# Comparison of GHG emissions from unconventional natural gas ("fracking") in key studies

**prepared for ExxonMobil Production Germany**

by


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Darmstadt, Washington DC, August 2014


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# 1 Introduction

This brief study commissioned by ExxonMobil Production Germany analyzes in detail the differences between life-cycle emissions of greenhouse gases (GHG) calculated for unconventional gas extraction (hydraulic fracturing, or “fracking”) in the US, the UK and the EU, and compares results of these studies with respective data from own research for Germany[1].

The studies analyzed are:

- Shale gas in the US (Howarth, Santoro, Ingraffea 2011; Santoro, Howarth, Ingraffea 2011),
- generic analysis for the UK by the Tyndall Centre for Climate Change Research (Broderick et al. 2011) and
- generic studies for the EU carried out by AEA (2012a+b).

In addition, two German studies on the energy and GHG balance of unconventional natural gas (Fritsche, Herling 2012; IINAS 2014) are used as a baseline for the comparison of results (see Section 5).

The analysis of the respective studies concerns:

- **Methodology**: which system boundaries are used (upstream processes, manufacturing, transport), which allocation rules and which time horizons
- **Data base**: which parameters are used to describe fracking activities (exploration and production, lifetime, auxiliary energy and materials etc.), which emission data for auxiliaries (chemicals, diesel, electricity, natural gas, water etc.) and respective downstream processes, e.g. gas processing, transport and electricity generation.

The analysis disaggregates the studies’ results into the key life-cycle steps:

- exploration and production,
- processing and transport,
- use (power generation) and post-production.

The exploration and production step is further disaggregated where possible.

The disaggregated process data were entered into the GEMIS computer model[2] which already contains German data.

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[1] See Fritsche, Herling (2012) which was carried out for the InfoDialog on Fracking (English summary: http://dialog-erdgasundfrac.de/sites/dialog-erdgasundfrac.de/files/Ex_HydrofrackingRiskAssessment_120611.pdf). The most recent work on potential GHG emissions from shale gas in Germany give reduced results (IINAS 2014).

[2] GEMIS is a model freely available, see http://www.iinas.org/gemis.html or www.gemis.de.

# 2 Data Disaggregation of US Studies

The US studies analyzed here (Howarth 2012a+b; Howarth, Santoro, Ingraffea 2011+2012; Santoro et al. 2011) represent the **upper end** in the range of life-cycle GHG emissions of shale gas provision in comparison to other US studies (Larson 2013) and have been cited by many. The studies also address conventional natural gas, and derive a range of estimates with base values.

The original data from the US studies were **converted here** into $CO_2$eq using the 100-year GWP from IPCC (2007) and based on lower heating values (LHV) to allow for a comparison with other studies[3].

## 2.1 Emissions from Exploration and Well Completion

Santoro et al. (2011) and Howarth, Santoro, Ingraffea (2011) assume 1.9% of the total lifetime gas production of unconventional shale-gas wells are emitted in the exploration and development phase, consisting of $CH_4$ release from initial flow-back (0.6 to 3.2 % with base value of 1.6%) and "drill-out" (0.33%), and based on data from EPA (2010)[4].

In addition, direct $CO_2$ emissions[5] from drilling, trucks and other diesel-using equipment are estimated as 0.92 g $CO_2$/MJ.

## 2.2 Emissions from Production

The US studies estimate that 0.3 to 1.9% of the total lifetime share gas production is emitted as "routine venting and equipment leaks at well site", referring to GAO (2010), and excluding any flaring.

## 2.3 Emissions from Processing

Howarth et al. (2011) give a range of 0 to 0.19% for gas emitted during processing (fugitive emissions, leaks etc.), with the higher number from US EPA default data for fugitive emissions from processing. The zero figure is for "pipeline ready" gas which requires no processing.

In addition, the US studies analyzed here give direct $CO_2$ emissions of 1.9 g/MJ from gas burnt in boilers etc. in the processing plants.

[3] The US studies use the 20-year time horizon for the GWP of $CH_4$, and the original data in the US studies use a higher GWP for $CH_4$ than given in IPCC (2007), citing Shindell (2009) who argued that indirect forcing effects of methane needs to be considered, i.e. they use a GWP of 33 over 100 years and 105 over 20 years. In this study, the US values were converted into $CO_2$eq using a 100-year GWP of 25 for $CH_4$ based on IPCC (2007).

[4] The studies assume that shale gas contains 79% $CH_4$ based on EPA (2010).

[5] Converted from original figure of 0.25 g C-$CO_2$/MJ, i.e. $CO_2$ is given as C in the source documents.

## 2.4 Emissions from Transmission, Storage, and Distribution

Howarth et al. (2011) give aggregated data for gas leakage during transmission, storage and distribution, with 1.4% as lower and 3.6% as the upper limit.

In addition, the US studies analyzed here give direct $CO_2$ emissions of 0.6 g/MJ from gas burnt in compressors etc. during transmission, storage and distribution of shale gas.

## 2.5 Summary of the Analysis of US Studies

The key results of the US studies, broken down into the main life-cycle phases and contributions from combustion-related $CO_2$ emissions and $CH_4$ losses are given in Table 1.

The $CH_4$-related GHG emissions dominate the life-cycle phases (except processing) and the total.

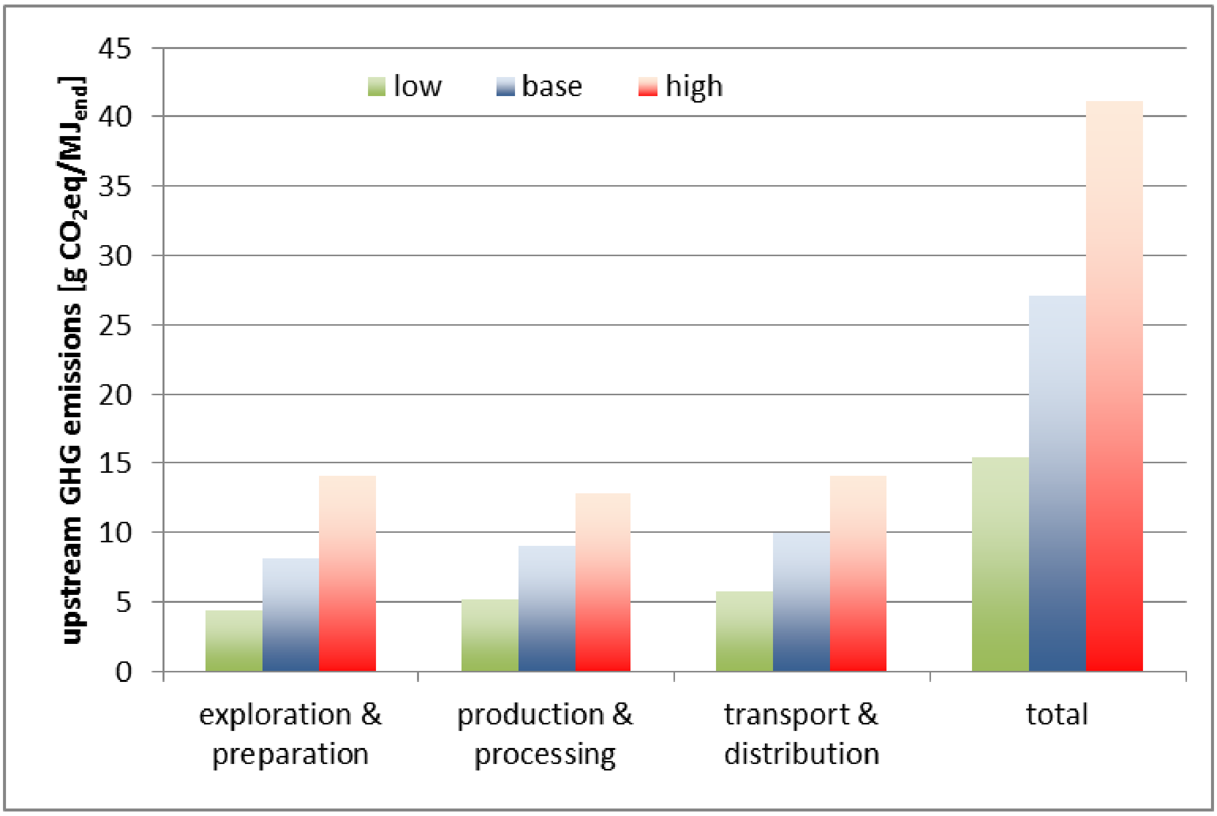
*Table 1 Breakdown of Life-Cycle GHG Emissions from US Shale Gas Provision given in the US Studies*

| | $CO_2$eq in g/$MJ_{LHV}$ | | | shares in total GHG emissions | | |
|---|---|---|---|---|---|---|
| **Life-cycle phase** | **low** | **base** | **high** | **low** | **base** | **high** |
| **exploration** | **4.4** | **8.2** | **14.2** | **29%** | **30%** | **34%** |
| - $CO_2$ from combustion | 0.9 | 0.9 | 0.9 | 6% | 3% | 2% |
| - $CH_4$ from losses etc. | 3.5 | 7.2 | 13.2 | 23% | 27% | 32% |
| **production** | **3.3** | **6.8** | **10.3** | **21%** | **25%** | **25%** |
| - $CO_2$ from combustion | 2.2 | 2.2 | 2.2 | 14% | 8% | 5% |
| - $CH_4$ from losses etc. | 1.1 | 4.6 | 8.1 | 7% | 17% | 20% |
| **processing** | **1.9** | **2.3** | **2.6** | **12%** | **8%** | **6%** |
| - $CO_2$ from combustion | 1.9 | 1.9 | 1.9 | 12% | 7% | 5% |
| - $CH_4$ from losses etc. | 0.0 | 0.4 | 0.7 | 0% | 1% | 2% |
| **transport & distribution** | **5.8** | **10.0** | **14.1** | **38%** | **37%** | **34%** |
| - $CO_2$ from combustion | 0.6 | 0.6 | 0.6 | 4% | 2% | 1% |
| - $CH_4$ from losses etc. | 5.3 | 9.4 | 13.5 | 34% | 35% | 33% |
| **total** | **15.4** | **27.2** | **41.1** | | | |
| - $CO_2$ from combustion | 5.6 | 5.6 | 5.6 | | | |
| - $CH_4$ from losses etc. | 9.9 | 21.6 | 35.6 | | | |

*Source: own compilation from Santoro et al. (2011) and Howarth, Santoro, Ingraffea (2011); original data converted using GWP from IPCC (2007) for 100 year time horizon*

Total GHG emissions (in $CO_2$eq) for US shale gas range from 15.4 to 41.1 g/$MJ_{LHV}$ with a base value of 27.2 g/$MJ_{LHV}$. A graphical representation of the US studies results is given in Figure 1.

*Figure 1 Breakdown of Life-Cycle GHG Emissions from Shale Gas Provision given in the US Studies*




*Source: own compilation from Santoro et al. (2011) and Howarth, Santoro, Ingraffea (2011); original data converted using GWP from IPCC (2007) for 100 year time horizon*

Larson (2013) gives a comparison of recent US studies, indicating a range of upstream GHG emissions from conventional and shale gas of 4 - 22 g $CO_2$eq/GJ for $CH_4$ and of 3 - 6 g $CO_2$eq/GJ for $CO_2$, with totals of 7 - 27 $CO_2$eq/GJ (all data for 100-year GWP of $CH_4$ and LHV figures).

# 3 Data Disaggregation of the UK Study

The UK study carried out by the Tyndall Centre for Climate Change Research (Broderick et al. 2011) analyses energy use and emission data from other (mainly US) studies, and additional information from UK sources. It specifies the **additional** emissions from shale gas compared to conventional natural gas.

## 3.1 Emissions from Exploration and Well Completion

Broderick et al. (2011) assume that exploration and vertical drilling for shale gas is similar to natural gas, but **additional** horizontal drilling and hydraulic fracturing is needed.

The respective $CO_2$ emissions of 15-17 t/well are calculated for horizontal drilling of 300-1500 m, and additional 295 t of $CO_2$ for fracturing (based on US Marcellus Shale data). Data for chemicals are not included.

Transportation of water to and wastewater from the well plus wastewater treatment are calculated to release additional 38 - 68 t of $CO_2$.

The total $CO_2$ emissions per well are determined as 348 - 438 t per well.

Regarding fugitive emissions and leakage of $CH_4$, the study uses the upper (3.2%) and lower (0.6%) percentage of lifetime production of methane that is potentially emitted during flow back, referring to Howarth et al. (2011). This translates into a range of $CO_2$eq emissions of 2.9 - 15.3 g/MJ.

## 3.2 Emissions from Production and Processing

The UK study does not give own estimates for the production and processing. To allow for a comparison, data from a German study (Fritsche, Herling 2012) was added in Table 2.

## 3.3 Emissions from Transmission, Storage, and Distribution

The UK study does not give own estimates for transmission, storage and distribution effects but refers to the Howarth et al. (2011) range of 1.4% - 3.6% of methane produced over the lifecycle being emitted as $CH_4$.

## 3.4 Summary of the Analysis of the UK Study

The key results of the UK study, broken down into the main life-cycle phases and contributions from combustion-related $CO_2$ emissions and $CH_4$ losses are given in Table 2.

Note that in this table, only the exploration and production stage are data from Broderick et al. (2011), while the production and processing data were added here from the German study (based on Fritsche, Herling 2012) and the transport

& distribution data are from Howarth et al. (2011), as this reference was given in the Tyndall study.

*Table 2 Breakdown of Life-Cycle GHG Emissions from Shale Gas Provision according to the UK Study*

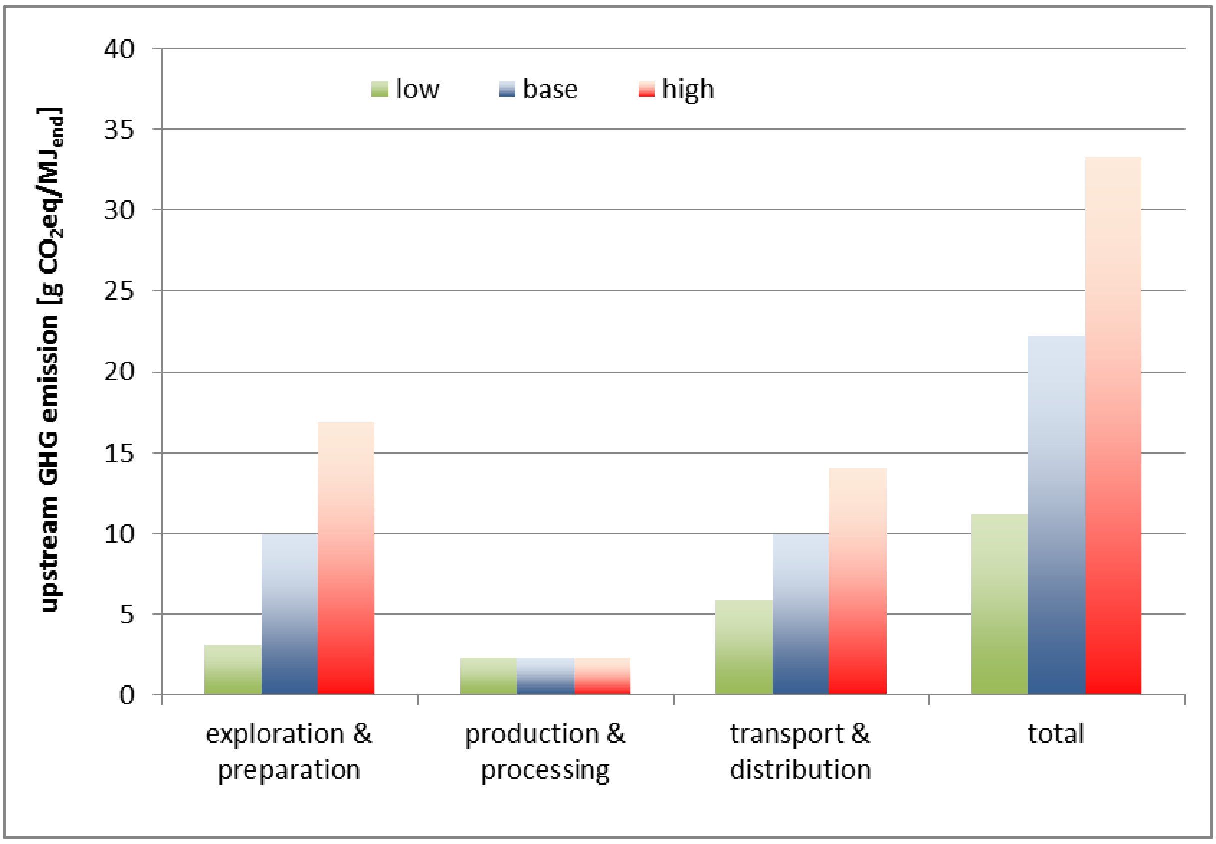
| | $CO_2$eq in g/$MJ_{LHV}$ | | | shares in total GHG emissions | | |
|---|---|---|---|---|---|---|
| **Life-cycle phase** | **low** | **base** | **high** | **low** | **base** | **high** |
| **exploration + preparation** | **3.0** | **10.0** | **16.9** | **27%** | **45%** | **51%** |
| - $CO_2$ from combustion | 0.1 | 0.9 | 1.6 | 1% | 4% | 5% |
| - $CH_4$ from losses etc. | 2.9 | 9.1 | 15.3 | 26% | 41% | 46% |
| **production & processing*** | **2.3** | **2.3** | **2.3** | **21%** | **10%** | **7%** |
| - $CO_2$ from combustion | 2.3 | 2.3 | 2.3 | 21% | 10% | 7% |
| - $CH_4$ from losses etc. | 0.0 | 0.0 | 0.0 | 0% | 0% | 0% |
| **transport & distribution**** | **5.8** | **10.0** | **14.1** | **52%** | **45%** | **42%** |
| - $CO_2$ from combustion | 0.6 | 0.6 | 0.6 | 5% | 3% | 2% |
| - $CH_4$ from losses etc. | 5.3 | 9.4 | 13.5 | 47% | 42% | 41% |
| **total** | **11.2** | **22.3** | **33.3** | | | |
| - $CO_2$ from combustion | 3.0 | 3.8 | 4.5 | | | |
| - $CH_4$ from losses etc. | 8.2 | 18.5 | 28.8 | | | |

*Source: own compilation based on Broderick et al. (2011); "base" = average of low and high computed here (no base data are given in the Tyndall study)*

**= production & processing data* ***were added*** *from the German study (Fritsche, Herling 2012) to allow for comparison **= transport & distribution data are from Howarth et al. (2011*

Total GHG emissions (in $CO_2$eq) for shale gas as given in the UK study range from 11.2 to 33.3 g/$MJ_{LHV}$. A graphical representation of the UK study results is given in Figure 2.

*Figure 2 Breakdown of Life-Cycle GHG Emissions from Shale Gas Provision in the UK Study*




*Source: own compilation based on Broderick et al. (2011); "base" = average of low and high computed here (no base data are given in the Tyndall study); note that production & processing data **were added** from the German study (Fritsche, Herling 2012) to allow for comparison*

# 4 Data Disaggregation of EU Studies

The EU studies carried out by AEA (2012a+b) consist of a compilation of emission data from other - mainly US - studies, and develop a series of scenarios to reflect key parameters influencing the GHG emissions from shale gas.

## 4.1 Emissions from Exploration and Well Completion

The EU studies consider site preparation in terms of land clearing, construction and auxiliary materials, vertical and horizontal drilling, water use and waste-water treatment. For drilling, they use the US data discussed in Section 2.1 of this study.

The total lifetime gas production of an unconventional shale-gas well is assumed to be 56.6 $Mm^3$ in the base case, with sensitivity cases of 28.3 $Mm^3$ (low) and 84.9 $Mm^3$ (high), respectively. The EU studies assume an emission volume of 312,008 $m^3$ of gas per well for the base case, and that 15% of these emissions are flared (98% combustion efficiency) while the remaining 85% are vented. The sensitivity cases assume a 90% flaring rate (low) and complete venting (high), with a higher emission volume of 396200 $m^3$ of gas.

## 4.2 Emissions from Production and Processing

The EU studies give estimates for conventional natural gas production and processing in several countries (NL, NO, RU, UK) without providing specific data for shale gas. To allow for a comparison, data from the German study (Fritsche, Herling 2012) were added in Table 3.

## 4.3 Emissions from Transmission, Storage, and Distribution

Similar to the production and processing stage, the EU studies give estimates for conventional natural gas pipeline transmission in several countries (NL, NO, RU, UK), and provide an assumption for shale gas: in the low and base case, pipeline emissions result from combustion emissions of 0.9% and diffuse emissions of 0.013 % of gas throughput (for 500 km transport distance). For the high case, a transport distance of 1000 km is assumed. The EU studies do not consider gas leakage during storage and distribution.

## 4.4 Summary of the Analysis of EU Studies

The key results of the EU studies, broken down into the main life-cycle phases and contributions from combustion-related $CO_2$ emissions and $CH_4$ losses are given in Table 3.

*Table 3 Breakdown of Life-Cycle GHG Emissions from Shale Gas Provision given in the EU studies*

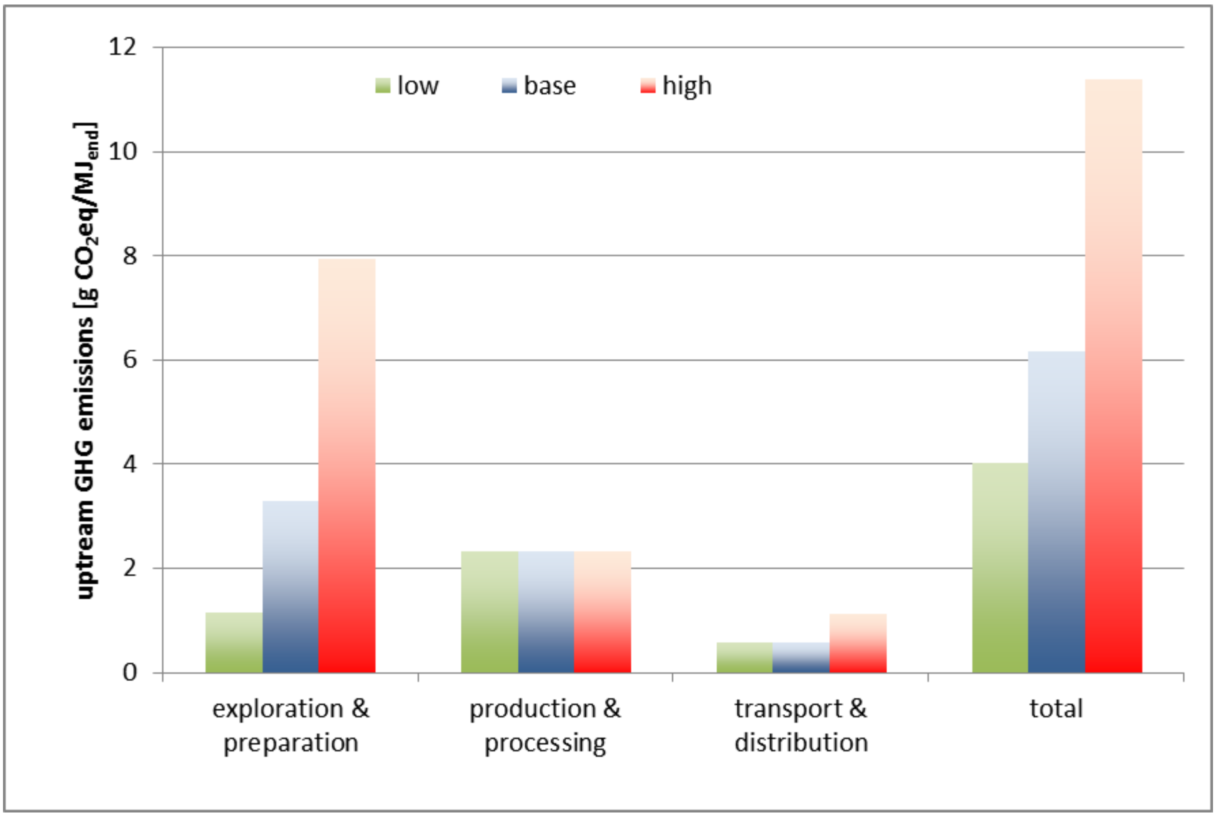
| | $CO_2eq$ in $g/MJ_{LHV}$ | | | shares in total GHG emissions | | |
|---|---|---|---|---|---|---|
| **Life-cycle phase** | **low** | **base** | **high** | **low** | **base** | **high** |
| **exploration + preparation** | **1.1** | **3.3** | **7.9** | **28%** | **53%** | **70%** |
| - $CO_2$ from combustion | 0.9 | 0.9 | 0.9 | 23% | 15% | 8% |
| - $CH_4$ from losses etc. | 0.2 | 2.4 | 7.0 | 5% | 38% | 62% |
| **production & processing** | **2.3** | **2.3** | **2.3** | **58%** | **38%** | **20%** |
| - $CO_2$ from combustion | 2.3 | 2.3 | 2.3 | 58% | 38% | 20% |
| - $CH_4$ from losses etc. | 0.0 | 0.0 | 0.0 | 0% | 0% | 0% |
| **transport & distribution** | **0.6** | **0.6** | **1.1** | **14%** | **9%** | **10%** |
| - $CO_2$ from combustion | 0.5 | 0.5 | 1.0 | 12% | 8% | 9% |
| - $CH_4$ from losses etc. | 0.1 | 0.1 | 0.1 | 2% | 1% | 1% |
| **total** | **4.0** | **6.2** | **11.4** | | | |
| - $CO_2$ from combustion | 3.7 | 3.7 | 4.2 | | | |
| - $CH_4$ from losses etc. | 0.3 | 2.4 | 7.2 | | | |

*Source: own compilation based on AEA (2012a+b)*

**= production & processing **were added** from the German study (Fritsche, Herling 2012) to allow for comparison*

Total GHG emissions in $CO_2eq$ for shale gas as given in the EU studies range from 4.0 to 11.4 $g/MJ_{LHV}$ with a “base” value of 6.2 $g/MJ_{LHV}$. Figure 3 gives a graphical representation of the EU studies results.

*Figure 3 Breakdown of Life-Cycle GHG Emissions from Shale Gas Provision given in the EU Studies*




*Source: own compilation based on AEA (2012a+b); note that production & processing data **are added here** from the German study (Fritsche, Herling 2012) to allow for comparison*

# 5 Comparison of Data

## 5.1 Comparison and Discussion of Life-Cycle GHG Emissions from Shale Gas Provision

Table 4 summarizes the analysis of the life-cycle GHG emissions of shale gas in the US, UK and EU studies.

*Table 4 Life-Cycle GHG Emissions from Shale Gas Provision given in the Studies*

| $CO_2$eq in g/$MJ_{LHV}$ | low | | | base | | | high | | |
|---|---|---|---|---|---|---|---|---|---|
| **Life-cycle phase** | **US** | **UK** | **EU** | **US** | **UK** | **EU** | **US** | **UK** | **EU** |
| **exploration & preparation** | **4.4** | **3.0** | **1.1** | **8.2** | **10.0** | **3.3** | **14.2** | **16.9** | **7.9** |
| - $CO_2$ from combustion | 0.9 | 0.1 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 1.6 | 0.9 |
| - $CH_4$ from losses etc. | 3.5 | 2.9 | 0.2 | 7.2 | 9.1 | 2.4 | 13.2 | 15.3 | 7.0 |
| **production & processing** | **5.2** | **2.3** | **2.3** | **9.0** | **2.3** | **2.3** | **12.9** | **2.3** | **2.3** |
| - $CO_2$ from combustion | 4.1 | 2.3 | 2.3 | 4.1 | 2.3 | 2.3 | 4.1 | 2.3 | 2.3 |
| - $CH_4$ from losses etc. | 1.1 | 0.0 | 0.0 | 5.0 | 0.0 | 0.0 | 8.8 | 0.0 | 0.0 |
| **transport & distribution** | **5.8** | **5.8** | **0.6** | **10.0** | **10.0** | **0.6** | **14.1** | **14.1** | **1.1** |
| - $CO_2$ from combustion | 0.6 | 0.6 | 0.5 | 0.6 | 0.6 | 0.5 | 0.6 | 0.6 | 1.0 |
| - $CH_4$ from losses etc. | 5.3 | 5.3 | 0.1 | 9.4 | 9.4 | 0.1 | 13.5 | 13.5 | 0.1 |
| **total** | **10.2** | **8.9** | **1.7** | **18.1** | **19.9** | **3.8** | **28.2** | **31.0** | **9.1** |
| **- $CO_2$ from combustion** | 1.5 | 0.7 | 1.4 | 1.5 | 1.5 | 1.4 | 1.5 | 2.2 | 1.9 |
| **- $CH_4$ from losses etc.** | 8.7 | 8.2 | 0.3 | 16.6 | 18.5 | 2.4 | 26.7 | 28.8 | 7.2 |

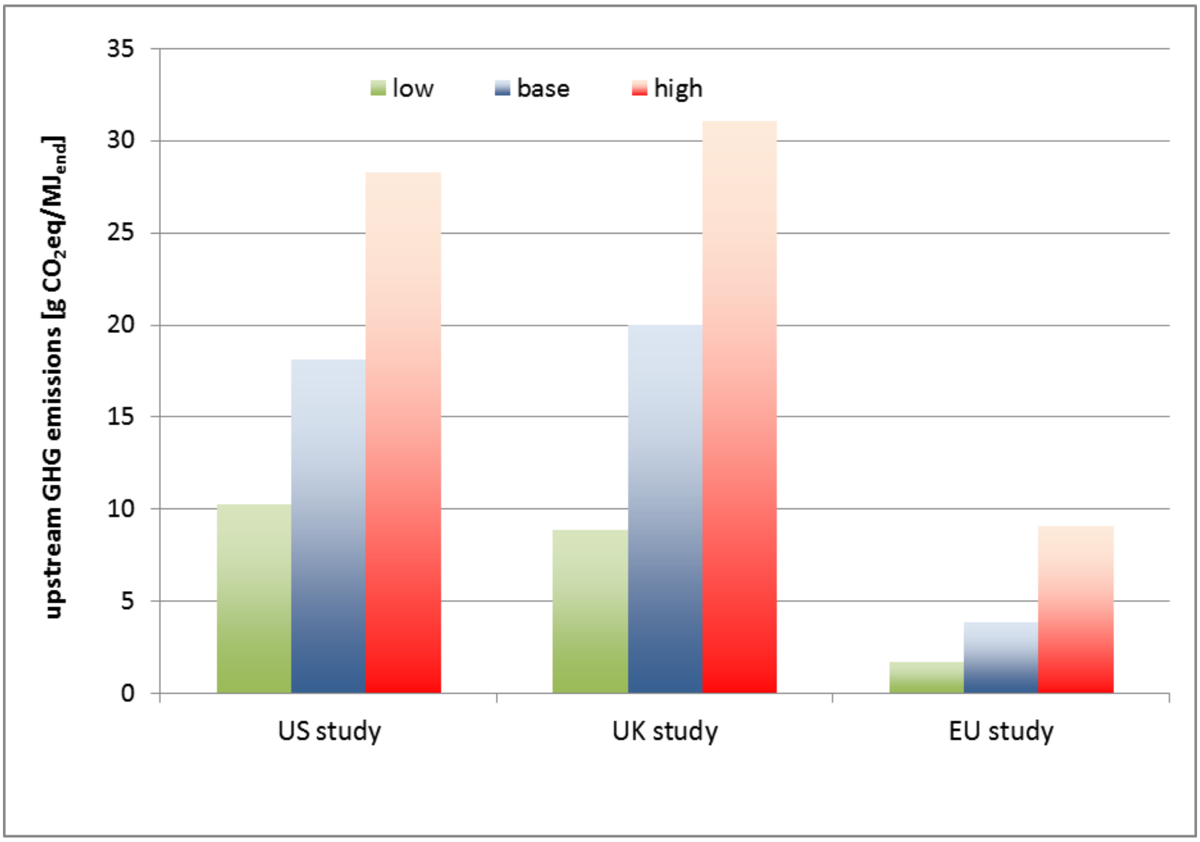
*Source: own compilation; note that for UK and EU, production & processing data* ***were added*** *from the German study (Fritsche, Herling 2012) to allow for comparison*

The US and UK studies are quite similar in their findings with the exception of the production and processing phase, but the totals are comparable.

The EU studies give **significantly lower** results: about half of the emissions for the exploration and preparation phase, and less than 10% for the transport and distribution phase, and less than 1/3 for the total.

Figure 4 shown shows this in graphical representation.

*Figure 4 Comparison of Life-Cycle GHG Emissions from Shale Gas Provision given in the Studies*

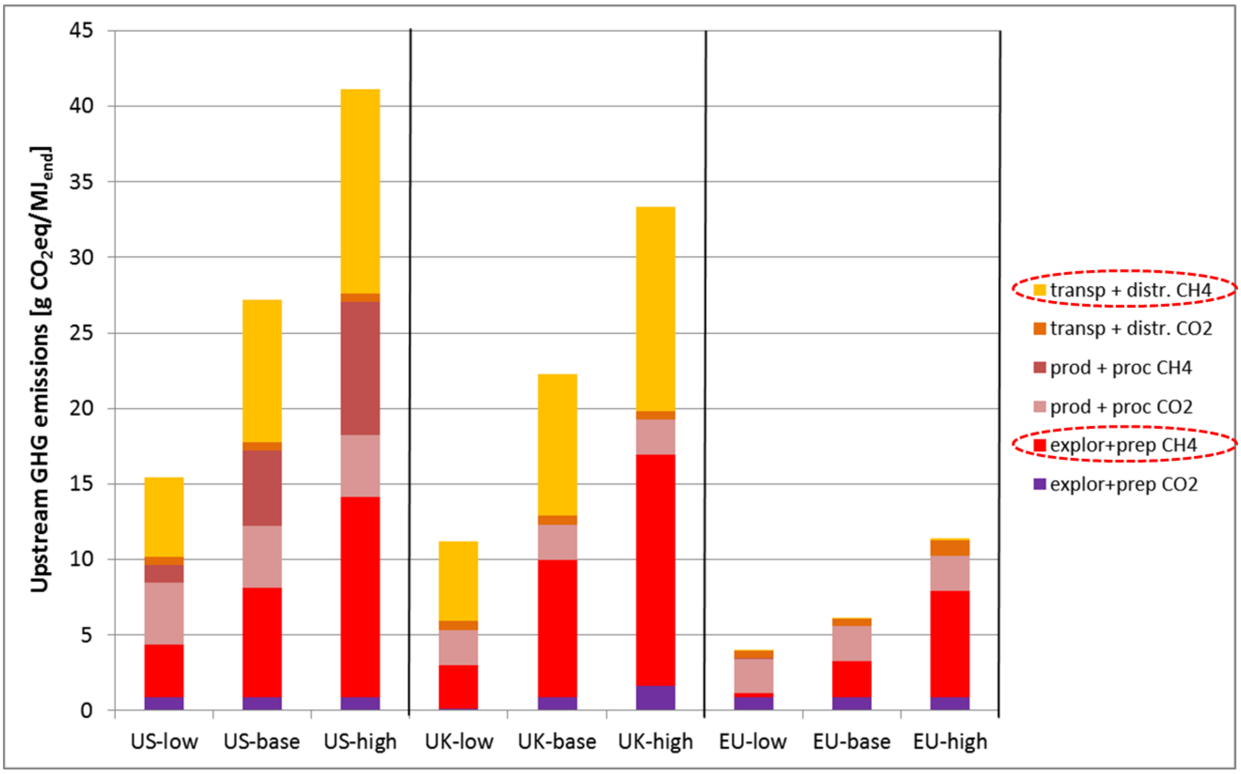



*Source: own compilation; note that for UK and EU, production & processing data* ***were added*** *from the German study (Fritsche, Herling 2012) to allow for comparison*

Figure 5 gives a further breakdown of the study results into emissions from combustion ($CO_2$) and leakage ($CH_4$) for the key life-cycle stages.

For the US and the UK, about 1/3 of total GHG emissions associated with shale gas provision result from $CH_4$ leakage during transmission and distribution, and about the same from $CH_4$ leakage during exploration and preparation.

*Figure 5 Breakdown of Life-Cycle GHG Emissions from Shale Gas Provision given in the Studies*




*Source: own compilation; note that for UK and EU, production & processing data* ***were added*** *from the German study (Fritsche, Herling 2012) to allow for comparison*

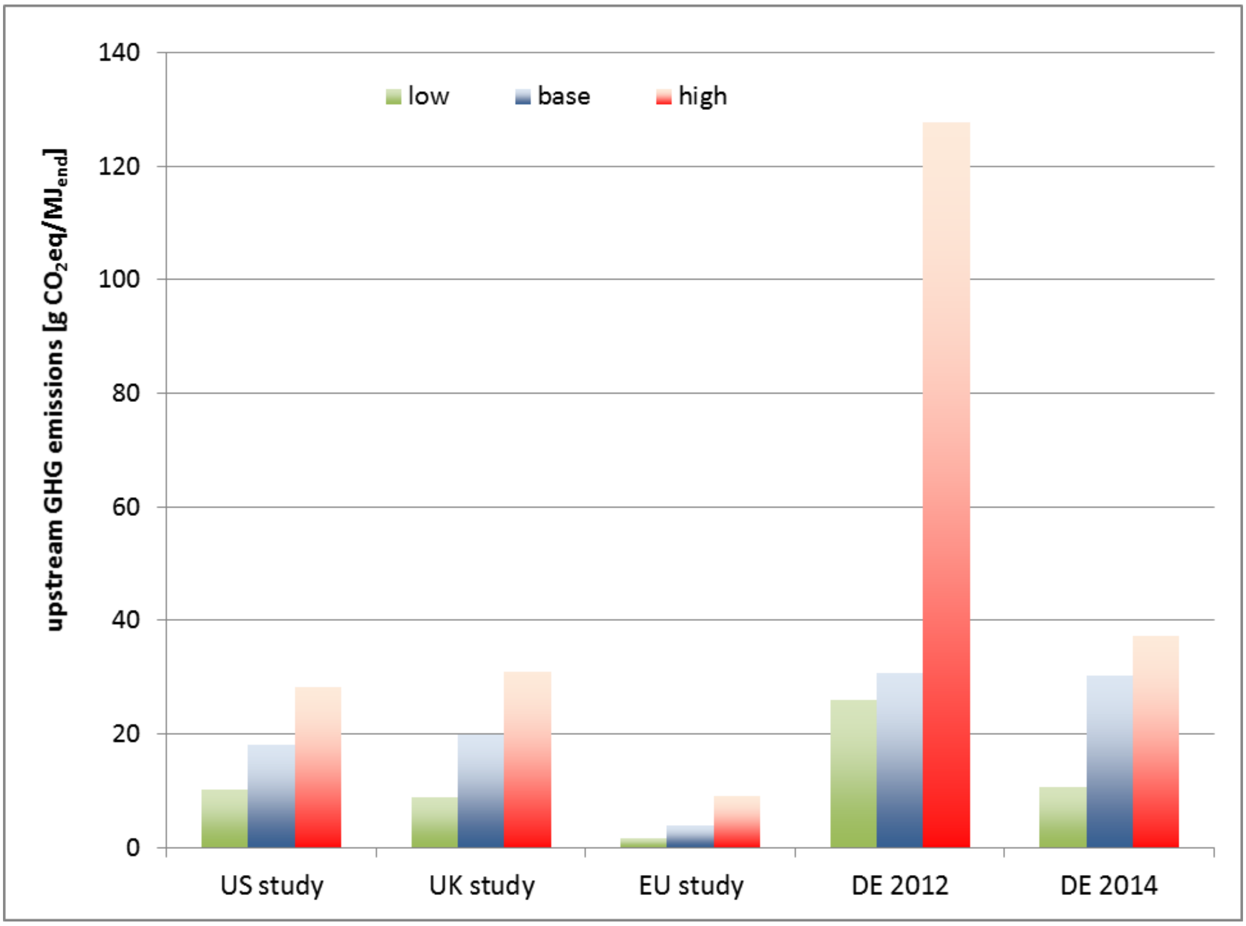
The results can be compared also to the ones for Germany (Fritsche, Herling 2012; IINAS 2014), as shown in Figure 6.

The "low" and "base" cases for Germany are comparable to the US and UK figures, while the "high" case is about **four times higher** than in these studies.

The reason for this is that the German "high" cases assumes a combination of "worst case" data, i.e. comparatively small reservoir, deep drilling (> 3,000 m) **and** consider **post-production** $CH_4$ releases[6].

[6] see for details Fritsche, Herling (2012), and the most recent work on potential GHG emissions from shale gas in Germany which gives reduced results (IINAS 2014).

*Figure 6 Comparison of Life-Cycle GHG Emissions from Shale Gas Provision given in the Studies plus German Data*




*Source: own compilation; note that for UK and EU, production & processing data* ***were added*** *from the German study (Fritsche, Herling 2012) to allow for comparison; DE 2014 = data from IINAS (2014)*

## 5.2 Comparison and Discussion of GHG Emissions from Electricity Generation based on Shale Gas

The data analysis presented so far considered the shale gas life-cycles until the provision of the gas to a customer, but excluded the combustion of the shale gas, i.e. the data represent the "upstream" life-cycle phases.

In the following, the combustion of the shale gas is assumed in a modern combined-cycle powerplant for electricity generation with an average electric net efficiency of 52.5 % (based on LHV).

The comparison of the respective GHG emission data given in Table 5 also includes a study of Shell (2011) which presents modeling data for US shale gas, and the German studies (Fritsche, Herling 2012; IINAS 2014).

As can be seen, the US and UK data as well as the Shell and the German studies give quite comparable results for the low and base cases, while the EU studies again give results which are typically 10-20% lower.

*Table 5 Life-Cycle GHG Emissions for Electricity from Shale Gas*

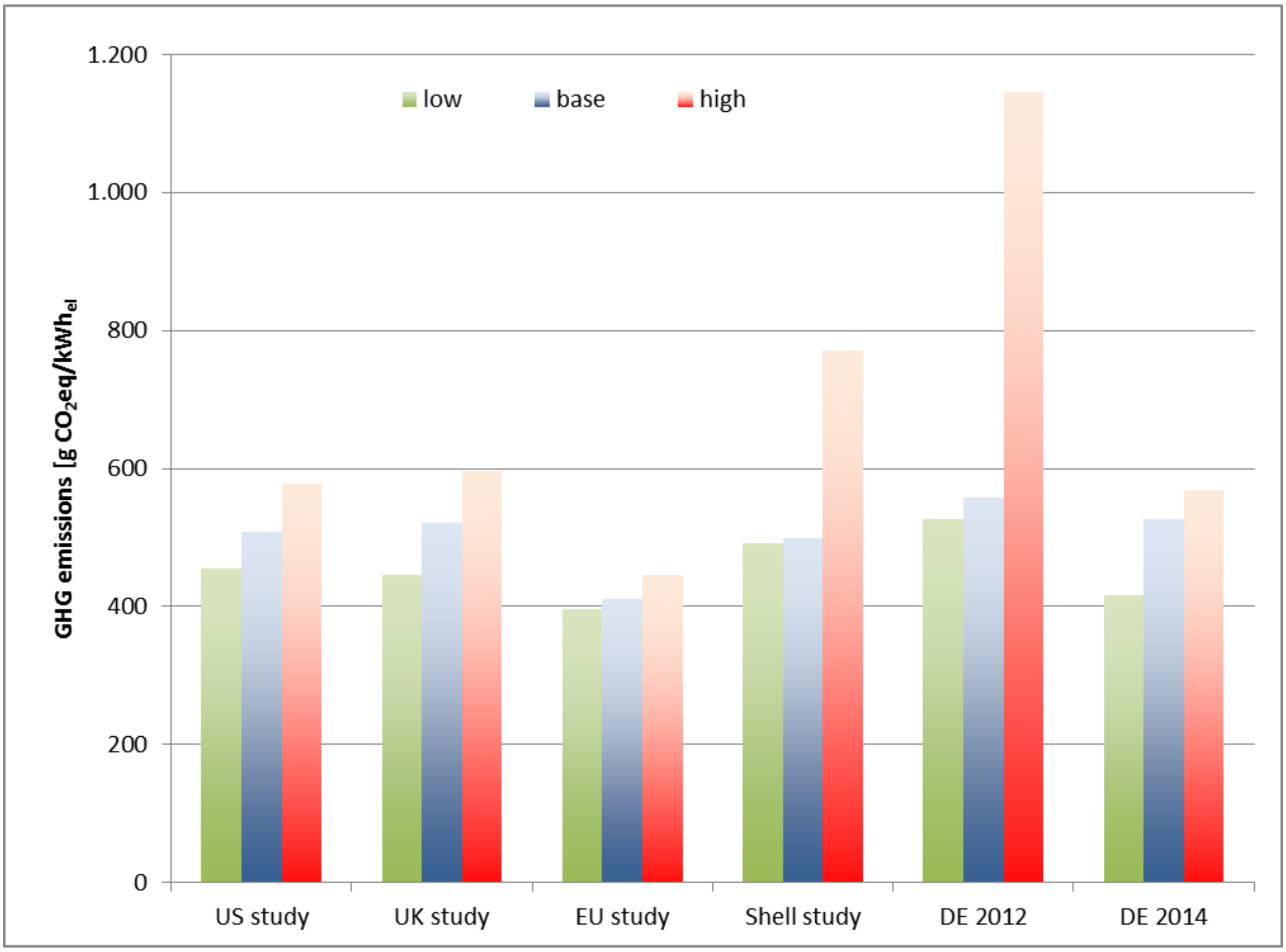
| **$CO_2$eq in g/kWh$_{el}$** | **low** | **base** | **high** |
|---|---|---|---|
| US studies | 454 | 508 | 578 |
| UK study | 445 | 521 | 597 |
| EU studies | 396 | 410 | 446 |
| **for comparison:** | | | |
| Shell study | 492 | 499 | 770 |
| DE 2012 | 527 | 558 | 1146 |
| DE 2014 | 417 | 526 | 569 |

*Source: own compilation; note that for UK and EU, production & processing data* ***were added*** *from Fritsche, Herling (2012) to allow for comparison; electricity generation efficiency was set to 52.5% (based on LHV); DE 2014 = data from IINAS (2014)*

The "high" cases from the Shell study assumes complete venting of diffuse $CH_4$ emissions (as a sensitivity case), while the German "high" cases again represent **extremely** unfavorable conditions and **include** post-production $CH_4$ releases.

The graphical comparison of results given in Figure 7 shows this clearly.

*Figure 7 Comparison of Life-Cycle GHG Emissions for Electricity from Shale Gas*




*Source: own compilation; note that for UK and EU, production & processing data **were added** from Fritsche, Herling (2012) to allow for comparison; electricity generation efficiency was set to 52.5% (based on LHV); DE 2014 = data from IINAS (2014)*

In the following Table 6, the total GHG emissions given above are **broken down** into the “upstream” parts from the shale gas provision, and the combustion emissions related to electricity generation in a combined-cycle powerplant.

*Table 6 Breakdown of Life-Cycle GHG Emissions for Electricity from Shale Gas*

| **g $CO_2$eq/kWh$_{el}$** | **upstream** | **combustion** | **total** | **upstream share** |
|---|---|---|---|---|
| US-low | 106 | 384 | **490** | 22% |
| US-base | 186 | 384 | **570** | 33% |
| US-high | 282 | 384 | **666** | 42% |
| UK-low | 77 | 384 | **461** | 17% |
| UK-base | 153 | 384 | **537** | 28% |
| UK-high | 229 | 384 | **613** | 37% |
| EU-low | 28 | 384 | **412** | 7% |
| EU-base | 42 | 384 | **426** | 10% |
| EU-high | 78 | 384 | **462** | 17% |

*Source: own compilation; note that for UK and EU, production & processing data **were added** from Fritsche, Herling (2012) to allow for comparison; electricity generation efficiency was set to 52.5% (based on LHV)*

For the US and UK studies, the “upstream” share is approx. 20-40 %, depending on the case, while in the EU studies, the share is only about half.

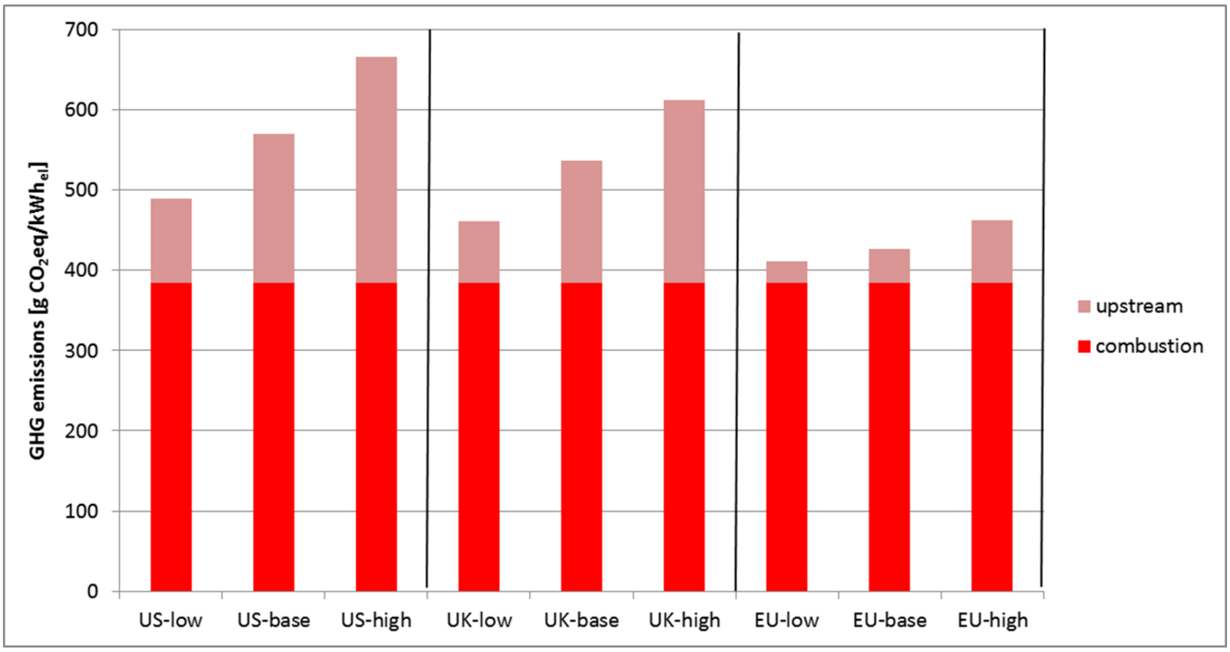
The “high” case in the EU corresponds to the “low” cases in the US and the UK, and corresponds to 69 (US) and 75 (UK) percent of the respective “high” cases in the US, and the UK.

The “base” case in the EU corresponds to 75 (US) and 79 (UK) percent of the respective “base” case emissions for shale-gas electricity in the US, and the UK.

The “low” case in the EU corresponds to 84 (US) and 89 (UK) percent of the respective “low” case GHG emissions for shale-gas electricity in the US, and the UK.

Figure 8 gives the graphical representation of these results.

*Figure 8 Breakdown of Life-Cycle GHG Emissions for Electricity from Shale Gas*




*Source: own compilation; note that for UK and EU, production & processing data* ***were added*** *from Fritsche, Herling (2012) to allow for comparison; electricity generation efficiency was set to 52.5% (based on LHV)*

# 6 Discussion and Conclusions

## 6.1 Discussion of the Studies and Results from other Work

The results of the US and UK studies as well as the "low" and "base" cases of the Shell (2011) and the German studies (Fritsche, Herling 2012; IINAS 2014) **indicate a robust range** of life-cycle emissions for electricity from shale gas which is comparable to other studies in the recent literature[7].

The EU studies give a more optimistic view, but their low and base cases are comparable to respective findings from the Shell (2011) and German studies, considering the slightly different system boundaries.

The "high" cases given in all studies can be compared only with **extreme caution**, as they represent **very different** assumptions on diffuse $CH_4$ releases.

When comparing study results from the US (and the UK study relying mainly on US sources) with those for the EU (and Germany), key differences must be seen regarding

- resource size and resource recovery rates: existing US shale gas plays represent large reservoirs and moderate drilling depths, while European sites appear smaller, and need deeper drilling;
- the EU and German studies assume modern low-leakage equipment and high flaring shares for non-used (but captured) shale gas, while the US situation most probably is less favorable for **existing** shale gas plays[8];
- for **new** shale developments in the US, GHG emissions are considered to be quite low (Allen et al. 2013; EPA 2013) due to "green completion" equipment which would bring the emissions into the EU and German range for the "low" and "base" cases;
- **downstream** processes, especially transmission and distribution, appear less prone to diffuse $CH_4$ losses and lower $CO_2$ emissions **in Europe** than in the US where older equipment and larger transport distances are prevalent (Allen et al. 2013)[9].

[7] See e.g. Burnham et al. (2012); CCA (2014); Heath et al. (2014); IEA (2012); Larson (2013); Laurenzi, Jersey (2013); O'Sullivan (2012); O'Sullivan, Paltsey (2012); Sandlin (2012); SRU (2013); Weber, Clavin (2012);

[8] See EPA (2011a+2013) for details. The situation might change for **new** shale developments, see EPA (2011b).

[9] The conditions for European natural gas imports **from Russia** are less favorable, though (Fritsche, Herling 2012).

## 6.2 Conclusions

The variety of data to describe the life-cycles of shale gas provision and its use for electricity generation does **not** allow deriving robust results **for all** relevant circumstances and possibly relevant situations, as e.g. post-production $CH_4$ releases were considered only in the German studies.

Still, "base" case estimates for the US and Europe give a **robust range** of emissions for electricity from shale gas, indicating life-cycle GHG emissions reductions compared to coal-based electricity between 40 and 50 %, i.e. life-cycle GHG emissions from coal-based electricity are 1.5 to 2 times higher[10].

For **new** shale gas plays in the US, the GHG emissions appear to be in the "low" range of the US studies, comparable to the respective cases for the EU, and Germany.

There are two major issues to be considered when assessing shale gas, though:

- The "per unit" comparison of GHG emissions from electricity generation based on shale gas and coal reflect the life-cycles, but **not** the overall balance of the real-world energy **system**. With increasing use of shale gas for electricity generation in the US, the domestic role of coal was reduced in the last years, leading to reduced domestic $CO_2$ emissions. Yet, exports of US coal to Europe increased due to favorable energy prices[11], leading to **increased GHG emissions** from coal-fired powerplants **in Europe** (Broderick, Allen 2012). This "leakage" must be considered when evaluating the **absolute** GHG impacts of shale gas development (SRU 2013; IINAS 2014).
- GHG emissions are important when discussing the environmental impacts from shale gas development, but other aspects such as
  - risks of groundwater contamination and induced seismicity as well as
  - local air pollution and noise (mainly due to truck transports)

  need to be reflected as well.

It is beyond the brief analysis presented here to discuss these issues, though.

[10] Note that this is calculated for the $GWP_{100}$ time horizon, and GWPs from IPCC (2007). For shorter time horizons and other GWPs as used in the original US studies, the GHG reductions from shale gas compared to coal would be smaller.

[11] Another factor contributing to this development is the currently very low price for $CO_2$ certificates in the European Emission Trading System (ETS).

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