M4ShaleGas - Measuring, monitoring, mitigating and managing the environmental impact of shale gas

MODEL TOOL TO CALCULATE CARBON FOOTPRINT FROM SHALE GAS AND OTHER FOSSIL FUELS IN EUROPE

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Public introduction

M4ShaleGas stands for *Measuring, monitoring, mitigating and managing the environmental impact of shale gas* and is funded by the *European Union's Horizon 2020 Research and Innovation Programme*. The main goal of the M4ShaleGas project is to study and evaluate potential risks and impacts of shale gas exploration and exploitation. The focus lies on four main areas of potential impact: the subsurface, the surface, the atmosphere, and social impacts. The European Commission's Energy Roadmap 2050 identifies gas as a critical fuel for the transformation of the energy system in the direction of lower CO_2 emissions and more renewable energy. Shale gas may contribute to this transformation. Shale gas is – by definition – a natural gas found trapped in shale, a fine grained sedimentary rock composed of mud. There are several concerns related to shale gas exploration and production, many of them being associated with hydraulic fracturing operations that are performed to stimulate gas flow in the shales. Potential risks and concerns include for example the fate of chemical compounds in the used hydraulic fracturing and drilling fluids and their potential impact on shallow ground water. The fracturing process may also induce small magnitude earthquakes. There is also an ongoing debate on greenhouse gas emissions of shale gas (CO_2 and methane) and its energy efficiency compared to other energy sources. There is a strong need for a better European knowledge base on shale gas operations and their environmental impacts particularly, if shale gas shall play a role in Europe's energy mix in the coming decennia. M4ShaleGas' main goal is to build such a knowledge base, including an inventory of best practices that minimise risks and impacts of shale gas exploration and production in Europe, as well as best practices for public engagement. The M4ShaleGas project is carried out by 18 European research institutions and is coordinated by TNO-Netherlands Organization for Applied Scientific Research.

Executive Report Summary

This report describes the development of a tool to estimate carbon footprint of shale gas produced in Europe for consumption within Europe. The tool builds on an existing tool: GHGenius. GHGenius is already able to estimate carbon footprints for conventional gas and oil delivered to four European regions (North, Central, Southwest, Southeast). This tool is extended with 8 European shale gas plays as production regions and extra emission sources during production such as fugitives from hydraulic fracturing or combustion emissions from horizontal drilling. Results are expressed as CO_2-equivalents per MJ delivered, but can also be calculated for a kWh of electricity generated. Per MJ delivered total GHG emissions range from 8 to 29 g CO_2-eq/MJ, in the range reported in literature. Differences are mainly due to differences between producing countries. Emissions are generally higher than average emissions from conventional gas delivered to Europe (from Europe and other countries). Total leakage rate related to production ranged from 1% to 1.8% for shale from European regions and to 2.5% for shale gas imported from the U.S. That is lower than the 3% often cited as being the maximum for natural gas to certainly have a lower carbon footprint than other fossil sources. A first sensitivity analysis indicates the importance of good estimations of the fugitive emissions from hydraulic fracturing flowback and the large variation in data sources on production emissions. On a per kWh basis our default calculations show negligible differences between carbon footprints of conventional and shale gas, both lower than those of oil and coal. Recommendations for further model improvement are also formulated and include a more thorough calculation of carbon footprints of European coal and attention on scenario developments for shale gas exploration and use.

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1 INTRODUCTION

1.1 Context of M4ShaleGas

Shale gas source rocks are widely distributed around the world and many countries have now started to investigate their shale gas potential. Some argue that shale gas has already proved to be a game changer in the U.S. energy market (EIA 2015[1]). The European Commission's Energy Roadmap 2050 identifies gas as a critical energy source for the transformation of the energy system to a system with lower CO_2 emissions that combines gas with increasing contributions of renewable energy and increasing energy efficiency. It may be argued that in Europe, natural gas replacing coal and oil will contribute to emissions reduction on the short and medium terms.

There are, however, several concerns related to shale gas exploration and production, many of them being associated with the process of hydraulic fracturing. There is also a debate on the greenhouse gas emissions of shale gas (CO_2 and methane) and its energy return on investment compared to other energy sources. Questions are raised about the specific environmental footprint of shale gas in Europe as a whole as well as in individual Member States. Shale gas basins are unevenly distributed among the European Member States and are not restricted within national borders, which makes close cooperation between the involved Member States essential. There is relatively little knowledge on the footprint in regions with a variety of geological and geopolitical settings as are present in Europe. Concerns and risks are clustered in the following four areas: subsurface, surface, atmosphere and society. As the European continent is densely populated, it is most certainly of vital importance to understand public perceptions of shale gas and for European publics to be fully engaged in the debate about its potential development.

Accordingly, Europe has a strong need for a comprehensive knowledge base on potential environmental, societal and economic consequences of shale gas exploration and exploitation. Knowledge needs to be science-based, needs to be developed by research institutes with a strong track record in shale gas studies, and needs to cover the different attitudes and approaches to shale gas exploration and exploitation in Europe. The M4ShaleGas project is seeking to provide such a scientific knowledge base, integrating the scientific outcome of 18 research institutes across Europe. It addresses the issues raised in the Horizon 2020 call LCE 16 – 2014 on *Understanding, preventing and mitigating the potential environmental risks and impacts of shale gas exploration and exploitation.*

[1] EIA (2015). Annual Energy Outlook 2015 with projections to 2040. U.S. Energy Information Administration (*www.eia.gov*).

1.2 Study objectives for this report

The IPCC (2011) Working Group III Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) assessment concludes that electricity production using (natural) gas instead of coal produces far less carbon dioxide (the carbon footprint of gas being about a factor 2 less). The median, 25th and 75th percentile GHG emission for gas and coal are still far apart, but the maximum for gas and minimum values for coal overlap. Therefore, the advantage of gas over coal is not undisputed, as leakage of CH_4 (a potent greenhouse gas) during exploitation could offset the advantage of gas over coal (Heath, et al., 2014; Weber and Clavin, 2012).

A proper comparison of GHG emissions between shale gas and other energy sources, specifically for Europe, will aid in assessing the CO_2 footprint of fuels and their potential impact on global climate forcing. The carbon footprint is a way to quantify climate impact and in this report encompasses the total emissions of the greenhouse gases (GHGs) carbon dioxide (CO_2) and methane (CH_4) over all life cycle stages (from gas extraction to delivery and use). These greenhouse gases can be compared by expressing the emissions of each gas in CO_2 equivalents based on their Global Warming Potentials (GWP) for a specific time horizon (100 years).

The main objective of M4ShaleGas WP15 is to provide recommendations for mitigating the CO_2 footprint of shale gas operations at various spatial scales in Europe. Additionally, this WP aims to compare the contributions of shale gas and other fossil fuels to global climate change by calculating the CO_2 footprint by fuel type for comparable applications like electricity production or transportation. A previous report (Hauck and Denier van der Gon, 2015) reviewed the existing knowledge on the carbon footprint of shale gas operations. The available knowledge on shale gas carbon footprint arises mostly from U.S. based studies and measurements. These studies indicate the carbon footprint of generating electricity from shale gas ranges from 420-850 g CO_2-equivalents/kWh, close to the range reported for conventional gas (480-750 kg CO_2-equivalents/kWh) for the United States. In general, as combustion of gas in power plants generally contributes to about 80% of total GHG emissions, differences in power plant efficiencies are by far most important factor accounting for the differences in carbon footprints. As a result, combustion emissions of shale gas are indistinguishable from emissions from conventional gas. Omitting the combustion phase, GHG emissions range between 7-27 g CO_2-equivalents per MJ of gas delivered. Most of these emissions arise from losses of gas during gas production from wells and preproduction (the preparation of these wells). At the same time, these emissions are most variable and uncertain over the gas life cycle because measurements show a wide range. In addition, emission estimates derived bottom-up (from equipment emission factors) or top-down (by measurements around or over a large production area) differ, suggesting large uncertainties. For comparison with other fossil sources, the fraction of shale gas from a producing well that is lost to the atmosphere is important. A turning point after which leakage results in a larger footprint for gas than coal is often suggested to be around 3% of well production (Heath et al., 2014). If emissions are expressed on basis of one MJ delivered from a specific well, absolute well drilling are smaller with higher production. However, the total production of a well is currently largest unknowns, making life cycle emission comparisons with coal and other fossil fuels difficult.

1.3 Aims of this report

Task 15.2 aims at developing a modelling tool to calculate the carbon footprint of shale gas operations in Europe. Additionally, this tool enables transparent comparison with other types of fossil fuel for various applications, mainly electricity generation. This tool helps to assess the potential effect of large scale shale gas exploitation and use in Europe on the global climate. Various tools are available that assess the life cycle GHG emissions of various fossil and alternative fuels for a number of applications, often transportation. Deliverable M4ShaleGas 15.1 reviewed several available tools: GREET, GHGenius, OPGEE and the NETL upstream dashboard. All of these tools primarily focus on Northern America. However, the GHGenius tool has been adapted for Europe for the oil and gas streams by COWI (2015). To our knowledge no other tools are available, that calculate the upstream processes of recovery and delivery of oil and gas for the European market in such a detailed way. Besides transportation it also includes other end-uses, such as electricity and heat.

Instead of developing a new tool and perform redundant data gathering, it was decided to build on the existing GHGenius tool and specifically add calculations for shale gas produced in Europe. The main aim of this report is the inclusion of the available knowledge on (future) shale gas operations in Europe in GHGenius. Another advantage of building on this existing tool is that it enables the comparison with other fossil fuels specifically modelled for Europe in a consistent way. In order to account for information gaps, a first estimation of uncertainty ranges is included in our modelling exercise (elaborated in Section 2.3.1). This report presents a first, preliminary comparison of overall CH_4 leakage rates and carbon foot print for shale gas from various plays in Europe when used in different European regions.

2 TOOL DEVELOPMENT

2.1 GHGenius description

GHGenius, a model for life cycle assessment of transportation fuels, was developed by (S&T)[2] Consultants Inc. for Natural Resources Canada based on a previous version called LEM (Life cycle Emission Model). GHGenius[2] includes 200 vehicle-fuel combinations (light, medium, heavy vehicles, busses, electric vehicles, driven by engines or fuel cells). Emissions are taken into account for air pollutants and several GHGs (CO_2, CH_4, N_2O). The model also allows for past and future time series calculations, cost assessment and Monte Carlo Simulations. The user can specify fuel composition and pathway, including countries of origin (for ethanol), efficiency of electricity generation and distribution of the electricity, or can decide to use default numbers. Details of the model are described in (S&T)[2] Consultants Inc (2013a). Endpoints include comparison of:

- ✓ Fuel on basis of km travelled;
- ✓ electricity generation (in kWh and MJ) for 29 electricity generation pathway and fuel combinations,
- ✓ heat for 5 fuels (in GJ);
- ✓ industrial steam use (in tonnes);

Gas sources included are:

- Conventional
- Associated
- Tight
- CBM
- Shale
- Frontier gas (arctic and offshore)

Originally the model included several regions of Canada and the United States and background data for other countries (India, Mexico) as origin of feedstock resources. Data are mainly based on EPA and Canadian statistics as referenced in (S&T)[2] Consultants Inc (2013a,b). The streams of gas and oil from producing regions to four European regions (North, Central, Southwest and Southeast, see COWI (2015) or Hauck and Denier van der Gon (2015) for an overview of countries per region) were included in the model for a report by COWI (2015) data mainly based on national statistics such as energy balances and inventory reports. These regions will hereafter be called consumption or receiving regions (were the gas is combusted) to distinguish from the production regions, where the gas is extracted (European countries in this research).

[2] The model and reports can be downloaded from http://www.ghgenius.ca/.

2.2 Model adaptations

Calculations have been performed with model version GHGenius 5.0 BETA 2c. Model structure was kept in place as much as possible. Therefore, some existing production regions irrelevant for Europe were replaced by the European shale gas plays. Consequently the adapted model version should no longer be applied for modeling fuel emissions in North America. Upstream emissions were calculated for ‘gas to power’ as electricity generation is the most likely application in Europe. The composition of raw gas and pipeline gas has been adapted to fit European average conditions based on a compilation by TNO (Costa et al., 2016) and Altfeld and Schley (2012).
New data have been added:

- On production regions (shale gas plays) that are not currently included in GHGenius;
- to add extra emissions during shale gas production that are not expected from conventional gas;
- to allow for all plays to deliver to all European consumption regions. This means the inclusion of transport distances that are currently not included. Transport distances influence gas leakage during transportation and are therefore included for emissions estimations.

The data and assumptions used are described in more detail below. For countries included in GHGenius and all life cycle stages except (pre-) production, GHG emissions were assumed equal to those of conventional natural gas. Emissions from the provision of infrastructure for gas exploitation are currently not included.

2.2.1 Shale gas plays in Europe

TNO developed indicative possible scenarios for shale gas exploitation in Europe which have been documented in Costa et al. (2016). Based on estimated (technically recoverable) reserves by EIA (2013) and Zijp (2016), eight major shale gas plays were identified in seven EU Member States (see Figure 1). These plays are considered the most promising based on earlier assessments. Current best estimates of the risked recoverable reserves were used to estimate the total potential amount of gas that can be produced. The areas of the plays have been calculated using GIS and play contours by EIA (2013). The estimated surface areas and reserves are shown in Table 1. It was assumed that one well pad covers $25km^2$ (a 5 x 5 km square) and that 25-30 wells are drilled in one pad. Based on these assumptions and the area per play, the required number of wells per play could be deduced.

Figure 1. Map of identified and selected shale gas plays for production in Europe created by TNO (Costa et al., 2016) based on data from EIA (2013).

Table 1. Recoverable reserves and surface areas for shale gas plays in Europe (EIA, 2013 and Zijp, 2016).

Country	Play	Reserve (m^3)	Surface (km^2)
UK	Bowland Basin	7.1E+11	24,785
Poland	Lublin Basin	2.6E+11	28,626
Poland	Podlasie Basin	2.7E+11	9,436
Poland	Baltic Basin	2.9E+12	47,935
Netherlands	Geverik Member (Epen Formation)	9.3E+10	10,118
Denmark	Alum Shale	2.6E+11	15,731
Sweden	Alum Shale	9.0E+11	7,004
Germany	Posidonia Shale	2.8E+11	23,646
France	Paris Basin	4.8E+11	26,297

2.2.2 Extra production emissions

Realistic data for shale gas operations in Europe are scarce or non-existent as only few explorative drillings have taken place. Most estimations performed for the European situations are based on Northern American experiences, a small number of company data and expert judgements (see Hauck and Denier van der Gon, 2015). In general (and for our modelling exercise), it is assumed that shale gas is not fundamentally different from conventional gas, except for some extra activities that are required, especially for (pre-) production of the gas (see also Hauck and Denier van der Gon, 2015). Once gas is injected in high pressure transmission pipelines, no distinction can be made any more. Based hereupon, data of conventional gas have been used and some extra emissions sources have been added, following the reasoning in Broderick et al. (2011). Calculation of these extra sources and assumptions made are described below. An overview of the values used is given in Table 2. All energy use and emissions are modelled per unit of gas produced. Play-specific total production numbers are included as described in Section 2.2. Table 2 also shows whether data are (modelled) play-specific and gives uncertainty ranges when available.

1. *Extra fuel use during production due to horizontal drilling*
   These are modelled as the product of the drilling width (2000m) and the use of diesel per meter drilled.
2. *Extra fuel use during production for hydraulic fracturing*
   These are modelled based on an average diesel use for hydraulic fracturing. The total fuel use depends on the number of (re-) fracturing events. All wells are fractured once for startup of the production and it is assumed that 50% of the wells are re-fractured once during their lifetime.
3. *Extra fuel use due to transport of water and chemicals during production*
   Total volumes and distances transported per (re-)fracturing event was derived from Broderick et al. (2011).
4. *Extra fugitive emissions from well completion (mainly assessed from flowback during fracturing)*
   Broderick et al. (2011) report that a range of 0.6%-3.2% of total production could leak during flowback, based on Howard (2011). They also report ranges of absolute production volumes per well as flowback emission volumes. Taking these into account, in this report a leakage rate of 0.85% of production (per fracturing event) is chosen based on the geometric mean of the absolute production data and a flowback emission volume in the middle range.

Table 2. Values and sources used for the calculation of extra shale specific emissions during gas production.

Value	Source	Play-specific	Uncertainty range from same reference
Fuel use for horizontal drilling			
837760 kJ diesel per meter drilled	Broderick et al., 2011	no	
2000 m horizontal drilling length per well	based on TNO scenario data (Costa et al., 2016)	Not modelled	
Fuel use for hydraulic fracturing			
110,000 l diesel/well	Broderick et al. (2011) based on wells in the Marcellus shale reported by New York state	No	
Number of hydraulic fracturing events: 1.5 (50% of the wells re-fracture once)	Broderick et al. (2011)	Not modelled	1-2[B]
Fuel use for transport			
Volume transported per fracturing event: 20,000 m^3	Assumption based on range on Broderick et al. (2011)	no	9,000-29,0000m^3
Transport distance: 60km	Broderick et al. (2011)	no	
0.001 kJ diesel per tkm transported	Ecoinvent lifecycle inventory database	no	
Fugitive emissions			
0.85%[A]	References in Broderick et al. (2011)		0.6%-3.2%
Data on shale gas plays in Europe			
Total production = recoverable reserve	EIA, 2013 and Zijp, 2016	yes	
25 wells per 25km^2	L. Cremonese, personal communication	Not modelled	20-30
Area per play	EIA, 2013	yes	

A: Broderick et al., 2011 reports emission volumes, from which the highest value of the ones indicating the lower range was chosen and divided by the geometric mean of all reported production volumes. Due to interdependence of emissions and production volumes, this value is highly uncertain.

2.2.3 Transport distances

Not all of the countries in Table 1 currently produce natural gas and therefore France and Sweden were originally not included in GHGenius. For these countries, average European production conditions from the European countries in GHGenius are used. Additionally, not all countries deliver gas to all four regions and transport distances lacked for these combinations of country-consumption regions. Transport distances were estimated based on existing data and expert judgement (see Table 3), applying the following lines of thought:

- For distances from a production country to the consumption region the country is located in, domestic transport distances from COWI (2015) were applied.
- For Poland, distances from Germany were applied. For Sweden the same distances as from Norway were applied.
- Transport from Denmark and the UK was assumed to go via the Netherlands (maps in COWI, 2015) and was calculated as the distances to Northern Europe (i.e. The Netherlands) plus the distances from the Netherlands to the Southern European countries.

Table 3. Transport distances (km) between European production countries and consumption regions. Distances printed in normal font were already included in GHGenius. Distances in italics were estimated in this research. Distances with an asterisk indicate, these countries lie within the respective regions.

	North EU	Central EU	Southeast EU	Southwest EU
Norway	1,000*	1,400	2,000	1,800
United Kingdom	600*	230	*1,230*	*1,530*
Netherlands	230*	*150*	1,000	1,300
Denmark	200*	600	*1,600*	*1,900*
Germany	*685*[A]	*300**	900	250[B]
Poland	*685*	*300**	*900*	*250*
Sweden	1,000*	1,400	2,000	1,800
France	1,715	600	1,000	*322**

A: Calculated as the sum of the distance to Central EU and 385 km^2 (the average distance for countries in North EU to Central EU (UK and Denmark) included in GHGenius.
B: This distance assumes transport from Germany to France.

2.3 Scenario assessment

A number of scenarios have been investigated to illustrate the capabilities of the tool and to give an overview of GHG footprints of shale gas in Europe at the current stage. Additionally, uncertainties in these estimations are explored. For these calculations the default settings of the model were used with modified input:

- The target year was set to 2016 (relevant for time series calculations);

- GWPs for a 100 year time horizon, excluding climate feedbacks, as reported by the IPCC 2013 report were used for comparison of GHGs (a value of 30 for methane).

A number of calculations were selected that seem relevant in context of the M4shale project. To illustrate possible results and identify improvement options, the following outcomes are presented:

- Carbon Footprints for shale gas from all European plays delivered to all four European consumption regions have been calculated. For comparison, also footprints of conventional gas and shale gas imported from the US as LNG are shown (modelled by $(S\&T)^2$ Consultants Inc., 2011). For shale gas calculations, it was assumed that 100% of gas consumption is derived from each specific play at a time. For conventional natural gas realistic production mixes were used (as derived by COWI, 2015).
- Carbon footprints were calculated per life cycle stage to show their relative importance.
- The total CH_4 leakage rate as a percentage of production is often used as an important variable to assess the carbon benefit of using natural gas over other fossil sources, such as coal (see also Hauck and Denier van der Gon, 2015 for review). Therefore, these total leakage rates related to production were calculated for shale gas produced and consumed in Europe.
- To illustrate the potential for further analysis, we assessed carbon footprints on the level of one kWh delivered to the user. For that analysis, we assume an efficiency of electricity generation of 40% for gas, coal and oil. As coal data in GHGenius relate to North America, we took carbon footprints of a GJ of hard coal briquettes produced in Europe from the ecoinvent 3.1 life cycle inventory database (Wernet et al., 2016). This approach ignores GHG emissions from imported coal and must be seen as a first approximation. According to Dones et al. (2007) most coal consumed in Europe comes from Europe (about 70% in 2015, Eurostat, 2016).

2.3.1 Uncertainties

Most shale specific data used in this report are first attempts derived from expert estimations and proxies from other regions, mostly North America. As can be seen in Table 2 for some of these estimates, uncertainty ranges are reported in literature. More sources of uncertainty are summarized in Hauck and Denier van der Gon (2015). For model testing a number of additional outcomes, including alternative values for uncertain parameters were performed.
Leakage during production and in particular (for shale gas) during flowback after hydraulic fracturing is often cited as an important source of uncertainty. This uncertainty is related to the leakage rate and the number of (re-) fracturing events during a well lifetime. Next to the uncertainty ranges reported in Broderick et al. (2011), data from other sources have been used to assess the robustness of our results. For shale gas from the Baltic Basin in Poland delivering to Central Europe, the following outcomes are presented:

- using the low production emission rate from Table 2 (0.6% of production);
- using the high production rate from Table 2 (3.2% of production);
- assuming that all wells have to be re-fractured once (2 fracturing events per well);
- assuming wells do not have to re-fracture at all (1 fracturing event per well);
- using well completions emissions from Foster and Perks (2012). In their tentative LCA for shale gas in Europe apply a value of 312,002 m^3 of completion emissions, independent of the lifetime productivity of the well.

Uncertainties based on UK shale gas LCA
Stamford and Azapagic (2014) published an LCA for shale gas produced in the UK. Their data compilation can be used in an uncertainty estimation for the data in our tool for the UK play (Table 4).

Table 4. Alternative values and ranges for drilling and completion fugitive emissions, water consumed for hydraulic fracturing and total production of a well.

	Base case	Minimum	Maximum
Drilling& completion emissions (%)	4.1	0	54
Drilling fluid consumption per well (m^3)[A]	1000	246	2271
Total expected production (m^3)	2.8E+10	8.5E+10	2.8E+09

A: interpreted as per hydraulic fracturing event.

2.4 First results and discussion

The contribution of each life cycle stage to the carbon footprints of delivering shale gas to Europe from each European play and the United States (as LNG) is shown in Figure 2. Per MJ delivered total GHG emissions range from 8 to 29 g CO_2-eq/MJ. This range of values is within the ranges reported in literature (summarized in Hauck and Denier van der Gon, 2015). As can be seen from Figure 2, production of shale gas is the largest contributor to total carbon footprint, with exception of shale gas from the U.S. For shale from the United States, processing emissions are comparable to production emissions. In the current model, CO_2 emissions from gas plants and energy use for processing are higher in the U.S. than the European countries. In the Netherlands, generally no processing occurs (COWI, 2015). Additionally, transmission emissions are higher for shale gas imported from the United States, due to the need to liquefy the gas. Variations between receiving regions are generally due to differences in transmission emissions. Comparison to Table 3 shows transmissions emissions are related to transport length. The bold black line in Figure 2 shows the carbon footprint for conventional gas delivered from the current mix of producing regions to a consumption weighted average EU.

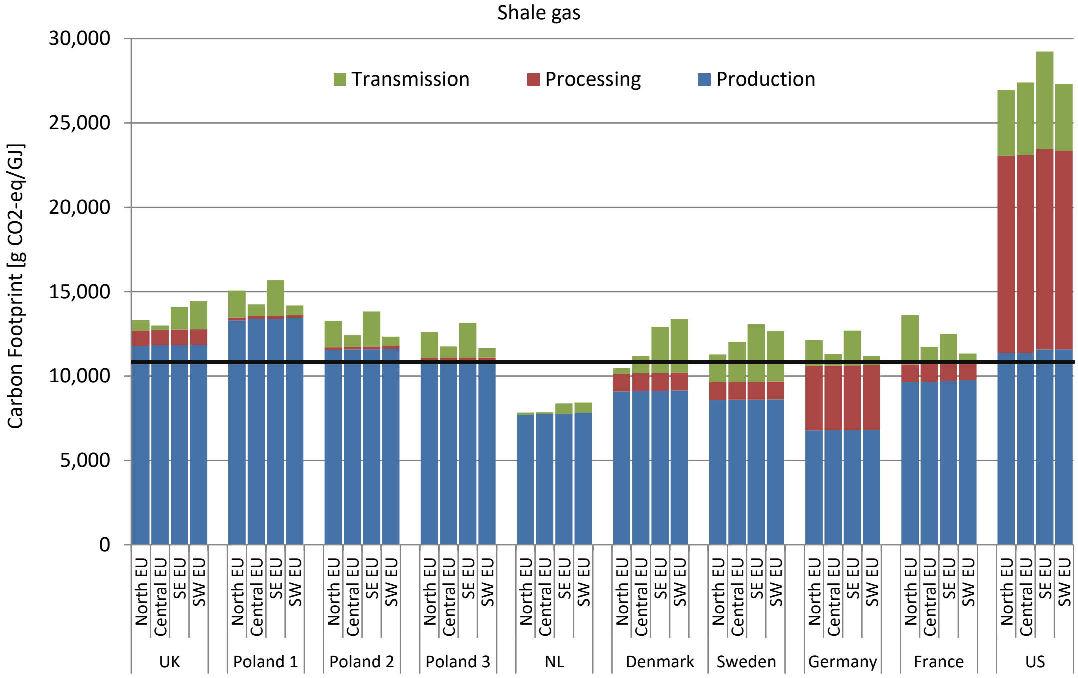

Figure 2. Carbon Footprints of shale gas from European plays and the U.S. delivered to European regions. Contributions of each life cycle are also shown. The thick black line indicates European average carbon footprint from conventional gas. SE: Southeast; SW: Southwest; Poland 1: Lublin Basin; Poland 2: Podlasie Basin; Poland 3: Baltic Basin.

For comparison, Figure 3Figure 3 shows the carbon footprints for conventional gas, delivered to the four European regions as well as the weighted average of these regions. It shows that the average is in the same range as the carbon footprints of shale gas and variation between regions is quite high (about 9,000 gCO_2-eq./GJ).

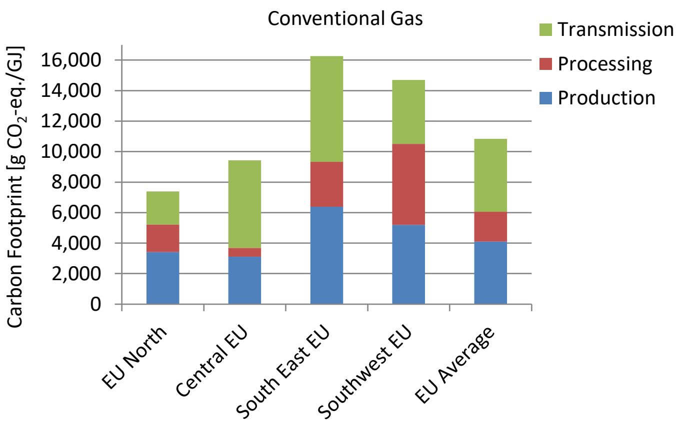

Figure 3. Carbon footprints and life cycle stage contributions for conventional gas delivered to four European regions and their weighted average.

Total leakage rate related to production ranged from 1% to 1.8% for shale from European regions and to 2.5% for shale gas imported from the U.S (Table 5).

Table 5. Leakage rate as percentage of production at the stage of delivery per production region and receiving region.

	UK	Poland Lublin	Poland Podlasie	Poland Baltic	NL	DK	S	D	France	US
North EU	1.8%	1.7%	1.6%	1.6%	1.0%	1.3%	1.3%	1.1%	1.4%	2.3%
Central EU	1.7%	1.6%	1.6%	1.6%	1.0%	1.3%	1.4%	1.1%	1.3%	2.3%
SE EU	1.8%	1.7%	1.7%	1.7%	1.0%	1.4%	1.4%	1.1%	1.4%	2.5%
SW EU	1.8%	1.6%	1.6%	1.6%	1.0%	1.4%	1.4%	1.1%	1.3%	2.3%

Uncertainties

Figure 4 shows the effect on total carbon footprint of using a higher or lower leakage rate and changing re-fracturing requirements (no re-fracturing needed, all wells re-fracture once) for shale gas from the Baltic Basin in Poland consumed in the Central EU. Higher leakage has the largest effect on total carbon footprint in these calculations. Emissions with higher leakage exceed carbon footprints from all European production and receiving areas. Also, this high leakage from flowback would result in an overall leakage rate from production of 4.2% (results not shown), indicating a more detailed comparison of emissions from shale gas with other fossil energy sources would be necessary. Carbon footprints using the absolute well completion emissions from Foster and Perks (2011) are also shown. The resulting emissions per GJ delivered are highly influenced by the total production of a play. Therefore, the same calculations are shown for a play with low expected recovery (NL).

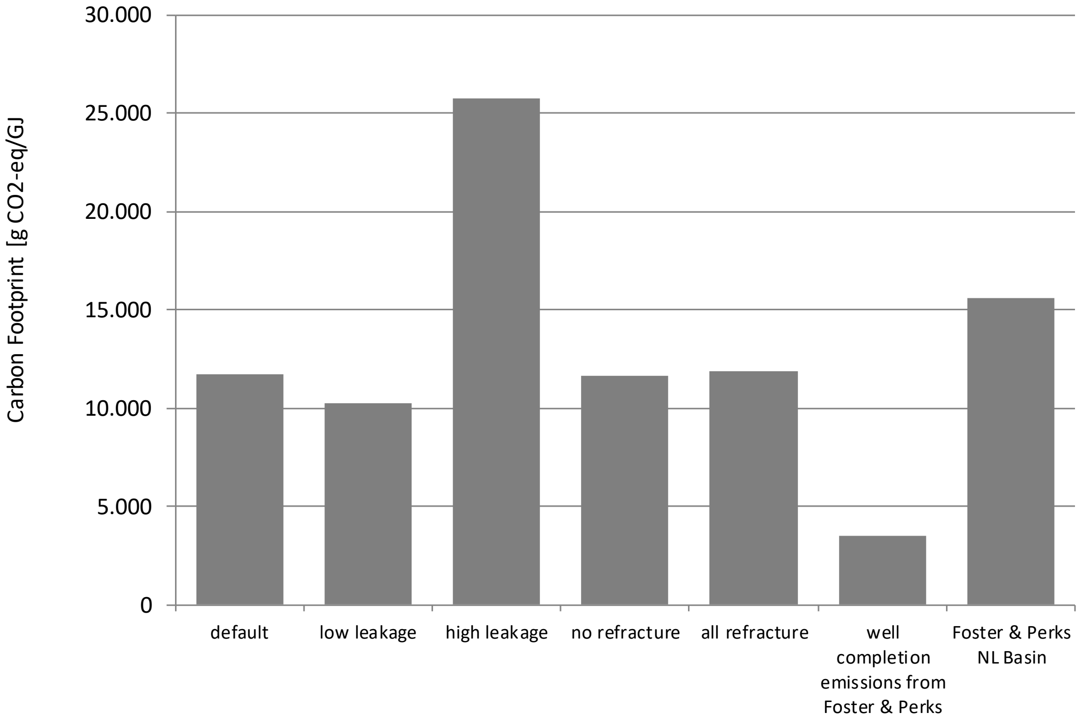

Figure 4. Carbon Footprints of shale gas produced in the Poland Baltic Basin and delivered to the Central EU for the default assumptions (same as Figure 2) with lower and higher leakage from fracturing, with one extra fracturing event, with high leakage and one extra fracturing event and with completion emissions from Foster and Perks (2011). Calculations for The Netherlands (NL) represent a play with low expected recovery.

Uncertainties based on UK shale gas LCA

Figure 5 shows total carbon footprints for shale gas delivered from the UK to Northern Europe (within region), calculated with our model, but using data from Stamford and Azapagic (2014) for fugitive emission from drilling and well completion, for amounts of water that need to be transported and for the expected lifetime productivity of wells. Ranges derived from Stamford and Azapagic (2014) are also included. Fugitive emissions are inserted in our model as percentage of production, combustion emissions are (partly) modelled as absolute numbers depending on drilling requirements or number of fracturing events. Therefore, only changes in expected total production only affects combustion emissions. Effects on total emissions can only be seen if these changes are high, because combustion emissions contribute less to total emissions than fugitive emissions. Effects of changing water transport are so minor that estimated footprints cannot be distinguished from those in Figure 2. Stamford and Azapagic (2014) have been criticized for overestimating emission from shale gas (Westaway et al., 2015). Using of data from Stamford and Azapagic (2014) for fugitive emission from drilling and well completion, for water transport lifetime productivity, however, reduces carbon footprint estimations in our model.

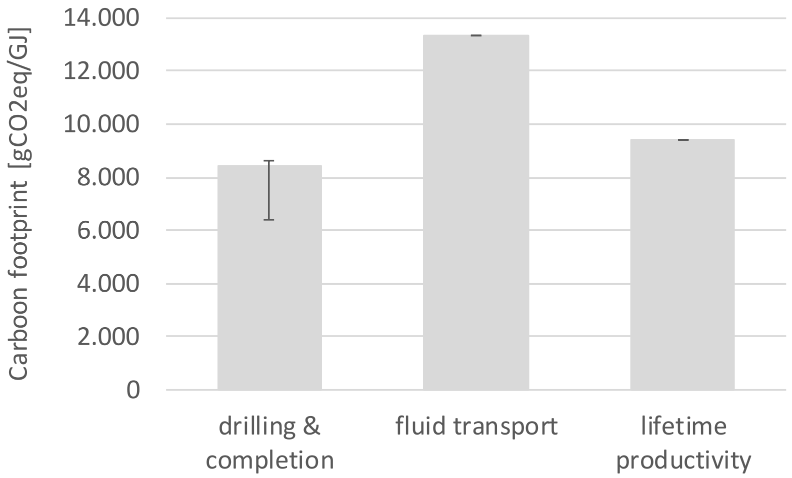

Figure 5. Total Carbon footprints for shale gas delivered from UK to Northern Europe calculated with our model, but using data from Stamford and Azapagic (2014) for fugitive emission from drilling and well completion, for amounts of water that need to be transported and for the expected lifetime productivity of wells.

Electricity Generation

This report intends to use electricity generation as a showcase for investigating the impact on global climate when using a low CO_2-emitting fossil fuel (gas) to a high CO_2 emitting fossil fuel (coal). Figure 6 shows carbon footprints of electricity generation in Central Europe from shale gas from the Baltic play in Poland, from the current mix of conventional gas and from oil. Emissions from oil are higher than emissions from both types of natural gas, even when assuming the same generation efficiency. Using upstream data from ecoinvent (Wernet et al., 2016). for hard coal briquettes produced in Europe shows even higher emissions. Choosing European coal and thereby ignoring additional coal imports might even underestimate the gap between coal and gas.

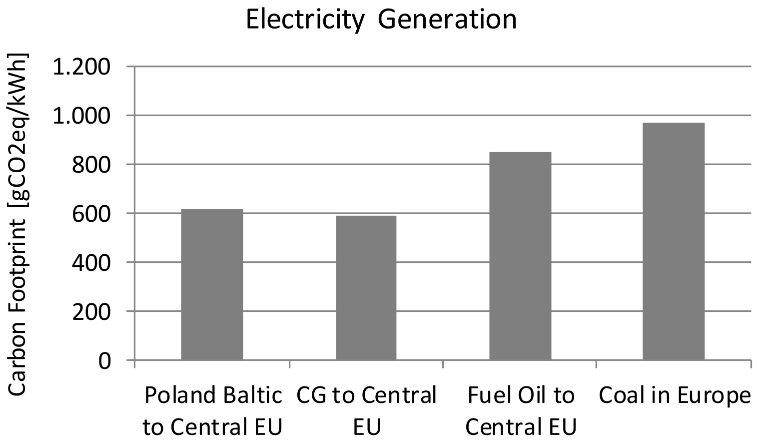

Figure 6. Carbon Footprints of electricity generation in Central EU from shale gas from the Baltic play in Poland, the current mix of conventional gas and oil and coal from Europe (assuming efficiency of electricity generation of 40%).

3 CONCLUSIONS AND RECOMMENDATIONS

We developed a tool which enables the calculation of the carbon footprint of potential (future) shale gas produced and consumed in Europe. This tool builds on an existing life cycle assessment tool, GHGenius, that has already been used for analysis for the European Commission (COWI, 2015). GHGenius has the advantage to already include several fuels (conventional gas and oil for the European continent) and end uses including transport, electricity generation and heat. For this report, results have been presented on the basis of one Gigajoule delivered, as emissions from the final use stage are not expected to differ between shale and conventional gas. Results show that GHG emissions from shale gas production, processing and transmission can be both higher and lower than the European average for conventional gas. The ranges in carbon footprints for producing and consuming regions are high for both types of gas (about 8,000 – 25,000 g CO_2-eq./GJ for European shale gas). It is found that the leakage rate has the largest effect on total carbon footprint calculations. The leakage during re-fracturing was more important than the number of re-fracturing events in our analysis. Total leakage rate related to production ranged from 1% to 1.8% for shale from European regions and to 2.5% for shale gas imported from the U.S. These values are lower than the 3% often cited as being the maximum for natural gas to certainly have a lower carbon footprint than other fossil sources.

Results are presented on the basis of one Gigajoule delivered from one specific play. However, the carbon footprint effects of using a combination of shale gas production regions can also be calculated if scenarios for the fuel mix are available. The tool is appropriate for estimations on a country level. Inclusion of end uses also allows for policy assessments such as changes in the electricity mix of a European region. It should be kept in mind that the results presented in this report represent a first attempt at quantifying GHG emissions from shale gas exploration in Europe and that all calculations are hampered by the lack of availability of actual monitoring data for Europe. Results show the feasibility of a tool for shale gas emission calculations and comparisons. However, the current modelling exercise is also a way to systematically identify improvements needs. Thus, a number of recommendations are derived for further research:

- To enable a comparison with all fossil sources relevant for electricity generation in Europe, GHG emissions arising from the delivery of coal to Europe should also be included.
- Currently, total production per play is derived from the recoverable reserves. This could be extended by more realistic production scenarios that take into account political or economic restraints. However, economic analysis or policy preferences could give insight in other possible or likely exploitation scenarios.
- Currently, the only difference between plays is the production and the country specific data also used for conventional gas. More data would allow a better comparison of the emissions from different producing regions.

- Comparison of shale gas to current electricity carbon footprints on a country level requires the inclusion of country-specific generation efficiencies.
- Since total CH_4 leakage rate is a dominant parameter, more research on realistic leakage rates will increase the accuracy. [Note that this will also apply to leakage of coal mine gas associated with the coal used in our comparison between coal and shale gas]
- Results showed that transmission emissions are generally related to transmission length. Data on pipeline length should be improved to give more accurate estimations.

Glossary

CG – Conventional Gas
CNG – Compressed Natural Gas
GHG – Greenhouse gas
GWP- Global Warming Potential
IPCC – Intergovernmental Panel on Climate Change
LNG – Liquefied Natural Gas
SG – Shale Gas
Eq – equivalent
GJ - GigaJoule

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