-04	kJ/(MJ*km)	[53] (17)
Flaring	0	7.54E-05	1.51E-04	2.26E-04	kJ/(MJ*km)	[53]
Pipeline length to CE border	4,725	4,725	4,725	4,725	km	[53]
Pipeline length to German border	5,485	5,485	5,485	5,485	km	[45, p. 71, 53, 58]

Table 13: Input Data for Russia 2 (Belarusian Corridor)

Parameter	Value				Unit	Source/ Remark
	2015	2016	2017	2018		
Gas production						
Natural gas	12.605	12.935	13.698	15.125	kJ/MJ	[53]
Electricity	0.113	0.111	0.105	0.100	kJ/MJ	[53]
Diesel fuel	0	0	0	0	kJ/MJ	[53]
Total	12.718	13.046	13.802	15.225	kJ/MJ	-
Gas losses	0.288	0.260	0.223	0.198	kJ/MJ	[53]
Flaring	2.870	2.245	2.022	1.620	kJ/MJ	[53]
Gas processing						
Natural gas	included in gas production data				kJ/MJ	[53]
Electricity	included in gas production data				kJ/MJ	[53]
Diesel fuel	included in gas production data				kJ/MJ	[53]
Total	included in gas production data				kJ/MJ	-
Gas losses	included in gas production data				kJ/MJ	[53]
Flaring	included in gas production data				kJ/MJ	[53]
CO_2 vented	1.08E-07	1.08E-07	1.08E-07	1.08E-07	$kgCO_2/MJ$	[57]
Gas transport to CE						
Natural gas	2.08E-02	2.05E-02	2.35E-02	2.53E-02	kJ/(MJ*km)	[53]
Electricity	1.36E-03	1.23E-03	1.21E-03	1.25E-03	kJ/(MJ*km)	[53]
Diesel fuel	0	0	0	0	kJ/(MJ*km)	[53]
Total	2.21E-02	2.17E-02	2.47E-02	2.65E-02	kJ/(MJ*km)	-
Gas losses	9.32E-04	8.69E-04	8.94E-04	7.54E-04	kJ/(MJ*km)	[53]
Flaring	1.00E-03	2.00E-03	1.00E-03	1.00E-03	kJ/(MJ*km)	[53]
Pipeline length to CE border	3,995	3,995	3,995	3,995	km	[53]
Pipeline length to German border	4,679	4,679	4,679	4,679	km	[53, 59]

Table 14: Input Data for Russia 3 (Northern Corridor)

Parameter	Value				Unit	Source/ Remark
	2015	2016	2017	2018		
Gas production						
Natural gas	12.402	12.603	13.350	14.543	kJ/MJ	[53]
Electricity	0.113	0.111	0.105	0.100	kJ/MJ	[53]
Diesel fuel	0	0	0	0	kJ/MJ	[53]
Total	12.515	12.714	13.455	14.643	kJ/MJ	-
Gas losses	0.279	0.252	0.216	0.191	kJ/MJ	[53]
Flaring	2.786	2.181	1.956	1.561	kJ/MJ	[53]
Gas processing						
Natural gas	included in gas production data				kJ/MJ	[53]
Electricity	included in gas production data				kJ/MJ	[53]
Diesel fuel	included in gas production data				kJ/MJ	[53]
Total	included in gas production data				kJ/MJ	-
Gas losses	included in gas production data				kJ/MJ	[53]
Flaring	included in gas production data				kJ/MJ	[53]
CO_2 vented	1.08E-07	1.08E-07	1.08E-07	1.08E-07	$kgCO_2/MJ$	[57]
Gas transport to CE						
Natural gas	1.88E-02	1.74E-02	1.96E-02	1.96E-02	kJ/(MJ*km)	[53]
Electricity	1.48E-03	1.31E-03	1.26E-03	1.22E-03	kJ/(MJ*km)	[53]
Diesel fuel	0	0	0	0	kJ/(MJ*km)	[53]
Total	2.03E-02	1.87E-02	2.09E-02	2.08E-02	kJ/(MJ*km)	-
Gas losses	7.23E-04	6.86E-04	6.59E-04	5.55E-04	kJ/(MJ*km)	[53]
Flaring	1.00E-03	2.00E-03	1.00E-03	1.00E-03	kJ/(MJ*km)	[53]
Pipeline length to CE border	4,166	4,166	4,166	4,166	km	[53]
Pipeline length to Germany	4,166	4,166	4,166	4,166	km	[53]

Compared to the previous study [3], differences occur in the specific gas consumption for gas transport. This is due to a methodological change in the data collection by the operator Gazprom, a former double counting has been avoided. With the new methodology, the data for the previous years are also lower as Table 15 shows.

Table 15: Specific Gas Consumption of the Russian Export Corridors

Year	Ukrainian Corridor	Belarussian Corridor	Northern Corridor	Unit	Source
Data from previous study [3] for comparison					
2012	30.3	30.3	20.5	m³/Mio.m³*km	[28]
2013	29.5	29.5	20.5	m³/Mio.m³*km	[28]
2014	24.2	24.2	20.5	m³/Mio.m³*km	[28]
2012	0.030	0.030	0.021	kJ/MJ*km	Conversion of 2016 data
2013	0.030	0.030	0.021	kJ/MJ*km	
2014	0.024	0.024	0.021	kJ/MJ*km	
Data provided for the study at hand					
2012	0.023	0.027	0.024	kJ/MJ*km	[53]
2013	0.023	0.026	0.019	kJ/MJ*km	[53]
2014	0.019	0.022	0.019	kJ/MJ*km	[53]
2015	0.018	0.021	0.019	kJ/MJ*km	[53]
2016	0.019	0.021	0.017	kJ/MJ*km	[53]
2017	0.021	0.024	0.020	kJ/MJ*km	[53]
2018	0.024	0.025	0.020	kJ/MJ*km	[53]
2019	0.030	0.030	0.021	kJ/MJ*km	[53]

Table 8 shows data on Russian methane emissions from different data sources. The number reported for methane emissions of gas production in the NIR is well in line with the value reported to the Russian Federal State Statistics Service [60]. However, the number for gas transport is much higher in the NIR than the one reported to Russian Federal State Statistics Service.

The methane tracker of the IEA [61] includes significantly higher data for the Russian gas production, but significantly lower data for gas transport. This data was not considered for the calculations in this study for two reasons:

- The methane tracker does not consider the Russian export corridors like this study but considers Russian gas production and gas transport in total.
- The methane tracker is not based on Russian data, but on studies which were carried out in the USA and were adjusted for other countries [62]. However, the adjustment might not reflect country-specific situations accurately. This has also been remarked by other countries like Norway. Nevertheless, the IEA is willing to include other data, for example, from measurement campaigns carried out in these countries [63].

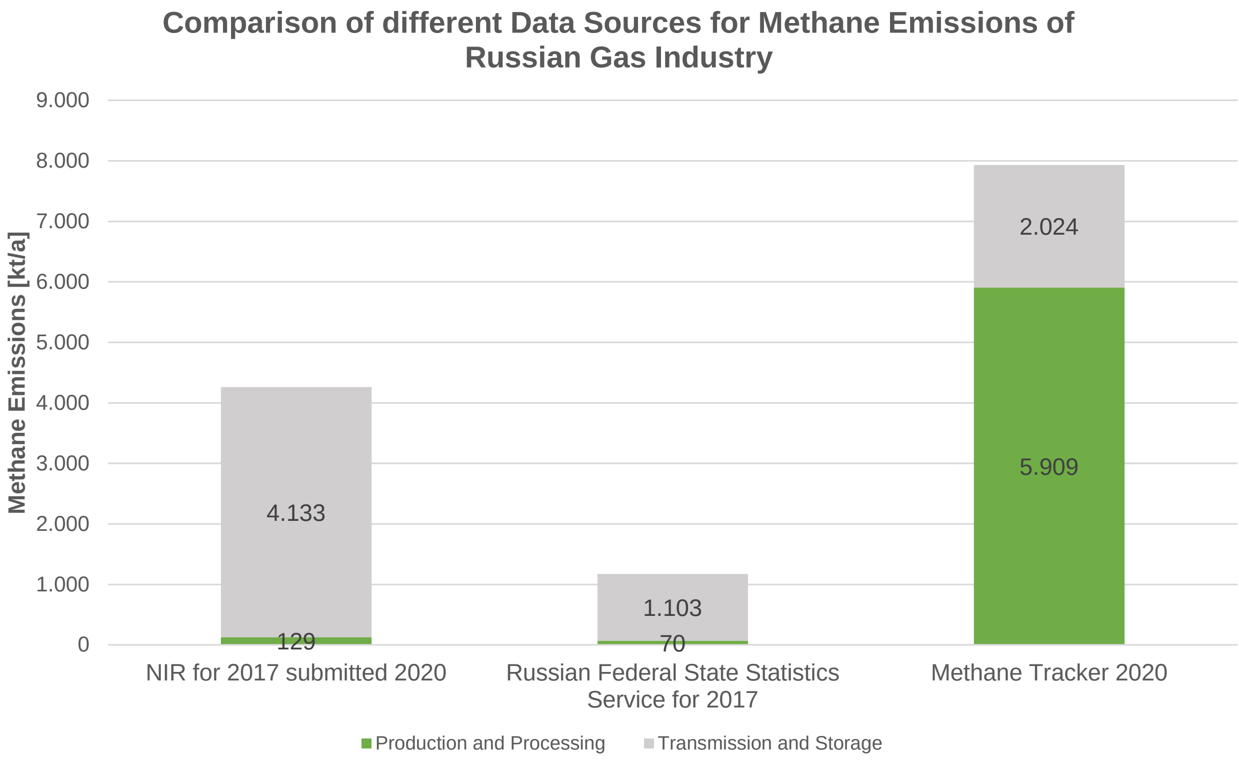

Figure 6: Comparison of Values for Methane Emissions of Russian Gas Industry

Gazprom publishes its GHG emissions in yearly environmental reports, which are audited by KPMG [64]. The figures in the report are aggregated figures for the company. For this reason, they could not be used directly for this study. However, the aggregated basis shows a good correlation to the figures provided by Gazprom for this study.

The international news organization Reuters reported large leaks found by satellite on the Russian Yamal-Pipeline in 2019 [65]. According to the operator Gazprom, these leaks were repair work activities (vented emissions). Such emissions are planned and necessary for safety reasons. The amount of vented gas is determined and included in the numbers that Gazprom reports to authorities. This was also confirmed by Kayrros [66]. This example shows that satellite data can help identifying leaks, but it is important to verify the sources together with the operator to avoid misinterpretation.

Since methane is classified as a pollutant in Russia (see list of pollutants under state control, No. 33 [67]), methane emissions have to be recorded and reported to the authorities. The methane emissions are estimated with the annual federal statistical data sheet № 2-TP (air) [68]. The completed forms are sent to the Russian Federal State Statistic Service. This published data is the basis to charge an environmental tax to the responsible polluter. The completed forms and charged environmental tax amounts are checked and verified by the Russian Federal Supervisory Natural Resources Management Service [69] during regular inspections and audits. On the website of the Russian Federal State Statistics Service [60] the hydrocarbon emissions of different sectors are published regularly.

3.2 Modelling

3.2.1 Comparison of LCA software

In order to compare the LCA results calculated with the different LCA software GHGenius and GaBi, results were calculated for one dataset with the same input data using both LCA models. For that comparison, the carbon footprint of the example functional unit “natural gas (pipeline) produced in Norway, distributed in Central Europe” was calculated. Data collected for the year 2014 from [3] was used as input dataset. The calculation of the CF yields the results displayed in Table 16. The deviation of the results due to the use of different models is less than 5 %. The reasons for the small differences in the results originate from different background datasets like electricity mixes, the value chain of the provision of diesel and other fuels, small differences in the equipment emission factors (e.g. exhaust of gas turbines) and characteristic values of gas, like net calorific value or molar composition. Considerable deviations occur in the step “Transport to CE border”. The Result from the GaBi model is about 25 % lower than the result from GHGenius, which might result from different assumptions for infrastructure emissions. However, other value chain elements (e.g. production) showed higher emissions in the GaBi model, which leads to the conclusions, that elements are just combined differently in GHGenius.

Table 16: Result of Comparative Modelling with GHGenius and GaBi for Natural Gas Produced in Norway, Distributed in CE in 2014

	GHGenius	GaBi	Unit
Production in Norway	1,867	2,026	gCO_2e/GJ
Processing in Norway	332	287	gCO_2e/GJ
Storage in Norway	0	0	gCO_2e/GJ
Transport to the border of CE	1,629	1,200	gCO_2e/GJ
Transport, Storage and Distribution in CE	1,801	1,843	gCO_2e/GJ
Sum	**5,629**	**5,356**	**gCO_2e/GJ**
Difference GaBi to GHGenius		-4.86	%

3.2.2 Modelling in GaBi

GaBi is a LCA software based on modularity. Both systems, “Natural Gas distributed in CE” and “Natural Gas distributed in Germany”, were set up in GaBi as overall plans. They are presented in Figure 7 and Figure 8, respectively. Each plan consists of additional plans und processes. These plans and processes are modules containing specific data for specific life cycle phases. They can consist of plans and processes themselves leading to a hierarchical structure of the system. The data comes from the GaBi Professional Database, literature or industry. To build up the whole system, the modules are connected via material and energy flows.

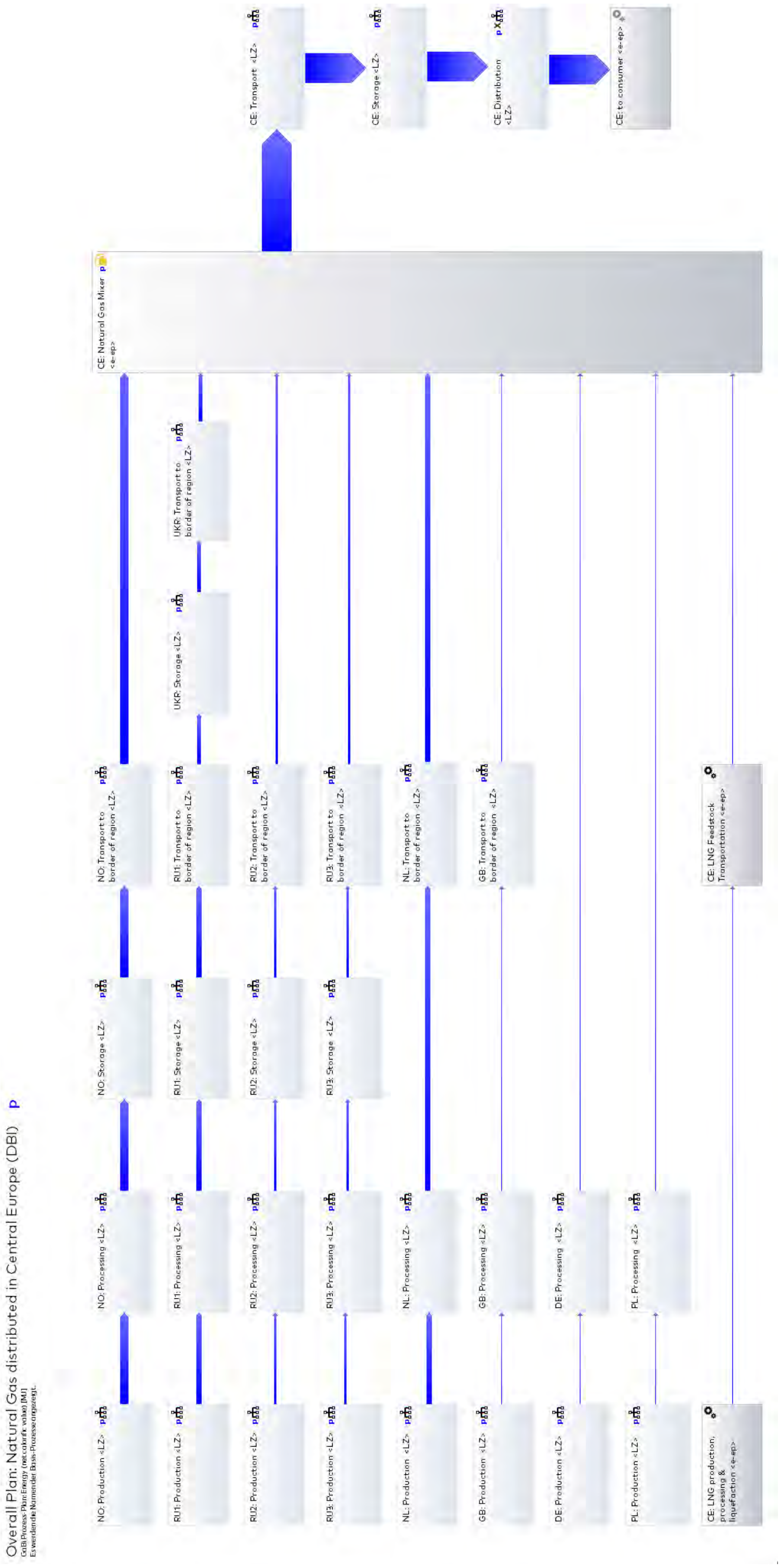

Figure 7: GaBi Model of Natural Gas Distributed in Central Europe (Sankey Diagram)

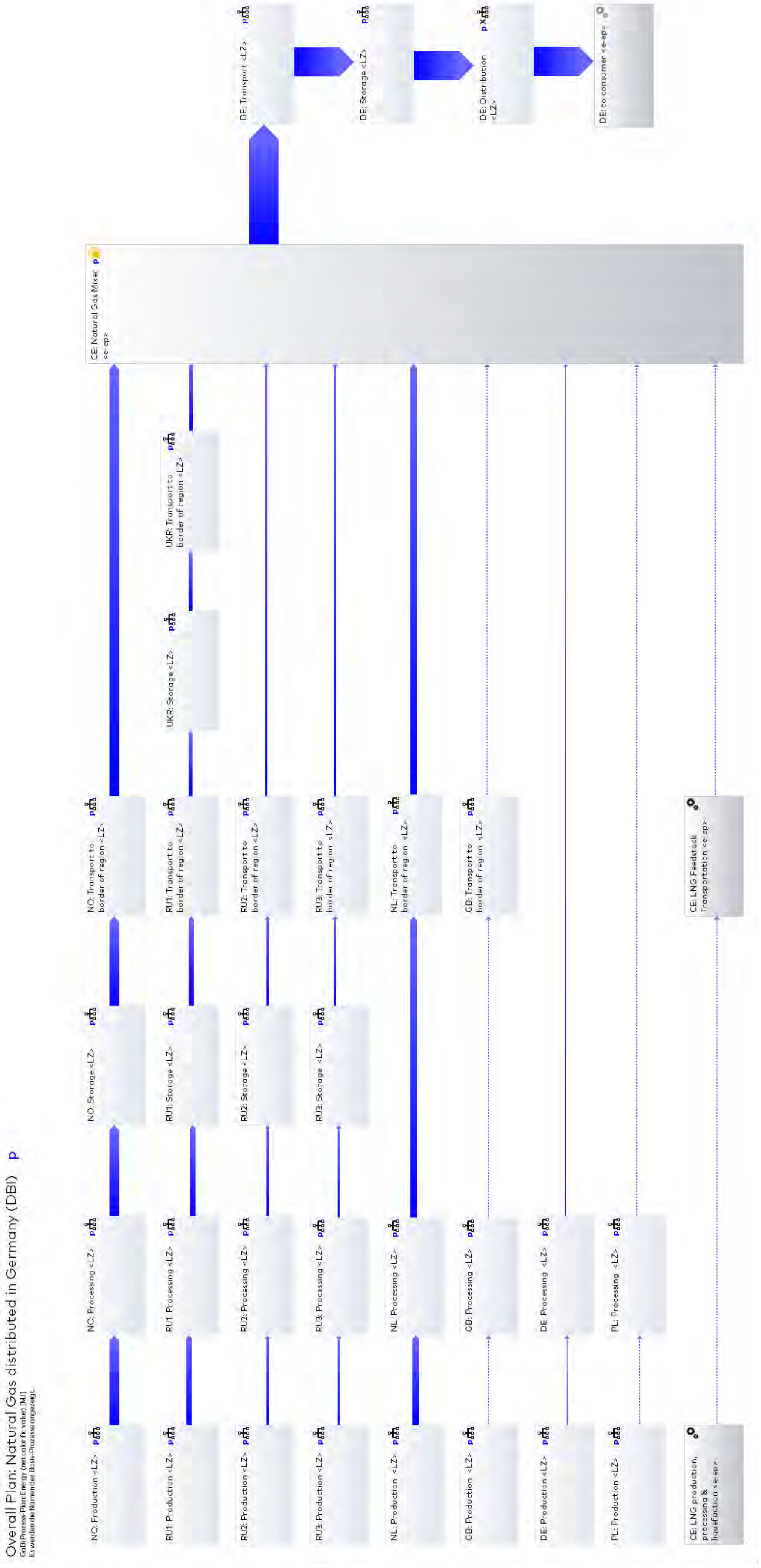

Figure 8: GaBi Model of Natural Gas Distributed in Germany (Sankey Diagram)

3.3 Data Calculation

With the help of the LCA software GaBi, all GHG emissions were calculated for both systems. In the following sections, only the results for the most important GHGs (CO_2, CH_4 and N_2O) are presented. The impact assessment in chapter 4 took all GHG emissions into account, however, differences are negligible.

3.3.1 Natural Gas Distributed in Central Europe

The following GHG amounts were calculated for natural gas that is distributed in CE:

Table 17: GHG Emissions of Natural Gas Distributed in CE [g/GJ (NCV)]

	CO_2	CH_4	N_2O
2015			
Production	1,715.53	11.74	0.03
Processing	228.32	0.54	0.00
Transport and Storage outside CE	1,903.66	26.65	0.04
Transport, Storage and Distribution in CE	284.81	64.82	0.01
Total	**4,132.32**	**103.75**	**0.08**
2016			
Production	1,645.72	10.18	0.03
Processing	221.20	0.49	0.00
Transport and Storage outside CE	2,157.77	29.03	0.04
Transport, Storage and Distribution in CE	283.67	63.42	0.01
Total	**4,308.36**	**103.12**	**0.08**
2017			
Production	1,707.22	10.46	0.03
Processing	212.41	0.42	0.00
Transport and Storage outside CE	2,461.42	30.82	0.05
Transport, Storage and Distribution in CE	285.15	62.69	0.01
Total	**4,666.20**	**104.39**	**0.09**
2018			
Production	1,887.35	8.60	0.03
Processing	182.39	0.37	0.00
Transport and Storage outside CE	2,765.20	29.90	0.05
Transport, Storage and Distribution in CE	288.05	64.13	0.01
Total	**5,122.99**	**103.00**	**0.09**

In order to determine the GHG emissions for a specific country of origin, the natural gas supply structure in the GaBi model was modified: It is assumed that the country under consideration is the only supplier of a region. Table 18 shows the GHG emissions for natural gas distributed in CE but produced in Germany, the Netherlands, Norway, or Russia as an example for the year 2018. The results for the remaining years are displayed in Annex 2.

Table 18: GHG Emissions of Natural Gas Distributed in CE and Produced in Germany, the Netherlands, Norway, or Russia in 2018 [g/GJ(NCV)]

	CO_2	CH_4	N_2O
Germany			
Production	3,536.99	6.06	0.11
Processing	3,625.83	2.01	0.02
Transport and Storage outside CE	0.00	0.00	0.00
Transport, Storage and Distribution in CE	288.05	64.13	0.01
Total	**7,450.87**	**72.20**	**0.14**
The Netherlands			
Production	2,066.83	9.72	0.04
Processing	229.02	0.46	0.00
Transport and Storage outside CE	40.84	1.29	0.00
Transport, Storage and Distribution in CE	288.05	64.13	0.01
Total	**2,624.74**	**75.60**	**0.05**
Norway			
Production	1,581.01	3.25	0.03
Processing	93.01	0.59	0.00
Transport and Storage outside CE	252.98	0.29	0.00
Transport, Storage and Distribution in CE	288.05	64.13	0.01
Total	**2,215.05**	**68.26**	**0.04**
Russia			
Production	1,057.70	4.27	0.02
Processing	0.12	0.00	0.00
Transport and Storage outside CE	5,659.17	65.30	0.11
Transport, Storage and Distribution in CE	288.05	64.13	0.01
Total	**7,005.04**	**133.70**	**0.14**

3.3.2 Natural Gas Distributed in Germany

Table 19 shows the GHG amounts calculated for natural gas that is distributed in Germany and Table 20 shows these results split by the different countries of origin.

The same GaBi model was used for determining the results for Germany, however, some adjustments were necessary compared to the calculations for CE:

1. The electricity mix of CE was replaced by the corresponding mix for Germany.
2. For the transport, storage and distribution within Germany, the German values were used instead of average values for all countries in CE.
3. The transport distances were adjusted, so that the distance up to the German border was used and not the distance to the EU border.
4. The natural gas supply structure was replaced by the one determined for Germany (ref. section 3.1.4).

Table 19: GHG Emissions of Natural Gas Distributed in Germany [g/GJ(NCV)]

	CO_2	CH_4	N_2O
2015			
Production	1,455.41	6.36	0.03
Processing	275.68	0.51	0.00
Transport and Storage outside GER	1,978.48	28.80	0.04
Transport, Storage and Distribution in GER	172.00	30.35	0.00
Total	**3,881.57**	**66.02**	**0.07**
2016			
Production	1,413.50	6.08	0.03
Processing	282.84	0.49	0.00
Transport and Storage outside GER	2,315.20	32.34	0.04
Transport, Storage and Distribution in GER	171.90	28.03	0.00
Total	**4,183.44**	**66.94**	**0.08**
2017			
Production	1,459.18	6.12	0.03
Processing	250.13	0.36	0.00
Transport and Storage outside GER	2,706.49	35.38	0.05
Transport, Storage and Distribution in GER	171.88	27.36	0.00
Total	**4,587.68**	**69.22**	**0.08**
2018			
Production	1,476.35	5.59	0.03
Processing	229.35	0.36	0.00
Transport and Storage outside GER	2,976.63	34.37	0.06
Transport, Storage and Distribution in GER	171.92	28.15	0.00
Total	**4,854.25**	**68.47**	**0.09**

Table 20: GHG Emissions of Natural Gas Distributed in Germany and Produced in Germany, the Netherlands, Norway, or Russia in 2018 [g/GJ (NCV)]

	CO_2	CH_4	N_2O
Germany			
Production	3,523.14	6.03	0.11
Processing	3,611.63	2.00	0.02
Transport and Storage outside GER	0.00	0.00	0.00
Transport, Storage and Distribution in GER	171.92	28.15	0.00
Total	**7,306.69**	**36.18**	**0.13**
The Netherlands			
Production	2,058.11	9.68	0.04
Processing	228.08	0.46	0.00
Transport and Storage outside GER	27.35	0.85	0.00
Transport, Storage and Distribution in GER	171.92	28.15	0.00
Total	**2,485.46**	**39.14**	**0.04**
Norway			
Production	1,469.64	2.90	0.03
Processing	92.65	0.59	0.00
Transport and Storage outside GER	251.99	0.28	0.00
Transport, Storage and Distribution in GER	171.92	28.15	0.00
Total	**1,986.20**	**31.92**	**0.03**
Russia			
Production	1,059.37	5.89	0.02
Processing	0.12	0.00	0.00
Transport and Storage outside GER	6,367.23	75.18	0.12
Transport, Storage and Distribution in GER	172.00	28.15	0.00
Total	**7,598.72**	**109.22**	**0.14**

4 Impact Assessment

This chapter evaluates the potential effects of the emitted greenhouse gases on climate change. This has been achieved by the conversion of the calculated greenhouse gas emissions into CO_2 equivalents (ref. section 2.5), and, therefore, expressing the carbon footprint [7, p. 62].

The GaBi software calculated the greenhouse gas emissions and converted them into CO_2 equivalents according to the LCIA method described in section 2.5. The results are shown in the following sections.

4.1 Natural Gas Distributed in Central Europe

The following CF is calculated for natural gas that is distributed in CE:

Table 21: Carbon Footprint of Natural Gas Distributed in CE [gCO2e/GJ (NCV)]

	2015	2016	2017	2018
Production	2,014.11	1,905.78	1,974.55	2,108.39
Processing	242.48	234.16	223.54	192.13
Transport and Storage outside CE	2,580.70	2,895.29	3245.79	3,528.17
Transport, Storage and Distribution in CE	1,907.27	1,871.07	1,854.41	1,893.15
Total	**6,744.56**	**6,906.3**	**7,298.29**	**7,721.84**

For some applications of natural gas, the CF is preferred in a different unit. Table 22 shows the results of Table 21 in gCO_2e/kWh[18].

Table 22: Carbon Footprint of Natural Gas Distributed in CE [gCO_2e/kWh (NCV)]

[18] The results are converted by dividing the values in Table 21 by 277.778 (=conversion of GJ into kWh).

	2015	2016	2017	2018
Production	7.25	6.86	7.11	7.59
Processing	0.87	0.84	0.80	0.69
Transport and Storage outside CE	9.29	10.42	11.68	12.70
Transport, Storage and Distribution in CE	6.87	6.74	6.68	6.82
Total	**24.28**	**24.86**	**26.27**	**27.80**

Figure 9 shows the contribution of individual GHGs to the total CF from Table 22.

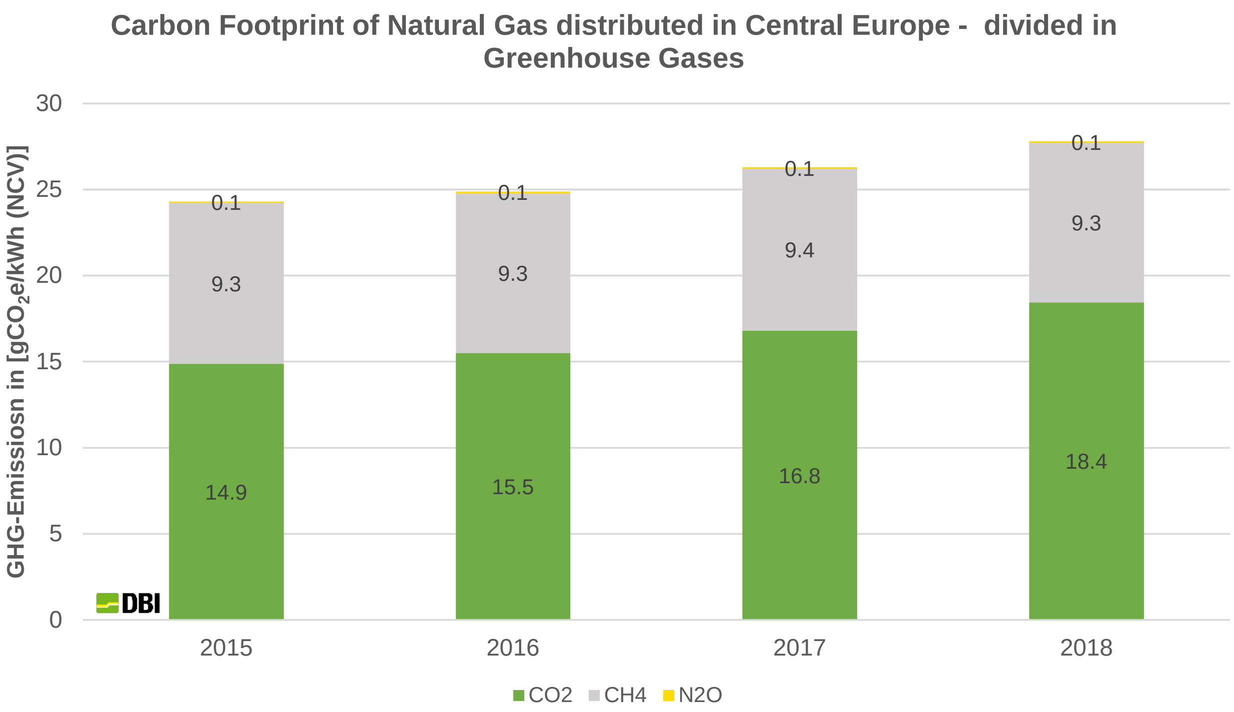

Figure 9: Contribution of different GHG to the Carbon Footprint of natural gas distributed in Central Europe in gCO_2e/kWh (NCV)

In order to determine the CF for a specific county of origin, the natural gas supply structure in the GaBi model was modified so that the country under consideration was presumed to be the only supplier of the region. Table 23 shows the CF for natural gas produced in Germany, the Netherlands, Norway, or Russia respectively and distributed in Central Europe as an example for the year 2018. The results for the remaining years are displayed in Annex 4.

Table 23: Carbon Footprint of Natural Gas Distributed in CE and Produced in Germany, the Netherlands, Norway, or Russia in 2018 [gCO2e/GJ(NCV)]

	Germany	the Netherlands	Norway	Russia
Production	3,728.74	2,318.70	1,665.05	1,170.45
Processing	3,682.91	241.30	108.32	0.12
Transport and Storage outside CE	0.00	73.22	261.60	7,324.61
Transport, Storage and Distribution in CE	1,893.15	1,893.15	1,893.15	1,893.15
Total	**9,304.80**	**4,526.37**	**3,928.12**	**10,388.33**

4.2 Natural Gas Distributed in Germany

The following CF is calculated for natural gas that is distributed in Germany:

Table 24: Carbon Footprint of Natural Gas Distributed in Germany [gCO2e/GJ(NCV)]

	2015	2016	2017	2018
Production	1,620.90	1,572.26	1,619.17	1,623.04
Processing	289.07	295.92	259.77	238.96
Transport and Storage outside GER	2,710.16	3,136.81	3,606.94	3,853.24
Transport, Storage and Distribution in GER	931.81	873.57	856.74	876.75
Total	**5,551.94**	**5,878.56**	**6,342.62**	**6,591.99**

In Table 25 the results are again converted to gCO_2e/kWh and Table 26 shows the results split by the different countries of origin.

Table 25: Carbon Footprint of Natural Gas Distributed in Germany [$gCO_2e/kWh(NCV)$]

	2015	2016	2017	2018
Production	5.84	5.66	5.83	5.84
Processing	1.04	1.07	0.94	0.86
Transport and Storage outside GER	9.76	11.29	12.98	13.87
Transport, Storage and Distribution in GER	3.35	3.14	3.08	3.16
Total	**19.99**	**21.16**	**22.83**	**23.73**

Table 26: Carbon Footprint of Natural Gas Distributed in Germany and Produced in Germany, the Netherlands, Norway, or Russia in 2018 [gCO2e/GJ(NCV)]

	Germany	the Netherlands	Norway	Russia
Production	3,714.14	2,308.94	1,544.78	1,212.41
Processing	3,668.48	240.31	107.90	0.12
Transport and Storage outside GER	0.00	48.87	260.57	8,283.26
Transport, Storage and Distribution in GER	876.75	876.75	876.75	876.75
Total	**8,259.37**	**3,474.87**	**2,790.00**	**10,372.54**

5 Interpretation

The results of the LCIA (Chapter 4) were interpreted according to the following topics:

- Identification of relevant findings and significant issues (contribution of different GHG to the CF, contribution of different process steps to the CF, effect of the metric on the CF)
- Assumptions and limitations
- Data quality (timeliness, completeness, consistency, etc.).

5.1 Relevant Findings of the Study

5.1.1 Results for Natural Gas Distributed in Central Europe or Germany

- The carbon footprint of natural gas that is distributed in Central Europe was calculated to be **7,722 gCO_2e/GJ (NCV) or 28 gCO_2e/kWh (NCV) in 2018.**
- The carbon footprint of natural gas that is distributed in Germany was calculated to be **6,592 gCO_2e/GJ (NCV) or 24 gCO_2e/kWh (NCV) in 2018,** thus, is lower than the CF of natural gas distributed in CE. This is mainly because of the different natural gas supply structures that lead to deviations in the contribution of individual producer countries.
- In CE, 103.0 gCH_4/GJ (NCV) contribute to the CF result in 2018, which corresponds to a methane loss of 0.5 % in relation to the gas distributed in CE[19].
- In DE, 68.5 gCH_4/GJ (NCV) contribute to the CF result in 2018, which corresponds to a methane loss of 0.3 % in relation to the gas distributed in DE[19].
- The main contribution to the total CF is the transport and storage of natural gas to the border of CE (> 45 %). This is due to the large transport distance in particular for Russian gas (about 4,000 km), but also for Norwegian gas (> 900 km). About 27 % of the CF occurs in the production stage and about 24 % of the CF is related to transport, storage and distribution within CE (Figure 10).

[19] Calculated on the basis of the mass of CH4 in relation to the mass of a GJ of distributed gas.

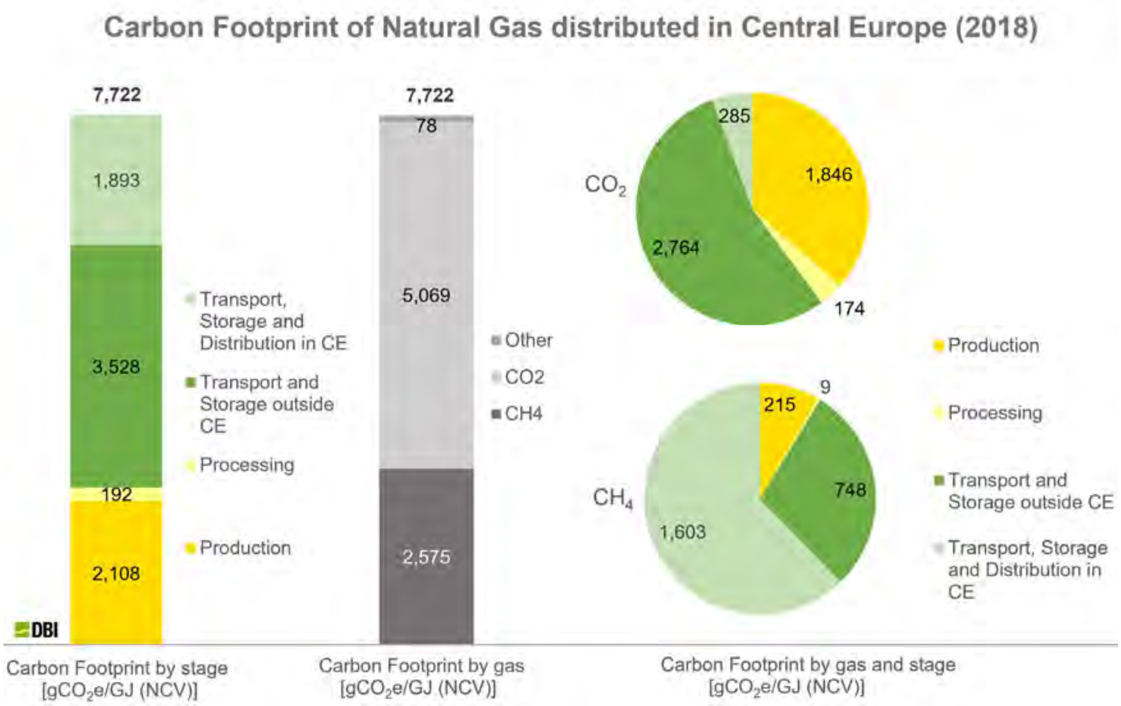

Figure 10: Breakdown of the Carbon Footprint of Natural Gas Distributed in CE by Stage and Greenhouse Gas in 2018

- Compared to the results of the previous study, the results of this study are significantly lower in 2015 (previous study: 7,939 gCO_2e/GJ (NCV) or 29 gCO_2e/kWh (NCV) in 2014, vs. 6,745 gCO_2e/GJ (NCV) or 24 gCO_2e/kWh (NCV) this study for the year 2015), but rise until 2018 to 7,722 gCO_2e/GJ (NCV) or 28 gCO_2e/kWh (NCV).
  - The previous study showed that inclusion of up-to-date best available data instead of assumptions or literature values leads to significant reductions of the results. This was also recognized in this study. In contrast to the previous study, data updates were made, in particular for Norway and Ukraine.
- The increase of the CF between 2015 and 2018 is due to:
  - The share of natural gas from Russia is increasing. Long transport distances are responsible for a higher CF of natural gas produced in Russia compared to other producing countries, even though methane emissions were reduced in Russia from 2014 to 2018 (ref. section 3.1.9).
  - Results for the individual producer countries rose slightly between 2015 and 2018 (ref. section 5.1.2).
- CO_2 is the main contributing GHG in all years, followed by CH_4. Other GHG are insignificant (Figure 11).

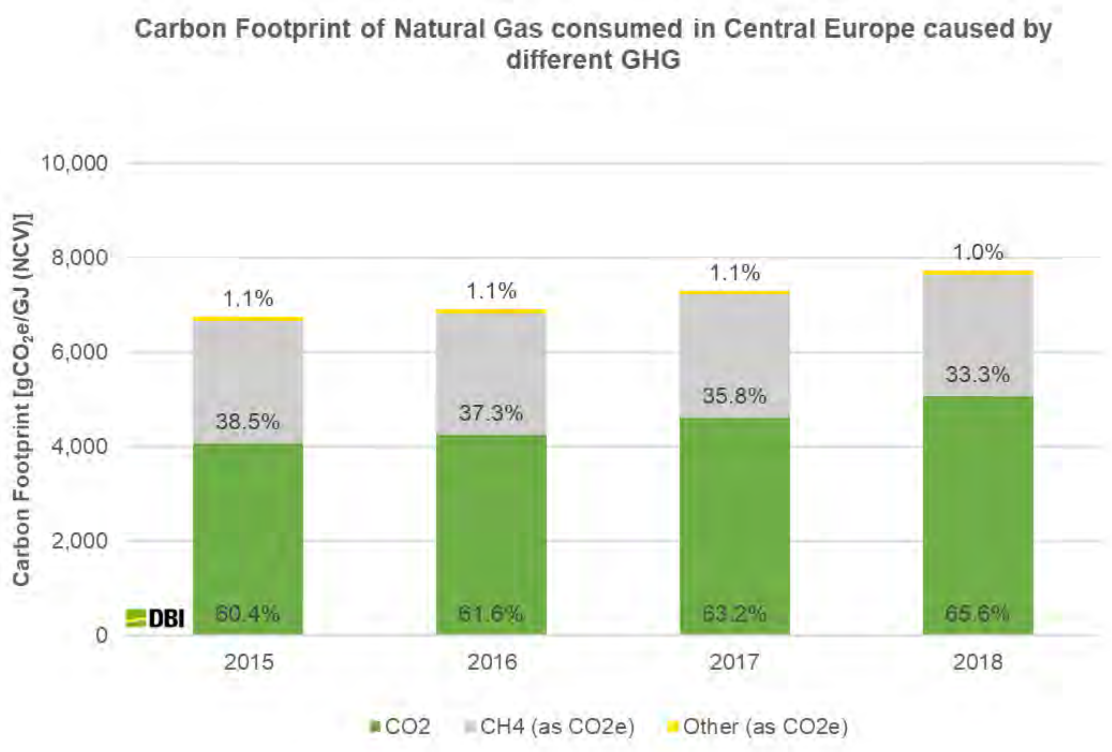

Figure 11: Contribution of Different GHG to the Total Carbon Footprint

- Deviations occurring from applying different LCA models (GHGenius and GaBi) were found to be small (< 5 %) and originate from the use of different background datasets (e.g. electricity and equipment emission factors, and characteristic values of gas).
  - Considerable deviations occurred in the step “Transport to the border of CE”. The result from the GaBi model is about 25 % lower than the result from GHGenius, which might be caused by different assumptions for infrastructure emissions. However, other value chain elements (e.g. gas production) showed higher emissions in the GaBi model, which led to the conclusion, that elements are combined differently in GHGenius.
- The impact of all GHG was assessed with the GWP100 values from the 4th Assessment Report of the IPCC, which is currently the basis for national inventories of GHG. The metric used for determining the impact on climate change was found to be important (Figure 12): The AR5 values for GWP_{100} with ccfb[20] increase the results for the CF calculated in this study by 14.7 %. The AR5 values for GWP_{100} without ccfb[21] lead to an increase in the CF of 6.6 %. The AR5 values for GTP_{100}[22] reduce the results by 25.4 %.

[20] GWP_{100} (CH_4) = 36
[21] GWP_{100} (CH_4) = 30
[22] GTP_{100} (CH_4) = 6

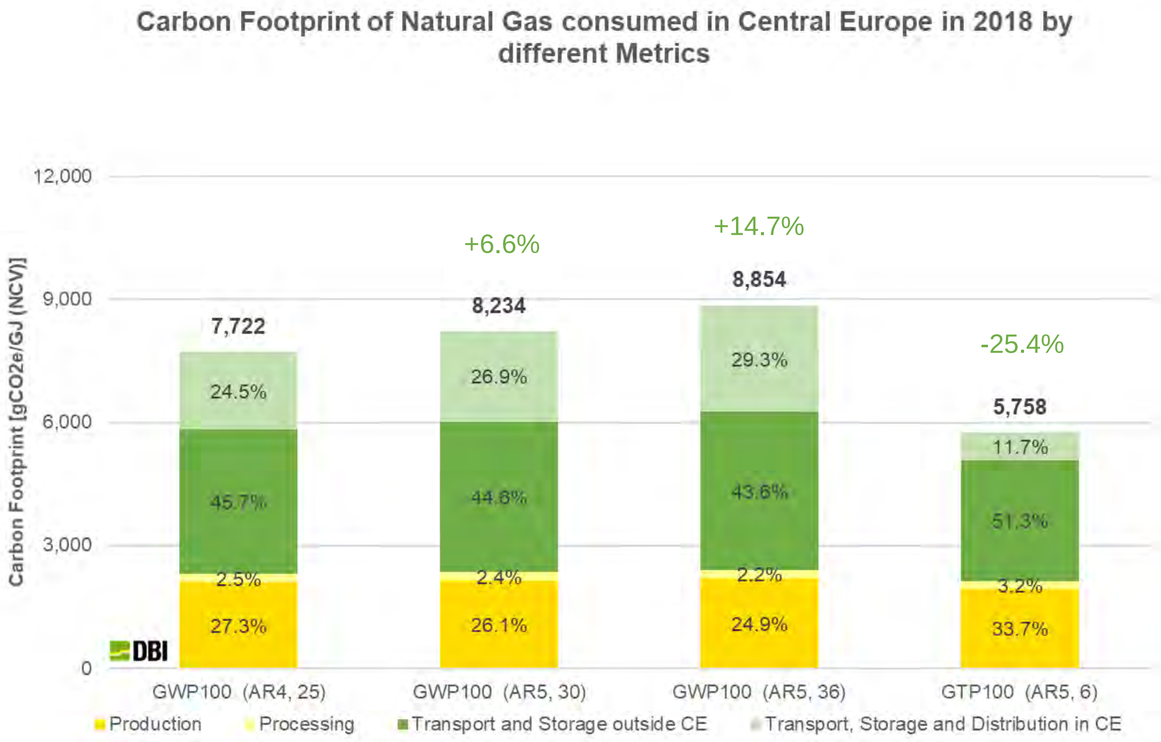

Figure 12: Effect of the Applied Metric on the Total Carbon Footprint

5.1.2 Results for Individual Producer Countries

- Figure 13 shows the results for the CF of natural gas distributed in CE but produced in individual countries. Norwegian natural gas has the lowest CF (3,928 gCO_2e/GJ (NCV) or 14 gCO_2e/kWh (NCV).

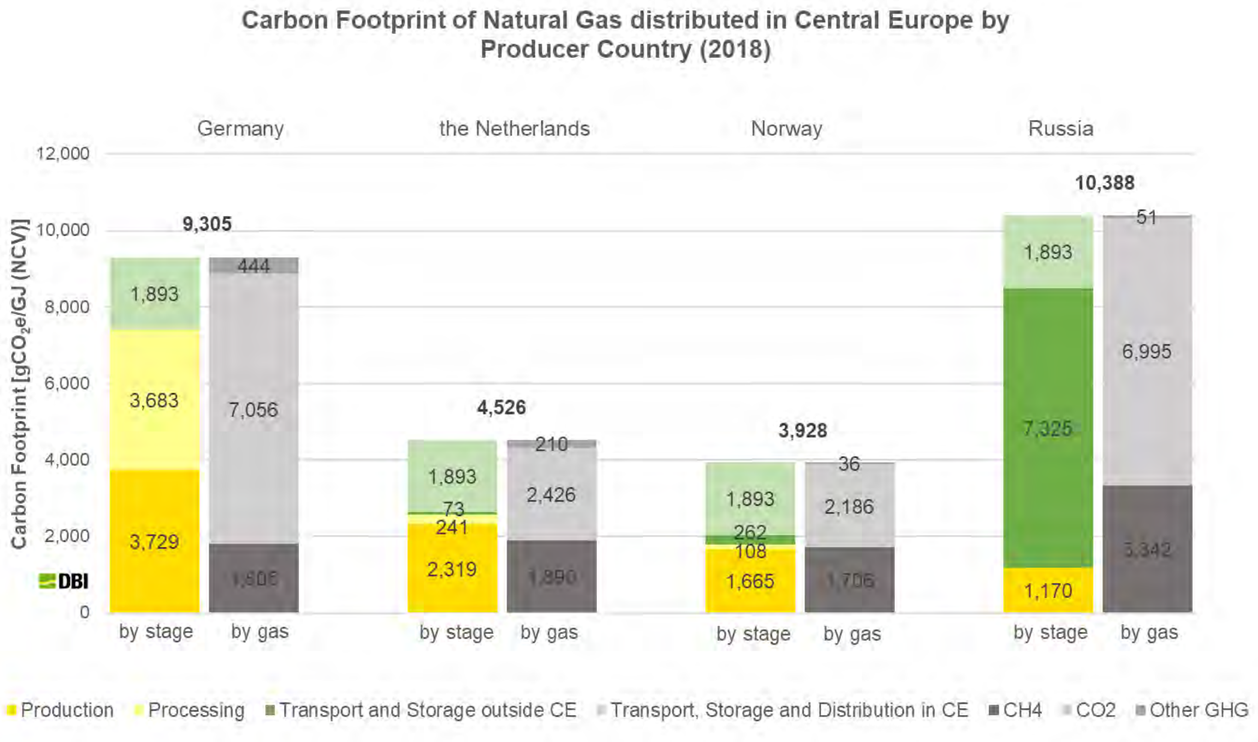

Figure 13: Breakdown of CF of Natural Gas Distributed in CE by Producing Country, Stage and Greenhouse Gas in 2018

- The CF of Norwegian gas is much lower than in the previous study. This is mainly related to the use of better data for Norway in the study at hand. The current results also align much better to the ones of other studies like [70] and [71].
- Processing emissions in Germany are highest compared to processing in the other producer countries. This is mainly due to sour gas conditioning and high CO_2 emissions related with that process.
- For Russia, an average CF of three import routes is shown in this study. The results for the single routes differ from each other. The northern corridor RU3 (with Nord Stream as subsea pipeline) has notably lower emissions than the other corridors that are completely onshore (Figure 14). This is, among others, because Nord Stream does not need recompression on its course. Thus, the Northern corridor has fewer compressor stations which leads to less methane emissions through leakages or venting.

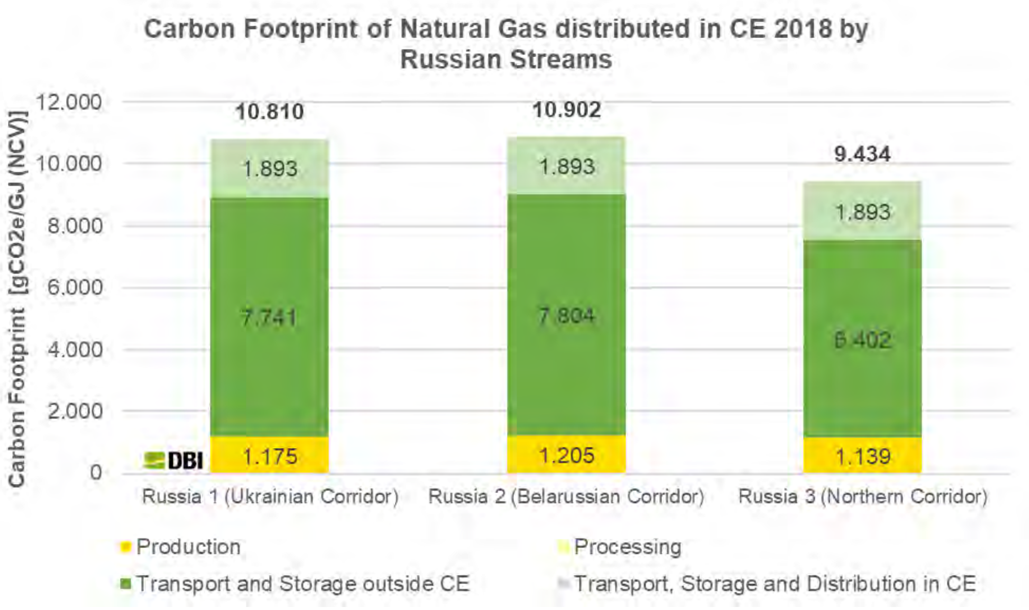

Figure 14: Carbon Footprint for Russian Streams in 2018

- After a slight drop between 2015 and 2016, the CF has been increasing slightly between 2016 and 2018 for all producing countries (except from Norway). Main reasons for that are:
    - Germany: The energy demand of the German gas production was stable or fell just slightly, whereas the produced amount of gas decreased significantly. This led to an increase of the specific energy consumption.
    - The Netherlands: The Dutch gas production decreased, but more energy was necessary for gas conditioning. Thus, the gas production became more energy intensive.
    - Russia: specific energy consumption for gas transport increased between 2015 and 2018.

5.2 Interpretation of Assumptions and Limitations

The following assumptions and limitations made in this study were expected to have no significant impact on the result for the CF of natural gas:

- Primary data was collected for the most important natural gas suppliers of CE. However, literature data (mainly from the EXERGIA study [19]) was used for some countries that do not influence the supply structure significantly (UK, Poland). Data for LNG from Norway/Qatar were taken from the NGVA study [8].
- Primary data refer in general to the years 2015-2018, but literature data sometimes refer to 2012 or even older (in particular, data taken from the EXERGIA study).

For drilling of production wells, no sufficient data was available. Thus, drilling was excluded from the product system. Nevertheless, a sensitivity analysis was made including drilling activities: In [8, p. 42] an assessment of the emission intensity of well drilling activities in Russia has been made. In conclusion, a conservative factor of 0.5 gCO_2e/MJ [8, p. 81] had been taken into account for the sensitivity analysis of the CF calculated in this study. Data for other countries was not available, for this reason, the factor was applied for all countries within the sensitivity analysis. The share of drilling of the total CF is about 4-5 % with the applied factor as Table 27 shows.

Table 27: Impact of Drilling on the Total Carbon Footprint of Natural Gas Distributed in CE [gCO2e/GJ(NCV)]

		2015	2016	2017	2018
Production	incl. Drilling	2,356.32	2,262.73	2,330.10	2,453.92
	excl. Drilling	2,014.11	1,905.78	1,974.55	2,108.39
Processing		242.48	234.16	223.54	192.13
Transport and Storage		2,580.70	2,895.29	3,245.79	3,528.17
Transport, Storage and Distribution in CE		1,907.27	1,871.07	1,854.41	1,893.15
Total	incl. Drilling	7,086.77	7,263.25	7,653.84	8,067.37
	excl. Drilling	6,744.56	6,906.30	7,298.29	7,721.84
Difference		**342.21**	**356.95**	**355.55**	**345.53**

5.3 Data Quality Assessment

Timeliness and Completeness

For the years 2015 - 2018, detailed considerations were possible in most cases, because sufficient data was available. For the year 2019, the required data from many sources (e.g. the national energy balances and the NIR) was missing. For this reason, the year 2019 was not included in this study.

Some data is based on literature values (in particular [3] and [19]), thus, date back until 2012. However, this data does not influence the results significantly.

Precision

A high precision of the data and the calculations was achieved. However, it was necessary to make some allocations because often only aggregated data was available (especially regarding gas production).

Representativeness

To examine the representativeness of the data, a comparison and assessment of the applied data with data from other sources took place. To increase the representativeness, the study considered not just one base year but four consecutive years.

Reproducibility

The presentation of the results and input data was made as comprehensible and transparent as possible to allow reproducing for third parties. For all input data, sources are provided. Nevertheless, not every source is publicly available (some raw data were delivered from operators and have been aggregated), therefore the reproducibility is somewhat limited.

Uncertainty

The uncertainty of the information should be minimised. However, significant uncertainties exist particularly in the field of methane emissions. These uncertainties are unavoidable because there are many elements which cause emissions and not every element can realistically be part of measurements. For emission estimation often equations are used. With these equations only an approximation of the real emissions is possible.

Consistency

In calculating the carbon footprint, the model GaBi Version 9.2.1 was always used. In consequence, all calculations were performed consistently.

The data quality assessment is summarised for the different countries and the individual life cycle steps in

Table 28. It highlights important insights from the data validation phase. In general, it can be stated, that the goal of the study (chapter 2) was reached. Anyhow, it is still possible to improve the data base, because it was partly necessary to work with allocations or assumptions and to use data from the previous study for the year 2014.

Table 28: Summary Evaluation of Data Quality

Sector	Country	Data Quality
Production	Germany	Current, complete, and representative data from the national energy balances and BVEG was used.
	The Netherlands	Current, complete, and representative data from the national energy balances and the NIR was used.
	Norway	The used data was obtained from the national energy balances and the NIR.
	Russia	Current, complete, and representative industry data was used.
Processing	Germany	Determination of vented CO_2 emissions based on published data from BVEG, which is up-to-date and representative. Methane emissions were taken from the NIR. Data for gas consumption are not published, thus, values were taken from the previous study for the year 2014 for all years.
	The Netherlands	Current and complete industry data was used, but this data was aggregated for transport, storage and processing and a breakdown was just partly possible. The data base even contains information (e.g. energy consumption for liquefaction of natural gas) which does not belong to the defined product system boundaries. However, it is assumed that the influence for the result is not significant.
	Norway	Current, complete, and complete industry data was used.
	Russia	The energy consumption and gas losses were contained in the data of gas production. The data for vented CO_2 emissions was taken from the NIR.
Transport and Storage	Germany	Data from the previous study for the year 2014 was applied for all years because more current data were not available. The data for storage losses was taken from the NIR. It is recommended to enhance the data basis with the help of new measurements of leaks and the collection of data from storage system operators.
	The Netherlands	Current, complete, and representative industry data was used.
	Norway	Current, complete, and representative industry data was used.
	Russia	Current, complete, and representative industry data was used.
Distribution	Germany	Usage of current information about methane emissions from the NIR. However, the data of the NIR contain additional information about methane emissions of natural gas filling stations, because in Germany these stations are part of the distribution grid.
	The Netherlands	Usage of current information about methane emissions from the NIR.
	Norway	Not considered in this study, since not part of the system boundaries.
	Russia	Not considered in this study, since not part of the system boundaries.

6 Conclusions and Recommendations

6.1 Conclusions

This study collected reliable and up-to-date industry life cycle data for the greenhouse gas emissions released during the different steps of the natural gas value chain. It has been conducted in accordance with DIN EN ISO 14040, 14044 and 14067 with respect to data quality, completeness, and consistency. The study was prepared to be critically reviewed by independent third parties.

Due to the limited timeframe of this study, only data that would have a notable influence on the resulting carbon footprint was collected. Certain input data, such as that for some countries within CE (e.g. Austria or Poland) or for the value chain of LNG, was taken from literature. It can be expected that a further adjustment of this data would lead to a to a higher precision of the results of the carbon footprint.

Although the CF has been increasing from 2015 to 2018, methane emissions have been decreasing in all countries and production steps, which is probably a result of measures taken by the operators to reduce methane emissions. Some countries (Norway and Russia) have tax systems on methane emissions in place, that lead to reduced emissions. At the same time, however, energy requirements have increased, resulting in higher CO_2 emissions.

Significant uncertainties are associated with the diffuse sources of methane emissions. There are many elements which cause emissions and not every element can realistically be part of measurements. To some extent these uncertainties are unavoidable.

6.2 Recommendations

Whereas many data was provided by operators or could be found publicly, some data gaps exist that lead to the use of literature data, assumptions, or limitations. These gaps should be addressed in future studies:

- Drilling for gas production wells
- Energy consumption of gas storage
- Biogas injection plants
- Energy consumption for the distribution of natural gas (e.g. for preheating)

Many data was provided by operators; however, they are not yet publicly available. The public availability and transparency of data have a strong influence on study results (as it was demonstrated in the Zukunft ERDGAS/DBI study in 2016). The public availability of data therefore has a direct influence on decision-making processes at the European level, since it cannot always be assumed that representatives of the natural gas industry are involved in studies that estimate the carbon footprint associated with the value chain of natural gas.

The ever-increasing transparency practice within the industry should continue its current course, so that measures undertaken by the industry to reduce emissions (e.g. the application of new technologies and new materials for pipeline construction) can be considered in the carbon footprint determination. Furthermore, industry and authorities should work more closely together to allow the inclusion of industry data in public databases like the NIR, thus, allowing the use of industry data also for studies that are not supported by industry partners.

The results of this study should be used for communication with relevant stakeholders (e.g. energy politics, European Commission) to promote the collection and harmonisation of data on lifecycle GHG emissions of natural gas. A particularly interested party might be the Working Group 14 "Methane Emissions" of the

Technical Committee 234 from the European Committee for Standardization (CEN), who is currently working on the standardization of reporting of methane emissions in the natural gas sector.

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Appendices

Annex 1: Gas Properties Applied for Conversion in This Study, based on [72] and Own Calculations

Parameter	Symbol	Unit	Russia	North See (Norway)	The Netherlands	Central Europe
Methane	CH_4	mol%	96.96	88.71	83.64	90.127
Nitrogen	N_2	mol%	0.86	0.82	10.21	2.671
Carbon Dioxide	CO_2	mol%	0.18	1.94	1.68	1.039
Ethane	C_2H_6	mol%	1.37	6.93	3.56	3.571
Propane	C_3H_8	mol%	0.45	1.25	0.61	0.732
Butane	C_4H_{10}	mol%	0.15	0.28	0.19	0.197
Pentane	C_5H_{12}	mol%	0.02	0.05	0.04	0.033
Hexane + higher	C_6H_{14}	mol%	0.01	0.02	0.07	0.025
Oxygen	O_2	mol%	0	0	0	0.000
Sulphur	S	mol%	0	0	0	0.000
Net Calorific Value	Hi,n	MJ/m³	36.3	37.9	33.3	35.637
Net Calorific Value	Hi,n	kWh/m³	10.1	10.5	9.2	9.899
Net Calorific Value	Hi,n	MJ/kg	48.9	46.6	40.1	45.649
Standard Density	ρn	kg/m³	0.74	0.81	0.83	0.768

Annex 2: GHG Emissions of Natural Gas Distributed in CE and Produced in Germany, the Netherlands, Norway, or Russia in 2015-2018 in [g/GJ(NCV)]

	2015			2016			2017			2018		
	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O
Germany												
Production	3,045.50	7.19	0.09	2,942.55	5.90	0.09	3,325.68	6.50	0.10	3,536.99	6.06	0.11
Processing	3,424.18	2.81	0.02	3,524.65	2.98	0.02	3,524.56	2.00	0.02	3,625.83	2.01	0.02
Transport and Storage outside CE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Transport, Storage and Distribution in CE	284.81	64.82	0.01	283.67	63.42	0.01	285.15	62.69	0.01	288.05	64.13	0.01
Total	**6,754.49**	**74.82**	**0.12**	**6,750.87**	**72.30**	**0.12**	**7,135.39**	**71.19**	**0.13**	**7,450.87**	**72.20**	**0.14**
the Netherlands												
Production	1,551.73	9.34	0.03	1,632.21	9.14	0.03	1,866.29	10.15	0.04	2,066.83	9.72	0.04
Processing	97.31	0.20	0.00	143.50	0.29	0.00	166.10	0.34	0.00	229.02	0.46	0.00
Transport and Storage outside CE	42.78	2.26	0.00	40.81	1.91	0.00	42.12	1.25	0.00	40.84	1.29	0.00
Transport, Storage and Distribution in CE	284.81	64.82	0.01	283.67	63.42	0.01	285.15	62.69	0.01	288.05	64.13	0.01
Total	**1,976.63**	**76.62**	**0.04**	**2,100.19**	**74.76**	**0.04**	**2,359.66**	**74.43**	**0.05**	**2,624.74**	**75.60**	**0.05**
Norway												
Production	1,591.53	3.06	0.03	1,550.62	3.01	0.03	1,523.48	3.16	0.03	1,581.01	3.25	0.03
Processing	98.30	0.83	0.00	96.68	0.78	0.00	96.52	0.60	0.00	93.01	0.59	0.00
Transport and Storage outside CE	269.69	0.29	0.00	268.09	0.29	0.00	262.87	0.29	0.00	252.98	0.29	0.00
Transport, Storage and Distribution in CE	284.81	64.82	0.01	283.67	63.42	0.01	285.15	62.69	0.01	288.05	64.13	0.01
Total	**2,244.33**	**69.00**	**0.04**	**2,199.06**	**67.50**	**0.04**	**2,168.02**	**66.74**	**0.04**	**2,215.05**	**68.26**	**0.04**
Russia												
Production	976.16	6.04	0.02	957.97	5.48	0.02	994.54	4.77	0.02	1,057.70	4.27	0.02
Processing	0.12	0.00	0.00	0.12	0.00	0.00	0.12	0.00	0.00	0.12	0.00	0.00
Transport and Storage outside CE	4,805.79	71.80	0.09	4,868.78	69.10	0.09	5,369.39	70.88	0.10	5,659.17	65.30	0.11
Transport, Storage and Distribution in CE	284.81	64.82	0.01	283.67	63.42	0.01	285.15	62.69	0.01	288.05	64.13	0.01
Total	**6,066.88**	**142.66**	**0.12**	**6,110.54**	**138.00**	**0.12**	**6,649.20**	**138.34**	**0.13**	**7,005.04**	**133.70**	**0.14**

Annex 3: GHG Emissions of Natural Gas Distributed in Germany and Produced in Germany, the Netherlands, Norway, or Russia in 2015-2018 in [g/GJ(NCV)]

	2015			2016			2017			2018		
	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O
Germany												
Production	3,034.00	7.16	0.09	2,931.34	5.88	0.09	3,312.94	6.48	0.10	3,523.14	6.03	0.11
Processing	3,411.25	2.80	0.02	3,511.22	2.97	0.02	3,511.06	1.99	0.02	3,611.63	2.00	0.02
Transport and Storage outside GER	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Transport, Storage and Distribution in GER	172.00	30.35	0.00	171.90	28.03	0.00	171.88	27.36	0.00	171.92	28.15	0.00
Total	**6,617.25**	**40.31**	**0.11**	**6,614.46**	**36.88**	**0.11**	**6,995.88**	**35.83**	**0.12**	**7,306.69**	**36.18**	**0.13**
the Netherlands												
Production	1,545.42	9.30	0.03	1,625.79	9.10	0.03	1,859.03	10.11	0.04	2,058.11	9.68	0.04
Processing	96.89	0.19	0.00	142.92	0.29	0.00	165.43	0.33	0.00	228.08	0.46	0.00
Transport and Storage outside GER	28.64	1.50	0.00	27.33	1.27	0.00	28.20	0.83	0.00	27.35	0.85	0.00
Transport, Storage and Distribution in GER	172.00	30.35	0.00	171.90	28.03	0.00	171.88	27.36	0.00	171.92	28.15	0.00
Total	**1,842.95**	**41.34**	**0.03**	**1,967.94**	**38.69**	**0.03**	**2,224.54**	**38.63**	**0.04**	**2,485.46**	**39.14**	**0.04**
Norway												
Production	1,585.51	3.04	0.03	1,544.71	3.00	0.03	1,517.65	3.15	0.03	1,469.64	2.90	0.03
Processing	97.92	0.82	0.00	96.31	0.78	0.00	96.15	0.60	0.00	92.65	0.59	0.00
Transport and Storage outside GER	268.67	0.29	0.00	267.07	0.29	0.00	261.86	0.29	0.00	251.99	0.28	0.00
Transport, Storage and Distribution in GER	172.00	30.35	0.00	171.90	28.03	0.00	171.88	27.36	0.00	171.92	28.15	0.00
Total	**2,124.10**	**34.50**	**0.03**	**2,079.99**	**32.10**	**0.03**	**2,047.54**	**31.40**	**0.03**	**1,986.20**	**31.92**	**0.03**
Russia												
Production	976.66	7.39	0.02	959.70	6.86	0.02	997.08	6.24	0.02	1,059.37	5.89	0.02
Processing	0.12	0.00	0.00	0.12	0.00	0.00	0.12	0.00	0.00	0.12	0.00	0.00
Transport and Storage outside GER	5,418.49	81.67	0.11	5,510.40	79.14	0.10	6,067.65	81.32	0.12	6,367.23	75.18	0.12
Transport, Storage and Distribution in GER	172.00	30.35	0.00	172.00	28.03	0.00	172.00	27.36	0.00	172.00	28.15	0.00
Total	**6,567.27**	**119.41**	**0.13**	**6,642.22**	**114.03**	**0.12**	**7,236.85**	**114.92**	**0.14**	**7,598.72**	**109.22**	**0.14**

Annex 4: CF of Natural Gas Distributed in CE and Produced in Germany, the Netherlands, Norway, or Russia in 2015-2018 in [gCO2e/GJ(NCV)]

	2015	2016	2017	2018
Germany				
Production	3,259.66	3,124.56	3,525.87	3,728.74
Processing	3,501.22	3,605.99	3,581.37	3,682.91
Transport and Storage outside CE	0	0	0	0
Transport, Storage and Distribution in CE	1,907.27	1,871.07	1,854.41	1,893.15
Total	**8,668.15**	**8,601.62**	**8,961.65**	**9,304.8**
The Netherlands				
Production	1,791.83	1,867.91	2,128.34	2,318.70
Processing	102.47	151.15	174.98	241.30
Transport and Storage outside CE	99.43	88.67	73.56	73.22
Transport, Storage and Distribution in CE	1,907.27	1,871.07	1,854.41	1,893.15
Total	**3,901.00**	**3,978.80**	**4,231.29**	**4,526.37**
Norway				
Production	1,670.31	1,628.51	1,605.96	1,665.05
Processing	119.55	116.88	112.22	108.32
Transport and Storage outside CE	278.61	276.99	271.67	261.6
Transport, Storage and Distribution in CE	1,907.27	1,871.07	1,854.41	1,893.15
Total	**3,975.74**	**3,893.45**	**3,844.26**	**3,928.12**
Russia				
Production	1,132.25	1,100.07	1,119.11	1,170.45
Processing[23]	0.12	0.12	0.12	0.12
Transport and Storage outside CE	6,628.69	6,624.05	7,172.75	7,324.61
Transport, Storage and Distribution in CE	1,907.27	1,871.07	1,854.41	1,893.15
Total	**9,668.33**	**9,595.31**	**10,146.39**	**10,388.33**

[23] Energy consumption for processing is included in the production data from Russia. This row only represents CO_2 vented emissions.

Annex 5: CF of Natural Gas Distributed in Germany and Produced in Germany, the Netherlands, Norway, or Russia in 2015-2018 in [gCO2e/GJ(NCV)]

	2015	2016	2017	2018
Germany				
Production	3,247.34	3,112.65	3,512.37	3,714.14
Processing	3,487.99	3,592.25	3,567.65	3,668.48
Transport and Storage outside GER	0.00	0.00	0.00	0.00
Transport, Storage and Distribution in GER	931.81	873.57	856.74	876.75
Total	**7,667.14**	**7,578.47**	**7,936.76**	**8,259.37**
The Netherlands				
Production	1,784.56	1,860.54	2,120.02	2,308.94
Processing	102.04	150.54	174.27	240.31
Transport and Storage outside GER	66.28	59.13	49.09	48.87
Transport, Storage and Distribution in GER	931.81	873.57	856.74	876.75
Total	**2,884.69**	**2,943.78**	**3,200.12**	**3,474.87**
Norway				
Production	1,664.00	1,622.31	1,599.80	1,544.78
Processing	119.10	116.44	111.79	107.90
Transport and Storage outside GER	277.56	275.93	270.63	260.57
Transport, Storage and Distribution in GER	931.81	873.57	856.74	876.75
Total	**2,992.47**	**2,888.25**	**2,838.96**	**2,790.00**
Russia				
Production	1,166.40	1,136.33	1,158.33	1,212.41
Processing	0.12	0.12	0.12	0.12
Transport and Storage outside GER	7,491.93	7,519.54	8,134.91	8,283.26
Transport, Storage and Distribution in GER	931.81	873.57	856.74	876.75
Total	**9,590.26**	**9,529.56**	**10,150.10**	**10,372.54**

Annex 6: Natural Gas Supply Structure in Central Europe, own calculation based on [31–34]

	2015	2016	2017	2018
The Netherlands	20.4%	19.2%	16.5%	13.8%
Norway	29.6%	27.8%	28.5%	28.8%
Russia	36.2%	41.1%	42.9%	45.3%
Germany	4.1%	3.9%	3.5%	2.8%
Poland	2.8%	2.5%	2.4%	2.4%
UK	4.3%	3.0%	3.6%	2.2%
LNG Norway	1.0%	1.2%	1.0%	2.0%
LNG Qatar	1.2%	0.9%	1.1%	2.0%
LNG others	0.3%	0.2%	0.4%	0.5%

Annex 7: Natural Gas Supply Structure in Germany, own calculation based on [31, 33, 35, 36]

	2015	2016	2017	2018
The Netherlands	22.8%	23.3%	21.8%	19.0%
Norway	31.4%	27.8%	24.6%	22.0%
Russia	37.2%	40.3%	46.0%	53.0%
Germany	8.6%	8.6%	7.7%	5.9%
LNG	0%	0%	0%	0%