Future European shale gas life cycle greenhouse gas emissions for electric power generation in comparison to other fossil fuels

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ABSTRACT

The carbon footprint of shale gas combusted in Europe was estimated from nine European shale gas plays as potential production regions. Greenhouse gas emission sources during shale gas production, such as fugitives from hydraulic fracturing or combustion emissions from horizontal drilling, were added to emissions occurring for conventional gas extraction. Greenhouse gas emissions are expressed as kg CO2-equivalents per MJ delivered, and calculated for a kWh of electricity generated. Estimated total GHG emissions from the use of European shale gas for electricity production range from 0.42 to 0.75 kg CO2-eq/kWh when the combustion in the power plant is included. This is within the range reported in the literature. The cumulative carbon footprints for a number of fossil electricity generation scenarios for Europe were also calculated. The results indicate an advantage of gas over other fossil sources in a wide range of scenarios. These results are only reversed with very high (10%) upstream losses for shale gas. With the current knowledge there is still a substantial climate benefit of replacing coal with (shale) gas even in the EU reference scenario.

Keywords: shale gas, carbon footprint, EU reference scenario, electricity generation

Introduction

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 proven to be a game changer in the U.S. energy market (EIA, 2015), where its contribution to electricity generation exceeded that of coal for the first time in 2016 (EIA, 2017). The European Commission's Energy Roadmap 2050 (EC, 2011) identifies gas as a critical energy source for the transformation of the energy system to a system with lower CO_2 emissions by combining 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 term. Greenhouse gas emissions for electricity generation from gas are generally lower than those from oil and coal due to a more beneficial heat per carbon density and higher combustion efficiencies (e.g. IPCC, 2011). This advantage has been confirmed in many life cycle assessments for the United States (Burnham et al., 2012; Dale et al., 2013; Heath et al., 2014a; Hultman et al., 2011; Jiang et al., 2011; Laurenzi & Jersey, 2013; Stephenson et al., 2013; Cooper et al., 2016) and China (Chang et al., 2015) even when using imported gas (Raj et al., 2016). However, uncertainty remains on the losses of methane to the atmosphere during production and transport of gas (Heath et al., 2014b; Jiang et al., 2011). Since methane is a more powerful greenhouse gas than CO_2, this uncertainty has led to the postulation that this leakage might offset the advantage of gas over coal during combustion (Howarth et al., 2011; Wigley, 2011). Estimations of the trade-off point where life cycle GHG emissions of electricity from gas would be higher than those from coal due to upstream emissions range from 3%-15% of production volumes (e.g. Sanchez and Mays, 2015; Howarth et al., 2012; Qin et al., 2017). Part of the variation in estimations can be explained by differences in system boundaries and assumptions on power plant efficiencies. Next to life cycle approaches, another way of assessing emissions is by measuring around and/or over a large production area and establishing an integrated overall source strength (e.g. Peischl et al., 2015; 2016; Johnson et al., 2017; Karion et al., 2015). Literature suggests discrepancies between emission inventory estimates based on activity data multiplied with emission factors and integrated overall source strength approaches for the oil and gas sector in the US may be in the order of 50-100% (Miller, et al., 2013; Moore, et al., 2014; Alvarez et al., 2018).

Most studies concerned with the life cycle greenhouse gas emissions of shale gas exploitation and use were conducted for the United States. Questions are raised about the specific environmental footprint of shale gas in Europe as a whole as well as in individual Member States. Few studies attempted to translate the U.S. based knowledge to the European conditions (Broderick et al., 2011; Foster & Perks, 2012), or perform a life cycle assessment based on U.S. experiences and few explorative measurements (Stamford & Azapagic, 2014; Tagliaferri et al., 2017; Mackay & Stone, 2013). Others (e.g. Mackay & Stone, 2013; McGlade et al., 2014) have assessed the potential of shale gas contribution to global greenhouse gas emissions reductions in the short and medium term, taking into consideration also indirect effects on coal use, e.g. via gas prices and export. None of them investigated how the total fossil carbon footprint of electricity generation in various European countries would change if shale gas was to replace other fossil sources.

Within the context of the European H2020 project M4 shale (Measuring, Monitoring, Mitigating and Managing the environmental impact of shale gas), the aim of our research was to estimate the carbon footprint of shale gas exploitation and combustion for electricity generation in Europe based on existing knowledge and models. We also compare the carbon footprints from fossil electricity generation with and without shale gas for Europe as a whole and for individual countries. For this purpose, the life cycle assessment model GHGenius was applied and extended with literature data on emissions related to shale gas operations, and several scenarios were developed for the potential use of shale gas in Europe taking the EU reference scenario as a starting point.

Materials and Method

Several modelling steps were combined to arrive at a comparison of carbon footprints in scenarios. First, carbon footprints of fuel delivery to Europe were derived, then carbon footprints from electricity generation were calculated and finally these were combined in a scenario comparison. An overview of the approach and the system boundaries is shown in Figure 1.

Upstream Carbon Footprint Modelling

Carbon Footprints of shale gas were modelled in two steps: First, upstream GHG emissions per MJ delivered to and from four European regions North, Central, Southeast and Southwest EU (see Table S1 for country allocation) were estimated. Second, emissions from electricity generation were calculated for every European country. Methane and CO_2 were taken into account as greenhouse gasses. To transfer fossil methane emissions to kg CO_2-equivalents (eq), a GWP of 30 was applied (IPCC, 2013).

Estimations of emissions from delivering one MJ of conventional gas and oil to European regions using GHGenius are given by (S&T)[2] Consultants Inc. (2013a,b) and COWI (2015). In short, these upstream emissions are the sum of several fugitive (E_f) and combustive (E_e) emission sources from production, processing and transport:

$$E_{up,i} = \sum_j E_{prod,e,j} \cdot f_{ji} + \sum_j E_{prod,f,j} \cdot f_{ji} + \sum_j E_{proc,e,j} \cdot f_{ji} + \sum_j E_{proc,f,j} \cdot f_{ji} + \sum_j E_{proc,v,j} \cdot f_{ji} + \sum_j E_{trans,e,j} \cdot f_{ji} \cdot d_{ji} + \sum_j E_{trans,f,j} \cdot f_{ji}$$

Where $E_{up,i}$ are the emissions (gCO_2-equivalent) related to a GJ of gas delivered to country i; Note that country j can also be the same as country i. $E_{prod,e,i}$ and $E_{prod,f,i}$ are the production emissions from energy use and fugitives in country j (g CO_2-eq per GJ of gas produced); fji is the contribution of gas from country j to the supply in country i; $E_{proc,e,i;}$ $E_{proc,f,i}$ $E_{proc,v,i}$ are the energy use, fugitive and vented emissions from gas produced in country i (g CO_2-eq per GJ of gas produced); $E_{trans,e,j}$ are the emissions from energy use for pipeline transmission (g CO_2-eq/km) and d_{ji} transport distances from country j to country i (km); $E_{trans,f,i}$, are the fugitive emissions from transport in country j (g CO_2-eq per GJ of gas transported). Emissions from energy use are calculated by multiplying the amount of fuel used by an emission factor and summing over the fuels. Emissions factors can be found in the Supporting Information (Table S5).

Footprints of electricity generation from coal were described by Hauck et al. (2015, see Supplementary Information for more details), which built on the methodology described by $(S\&T)^2$ Consultants Inc. (2013a,b) and COWI (2015) . Upstream emission factors for oil shale which is used in Estonia have been taken from Siirde et al. (2013), the only sources that does not rely on national energy balances and IPCC factors, possibly leading to minor discrepancies between the studies. All of these studies cover full extraction, processing (if necessary) and transportation. The system boundaries are also represented in Figure 1.

Shale gas

Realistic data for shale gas future operations in Europe are scarce or non-existent as only few explorative drillings have taken place (Cooper et al., 2016). In particular, total production from a well, an important parameter to estimate emissions per unit output, is currently unknown. In general, and for our modelling exercise, it is assumed that production and processing of shale gas is not fundamentally different from conventional gas, except for extra activities that are required, especially for (pre-) production of the gas. Activities before actual start of production like well preparation are referred to as pre-production. As summarized by e.g. Moore et al. (2014) extra activities are mainly more and additional drilling (horizontal next to vertical) and (more) hydraulic fracturing during well completion and potentially re-fracturing during the well lifetime. Once gas is injected in high pressure transmission pipelines, no distinction can be made between shale gas and conventional gas. Based hereupon, for all life cycle stages except pre-production and production, GHG emissions were assumed equal to those of conventional natural gas (see calculations above). Extra emissions sources during production were added, following the reasoning in earlier life cycle assessments (Broderick et al., 2011; Qin et al., 2017; Tagliaferri et al., 2017).

Data used to estimate shale gas production in Europe and additional emissions are described below. The composition of raw gas and pipeline gas was set to fit European average conditions based on a compilation by TNO (Costa et al., 2016, Visschedijk et al, 2018) and Altfeld and Schley (2012). The same compositions were assumed for shale gas as for conventional gas from the same country. Emissions from the construction of infrastructure for gas exploitation were not included. For all EU countries, the same consumption mix of shale gas was assumed: proportional to reserve size.

Shale gas reserves

The selection of shale gas plays, geologically similar areas where shale gas accumulation is proven or postulated, was taken from Visschedijk et al. (2018). They identified nine major shale gas plays in seven EU Member States. Maximum production (expected ultimate recovery) per play was based on estimated technically recoverable reserves by EIA (2013). The areas of the plays were calculated in Visschedijk et al. (2018) using GIS and play contours by EIA (2013). The estimated surface areas and reserves are shown in Table 1. Based on the area per play shown in Table 1 and on the assumption that one well pad covers 25km^2 (a 5 x 5 km square) and that 25 (20-30) wells are drilled in one pad (Cremonese, 2016) the required number of wells per play was deduced.

Additional emissions during shale gas production

Additional emission sources occurring during shale gas production and not occurring during conventional gas production have been added based on Broderick et al. (2011). An overview of the values used is given in Table 2. All energy use and emissions are modelled per unit of gas produced. Added emission sources include the following processes:

- *Extra fuel use during production due to horizontal drilling:* These were modelled as the product of the drilling width and the use of diesel per meter drilled.
- *Extra fuel use during production for hydraulic fracturing:* These were modelled based on an average diesel use for one hydraulic fracturing event (Broderick et al. 2011). The total fuel use depends on the number of (re-) fracturing events. All wells are fractured once for startup of the production and it was assumed that 50% of the wells are re-fractured once during their lifetime (Broderick et al., 2011). The extra diesel use per well was calculated as the product of the diesel use per hydraulic fracturing and the number of (re-) fracturing events.
- *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). These were multiplied by the diesel use per tkm of transport

taken from ecoinvent (Spielmann et al., 2007). Ecoinvent is a widely used European life cycle inventory data base, recently updated by Wernet et al., (2016).

- *Extra fugitive emissions from well completion and workovers (fracturing and flowback):* Broderick et al. (2011) report that a range of 0.6%-3.2% of total production could leak during flowback, based on Howarth (2011). They also report ranges of absolute production volumes per well as fugitive emission volumes. From the emission range given by Broderick et al. (2011) we took 300,000m^3 per well lifetime as a representative number and divide it by the geometric mean of the absolute production to arrive at an intermediate leakage rate of 0.77% of production. This value is at the lower end of the range given by Howarth (2011). This choice seemed justified by the fact that Howarths estimates have been criticized to focus on the high end (Cathles, 2012) and were identified as much higher than even the next highest values reported by others by MacKay & Stone (2013).

Calculation of emissions from electricity generation

The total carbon footprint of electricity generation in one country from one fuel was calculated as the sum of the upstream emissions of that fuel delivered to the European region the country belongs to, and the emissions from electricity generation from that fuel in that country. Emissions from the distribution of fuel within a region were not included.

Emissions from electricity generation were derived as:

$$CF_{el} = \frac{CC_{fuel}}{eff_{fuel,country}} \cdot f \cdot g$$

Where CF_{el} is the carbon footprint from electricity generation [g CO_2/kWh], CC_{fuel} is the carbon content of a specific fuel [gC/GJ], $eff_{fuel,country}$ is the efficiency of electricity generation from that fuel in that country and f and g are factors to recalculate from GJ to kWh (0.0036) and from gram carbon to gram CO_2 (44/12).

The efficiency per fuel per country was derived by dividing the total amount of fuel input to electricity generation in one country in one year (2010) by the electricity output from that fuel in the same country and year over all types of power plants for a specific fuel (both data taken from IEA energy balances 2016). The year 2010 was chosen as reference year in line with the base year for the scenario analysis (see below). For countries where all electricity generation from a specific fuel took place in CHP plants only or less than 10,000 TJ were produced, the European average efficiency was applied.

Uncertainties in production emissions

Due to lack of specific data, some parameters were calculated based on studies relating to the United Kingdom or the United States. However, conditions may differ for or between European countries. Some extra scenarios have therefore been included to show the effect of these uncertainties on the results. Based on literature (Foster & Perks, 2012; Mackay & Stone, 2013; Westaway et al., 2015; Bond et al., 2014) these include:

- Obligatory green or reduced emissions well completions, where gas is captured, by reducing well completion emission by 90% in our calculations;
- Electrification, where grid electricity is used instead of diesel for pumping of fracking fluid. To show the largest range in emissions reduction, we assume zero GHG emissions from fracking (representing a grid solely based on non-fossil sources).
- Variation in the number of fracking events (1 or 2);
- Variation in transport distance for water and additives.

Next to the combustion phase, the greenhouse gas emissions of electricity from (shale) gas relative to that of coal also depend on the losses upstream. Sanchez and Mays

(2015) and Howarth et al. (2012) summarize several studies that report upstream losses. Values range from 0.42% to 10% for conventional and unconventional natural gas sources. To assess the relation between shale gas and the other fossil sources in a worst case scenario, additional calculations were performed where losses during production were manually set to 5% and 10% of the production stage output, values at the high end of the percentages given in Table S5. These losses are not allocated to any specific process, but encompass all the sources described above. Likely, higher flowback emissions will contribute substantially to higher production emissions.

Scenario analysis

The effect of changes in the fossil electricity mix, such as the possible future inclusion of shale gas in the electricity generation, was assessed in several scenarios. For each scenario the cumulative carbon footprint was calculated for the EU-28 as a whole and each country separately. The cumulative carbon footprint was defined as the life cycle GHG emissions for total fossil electricity generation summed over the total period in g CO_2-equivalents up to 2050. The scenarios were based on the EU Reference Scenario 2016 (EC, 2016). The EU Reference Scenario is based on current legislation and provides estimations of electricity generation per source for every 5 years from 2010 to 2050 and rates of change per decade. From these, the fossil electricity generation per fuel was calculated for each year. The fuel type "solids" was taken to represent coal, with exception of Estonia where it refers to shale oil products. The EU reference scenario also provides an import dependency percentage. These data were applied to derive the following scenarios:

1. The reference scenario (EC, 2016).

2. A business as usual scenario, where the contribution of each fuel to the fossil electricity mix was fixed at the 2010 percentage. Total electricity generation from fossil sources developed in the same way as in the reference scenario.
3. A fuel independence scenario where all imported fossil fuels to Europe are replaced by shale gas from Europe. Hereby it is assumed that the import dependency fraction applies equally to all fuels. For some years/countries, a negative import dependency was estimated in the reference scenario, for these countries no replacements were calculated. In our calculations, all imported fuels were replaced starting from 2020. This replacement would probably take time, but as the rate is unknown, we assume a five year period from 2017-2022, in which we would first overestimate replacement rates, compensated by an underestimation in the second half of this period.
4. Two ‘coal phase out’ scenarios where all coal fired power plants in Europe are closed down before 2030. The cumulative percentage decrease in coal capacity per country was calculated from Rocha et al. (2017). In these scenarios, the capacity was replaced either by shale gas from Europe (scenario 4a) or by conventional gas from current sources (scenario 4b).

The replacement of other fuels by shale gas is based on these assumptions to provide a transparent indication of emissions effects. It is not based on economical or technical prediction. We realize it is unlikely, that shale gas production in the EU could be introduced at such a fast pace.

Results

Carbon Footprints from shale gas

The upstream carbon footprints per MJ of shale gas from 9 European basins delivered to four regions in Europe are presented in Figure 2. For every consuming region (North, Central, Southeast and Southwest EU) and shale gas play combination in Figure 2 it is assumed that the shale gas comes uniquely from the one play present in that combination. Total GHG emissions for gas delivered range from 8 to 29 g CO_2-eq/MJ. Contributions of life cycle stages are also shown, illustrating that the largest contribution comes from the production phase of shale gas (6-13 g CO_2-eq/MJ).

Carbon footprints for electricity generation from reserve-weighted average shale gas in EU countries is shown in Figure 3. Differences between countries in the same consuming region are entirely related to differences in generation efficiencies. For Europe as a whole, the carbon footprint was 0.45 kg CO_2-eq/kWh.

Gas losses during production relative to the production output were between 0.01%-1.8% for conventional gas coming from all countries exporting to Europe and 0.8%-1.3% for shale gas from Europe (SI Table S6).

Figure 4 shows changes in carbon footprints for the European average, if a number of alternative scenarios (no fracking energy emissions, reduced emissions completions and variation of number of fracking events) are included. Changes in transport distances lead to minor changes in results that weren't visible in the figure and are therefore not shown. Reducing emissions during well completions had the largest effecton the carbon footprints, in line with earlier results (Bond et al., 2014; Weber & Clavin, 2012).

Scenario analysis

The cumulative carbon footprint for 2020 up to 2050 for each scenario for the EU-total is presented in Figure 5. All scenarios with more gas use (EU independence to a lesser extent, coal phase out and coal phase out with conventional gas to a larger extent) have a lower cumulative carbon footprint than the reference and the business as usual scenario. Changes of the fossil fuel carbon footprint over time are shown in Figure 6. It can be seen that in the first years, the business as usual (keeping 2010 values) carbon footprint is actually lower than in the reference scenario and the other scenarios builton the reference scenario, hence also are higher in the first years..

To facilitate discussion, Figure 5 also shows the range in cumulated emissions if losses during shale gas production were 5% or even 10% of production output. Losses of 5-10% of overall production are the high-end ranges reported from top-down studies in the US (e.g. Peischl et al., 2015; 2016). Setting production losses to 10% of production stage output increased the European carbon footprint per kWh generated to 0.82 kg CO_2-eq/kWh and for 5% to 0.61 kg CO_2-eq/kWh (results not shown). With 10% production losses, the independence scenario would have a higher cumulative carbon footprint than the reference scenario (vertically striped bars in Figure 5). For 5% production losses and the coal phase out scenarios, this was not the case (dotted bars in Figure 5) but the differences became fairly small.

Results on a country level are shown in Figure S2 in the SI. In general, the country scenario footprints show the same trends as seen for the average EU (Figure 5) but deviations exist (e.g. Belgium and Denmark). Figure 7 shows on a country level the comparison between the reference and the coal phase out scenario in percentage. There are two groups of countries with no change: countries that do not or hardly use any coal for electricity production (Belgium, Latvia, Lithuania, Luxembourg, Malta, Sweden, Cyprus) or countries where the timing and capacity of the coal phase out coincides with the expected development in the reference scenario (France, Portugal).

Discussion

Upstream Carbon Footprints

In the literature reported in Table S5 production emissions range between a 1-9 g CO_2-eq/MJ (from below 1% to more than half of the upstream emissions). In a recent LCA for shale gas production in the UK, Tagliaferri et al. (2016) report maximum GHG emissions of 10 g CO_2-eq/MJ, a value only slightly lower than presented in Figure 2. Differences between carbon footprints for play-country combinations arise from differences in production (fugitives and energy use), processing and transport. Due to the large contribution of the production stage to total upstream emissions, differences between production plays are larger than between consuming regions. As can be seen in Figure 2, differences in carbon footprint of gas between consuming regions are caused by differences in transportation emissions, mainly related to distances but also to losses per unit transport. Processing emissions were relatively high in Germany and were negligible in the Netherlands. This has already been concluded by the COWI report (COWI, 2015): They state that there are no data reported on processing energy use in the Netherlands and that the fugitive emission rate is low. This is in line with the Dutch National Inventory Report to the UNFCC (Coenen et al., 2017). For Germany, higher processing emissions are related to the fact that the gas is relatively acidic in Germany and requires more processing. For Poland, three basins were included: Lublin, Podlasie and Baltic. Production emissions were higher for the Lublin basin. This is related to the fact that the area covered by the reserve (in m^2 per m^3) is larger for the Lublin basin, requiring more wells and well pads and therefore leading to higher emissions.

The bold black line in Figure 2 indicates carbon footprints of conventional gas for the European average around 11 g CO_2-eq/MJ, also in line with earlier studies. For example Faist Emenegger et al. (2007) report a range of 2-26 g CO_2-eq/MJ for Europe and Hauck et al. (2014) report for combined cycle power plants in the US 12 g CO_2-eq/MJ (with a range from 9-17 g CO_2-eq/MJ).

Sanchez and Mays (2015) and Howarth et al. (2012) summarize several studies that report upstream losses. Values range from 0.42-10% for conventional and unconventional natural gas sources. Le Fevre (2017) reports this range to be between 0 and 1.2%. Our values

(0.01%-1.8%, SI Table S6) were more close to Bouman et al. (2015) who cite a lower range of 0.006–2.75% of natural gas production. Schwietzke et al. (2014) in a global modelling study based on atmospheric methane measurements estimates an upper bound for current fugitive emission rates of 5% (on average). Losses of around 3% are often cited as a turning point where natural gas might no longer constitute benefits over coal (Heath, et al., 2014b). Recently Alvarez et al. (2018) report an average leakage rate for the US of 2.3%. This value is estimated using ground-based, facility-scale measurements and validated with aircraft observations in areas accounting for ~30% of U.S. gas production. Our loss rates for the European domain were below this value.

Electricity generation

Our carbon footprints for electricity from shale gas were within the range reported in literature and summarized in Table S5. Our carbon footprint for electricity from shale gas is slightly lower than the one reported by Stamford & Azapagic (2014). However, their results have been contested by Westaway (2014) mainly due to low expected ultimate recovery assumptions (and hence high production emissions per unit produced). Our estimates were indeed comparable to the lower ranges often reported for the US (Hauck et al., 2014 and references summarized therein). For other regions, comparable ranges (0.35-0.98 kg CO_2-eq/kWh) are reported (Hayhoe et al., 2002; Faist Emmenegger et al., 2007; Turconi et al., 2013). Figure S1 shows the carbon footprints for electricity from conventional gas (0.35 kg CO_2eq/kWh for the EU) and oil (0.77 kg CO_2eq/kWh for the EU) and coal (1.1 kg CO_2eq/kWh for the EU), confirming that shale gas has a slightly higher carbon footprint than conventional gas and a lower carbon footprint than oil and coal in our calculations. Striking are the high footprints from Romania and France, that are caused by the low power plant efficiencies (about

30%) as derived from the energy balances. Possible reasons could lie in the specific technologies used in these countries, for instance if gas is mainly used for peak demand (for instance if the baseload is nuclear as in France)and upgrading the small gas-fired powerplants may not be seen as cost-efficient.

Scenario analysis

Low carbon transition according to the EU Roadmap should combine gas with increasing contributions of renewable energy and increasing energy efficiency. Renewable fuels and energy efficiencies were explicitly not addressed in this research and no conclusions can be drawn on their (relative) contributions. Also note, that the total fossil energy use has been kept unchanged compared to the reference scenario in our analysis. Therefore, effects of earlier or later phase out of fossil fuels are not quantified and cannot be judged based on our analysis. Finally, no assessment has been made of gas use after 2050. For instance, McGlade et al. (2014) point out that gas could be a climate beneficial bridge fuel only if it's timely phased out after a transition period is guaranteed.

Figure 5 shows a reduction in the cumulated carbon footprint from fossil energy of about 9000 Mt CO_2-eq. in 2050 between the reference and the coal phase out scenario. Rocha et al. (2017) estimate the total cumulative CO_2 emissions from coal electricity with current plants in 2050 to be about 12145 Mt, indicating that a large part of these emissions would indeed be mitigated by the phase out scenario using gas.

The country analysis (Figure S2), shows that the reduction potentials depend on the reference scenario development. For some countries, for instance Denmark, Lithuania and the UK, the difference between BAU and other scenarios is more prominent than on the EU level (and the difference between the reference scenario and the other scenarios is smaller). The main reason is that these countries already have a reduction of carbon intensive energy generation (i.e. a decreasing fossil source) in the reference scenario early after 2010.

Several aspects could influence the relation between scenarios in the future. Reserve availability could also affect shale gas potential. In our analysis for the whole EU, 66% and 45% of the total shale gas reserves (as defined in this research) would be used by 2050 in the independence scenario and in the coal phase out scenario, respectively. However, our estimated reserves are technically recoverable reserves. These reserves might not be (fully) economically recoverable in the future. Lower production would lead to higher upstream emissions per unit of gas produced and less benefits for scenarios using shale gas. On the other hand, current estimates might not represent future practices. For instance, MacKay and Stone (2013) state that flowback fugitives might be completely captured in the future, increasing future benefits of using (shale) gas by reducing CH_4 losses.

Note that only uncertainties in the carbon footprint of shale gas were taken into account in our scenarios. Uncertainties in the upstream emissions of other fuels could also influence the comparison of our results. For instance, for CH_4 losses during coal mining the country-level IPCC reported factors were used for coal carbon footprints. Recently, Zhu et al. (2017) showed that, for China these factors might overestimate actual emissions and ignore variations between mines in the same country. This illustrates that, like the US studies for shale gas, more top-down studies are needed for coal production regions as well. Lower upstream emissions for coal would slightly reduce the benefits of the coal phase out scenarios. Likewise, sources of conventional gas and oil are kept constant in our analysis. Reserve availability as well as political and economic changes might lead to a shift in these sources, thereby changing also the carbon footprint of the European gas mix. Several authors (Stamford & Azapagic, 2014; Faist-Emenegger et al., 2007; Russ, 2017) concluded that gas imported as LNG has a higher carbon footprint than gas transported by pipeline due to energy use for liquefaction and losses at the LNG terminal. Therefore, depending on this shift in mix, benefits of using more conventional gas could actually increase or decrease.

Conclusions

To estimate the carbon footprint of shale gas produced in Europe for consumption within Europe we modified and expanded an existing GHG emission estimation model. We used 9 European shale gas plays as potential production regions. Moreover, extra (compared to conventional gas) GHG emission sources during shale gas production, such as fugitives from hydraulic fracturing or combustion emissions from horizontal drilling were added to conventional gas emissions. Results are expressed as g CO_2-equivalents per MJ delivered, and calculated for a kWh of electricity generated. Total GHG emissions from the use of European shale gas for electricity production range from 0.42 to 0.78 kg CO_2-eq/kWh when the combustion phase emissions are included. This is in the range reported in literature.

Our results indicate an advantage of gas over other fossil sources in a wide range of scenarios. Comparison to non-fossil sources, however, was outside the scope of this study. Additionally, the fossil energy use was kept in line with the EU reference scenario for all scenarios over our scenarios. Conclusions are relevant for the period up to 2050 and not beyond. Several lessons can be learned from our calculations:

- Lower carbon footprints of (shale) gas over coal for electricity generation were confirmed. This was also true when considering EU wide scenarios, as mostly when
- gas was used instead of other fossil fuels, the scenarios had lower cumulative footprints.
- These are only reversed with very high (10%) upstream losses for shale gas for our independence scenario. From this, we conclude that with the current knowledge there is still a substantial climate benefit to replace coal with (shale) gas even in the EU reference scenario.

- We highlight, however, that for the carbon footprints of electricity generation the efficiencies in the power plants are most important, which is clearly seen for two countries with low-efficiency gas fired powerplants still in place . Likewise, reliable estimations of footprints depend on the quality of underlying statistics.
- Assessing timelines as done in our research gives additional insights compared to assessment on a side-year, because emissions during the transition path are also taken into account.
- Several policy recommendations can be deduced from our analysis: Considering the relevance of the combustion phase, high efficiency power plants should be preferred in any case and scenario. To reduce the carbon footprint of shale gas, reducing well completions emissions (green or reduced emissions completions) are most relevant.

Declaration of interest statement. We declare no financial interest or benefit that has arisen from the direct applications of our research.

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Tables and Figures

Table 1. Recoverable reserves and surface areas for shale gas plays in Europe (Visschedijk et al, 2018).

Country	Play	Reserve (m^3)	Surface (km^2)
UK	Bowland Basin	7.1E+11	2.5E+04
Poland	Lublin Basin	2.6E+11	2.9E+04
Poland	Podlasie Basin	2.7E+11	9.4E+03
Poland	Baltic Basin	2.9E+12	4.8E+04
Netherlands[a)]	Geverik Member (Epen Formation)	9.3E+10	1.0E+04
Denmark	Alum Shale	2.6E+11	1.6E+04
Sweden	Alum Shale	9.0E+11	7.0E+03
Germany	Posidonia Shale	2.8E+11	2.4E+04
France	Paris Basin	4.8E+11	2.6E+04

a) For the Netherlands, including the Dutch continental shelf, the estimated risked recoverable reserve and SG play's contours according to EIA have been replaced by other more recent and accurate data provided by petroleum geologists from TNO. Based on ongoing research at TNO (e.g. Zijp et al., 2015) the SG data for the Netherlands is continuously updated and form the basis on which TNO annually reports on the Dutch energy reserves to the Ministry.

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

Value	Source
Fuel use for horizontal drilling	
837760 kJ diesel per meter drilled	Broderick et al., 2011
2000 m horizontal drilling length per well	Costa et al., 2016; Cremonese, 2016
Hydraulic fracturing and flowback	
Fuel use for pumping	
110,000 l diesel/event	Broderick et al. (2011) based on wells in the Marcellus shale reported by New York state
Number of hydraulic fracturing events: 1.5 (50% of the wells re-fracture once)	Broderick et al. (2011), with a range from 1 to 2
Fuel use for transport	
Volume transported per fracturing event: 20,000 m^3	Assumption based on range in Broderick et al. (2011); with a range from 9,000-29,000m^3
Transport distance: 60km	Broderick et al. (2011)
0.001 kJ diesel per tkm transported	Ecoinvent lifecycle inventory database (Spielmann et al., 2007; Wernet et al., 2016)
Fugitive emissions	

0.77%[a] of production volume	References in Broderick et al. (2011), giving a range of 0.6%-3.2%

[a)] Due to interdependence of emissions and production volumes, this value is highly uncertain.

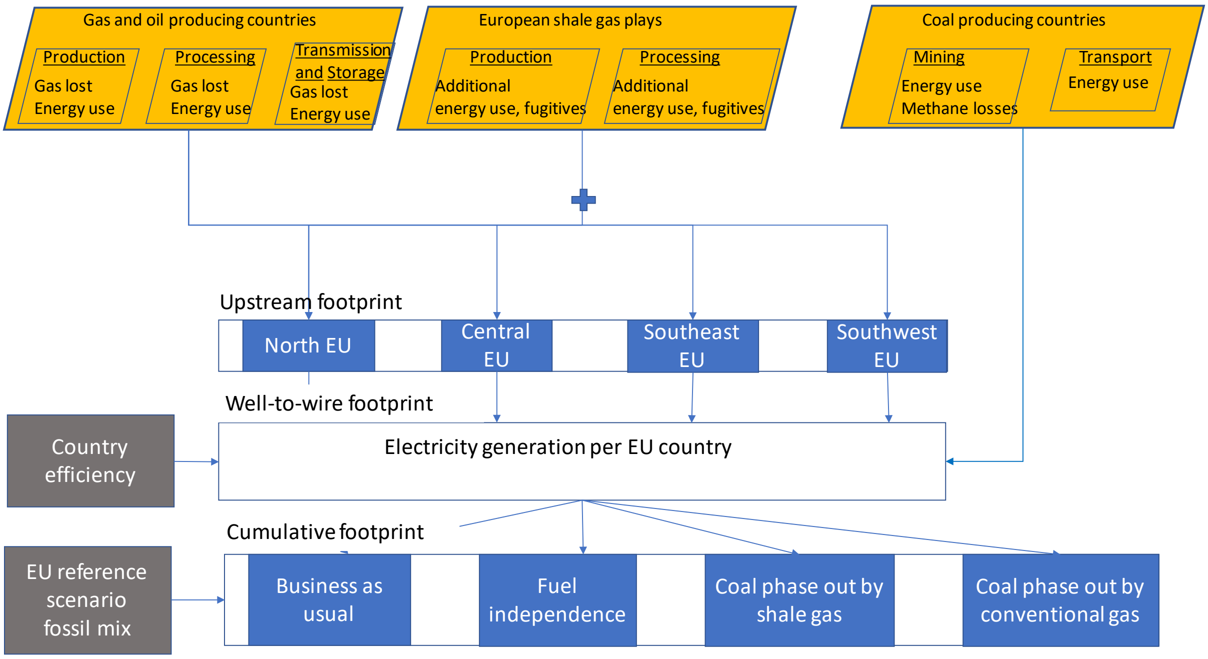

Figure 1

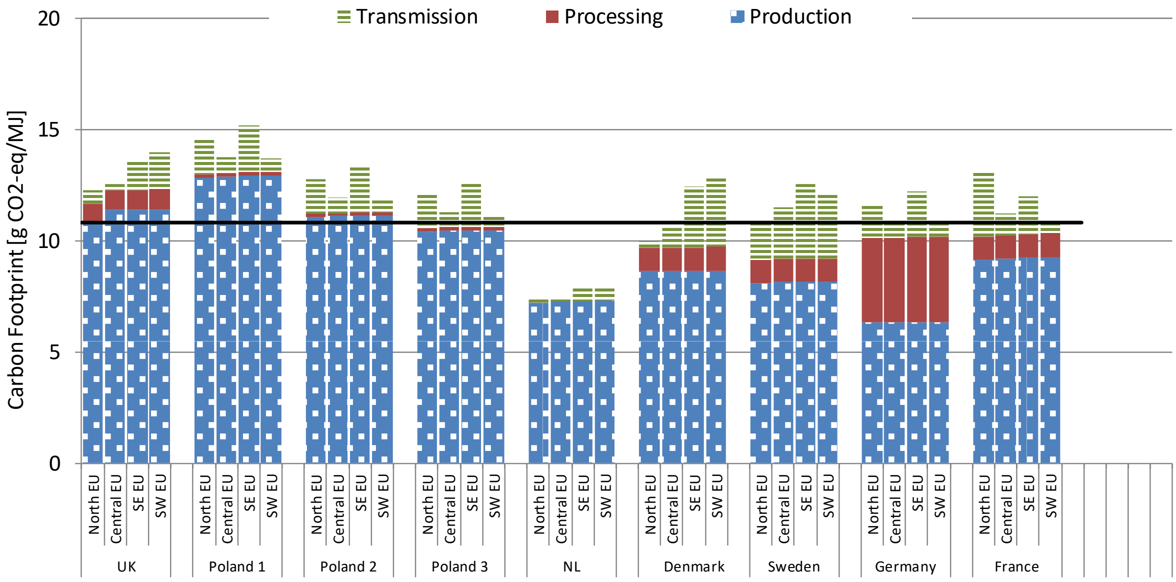

Figure 2

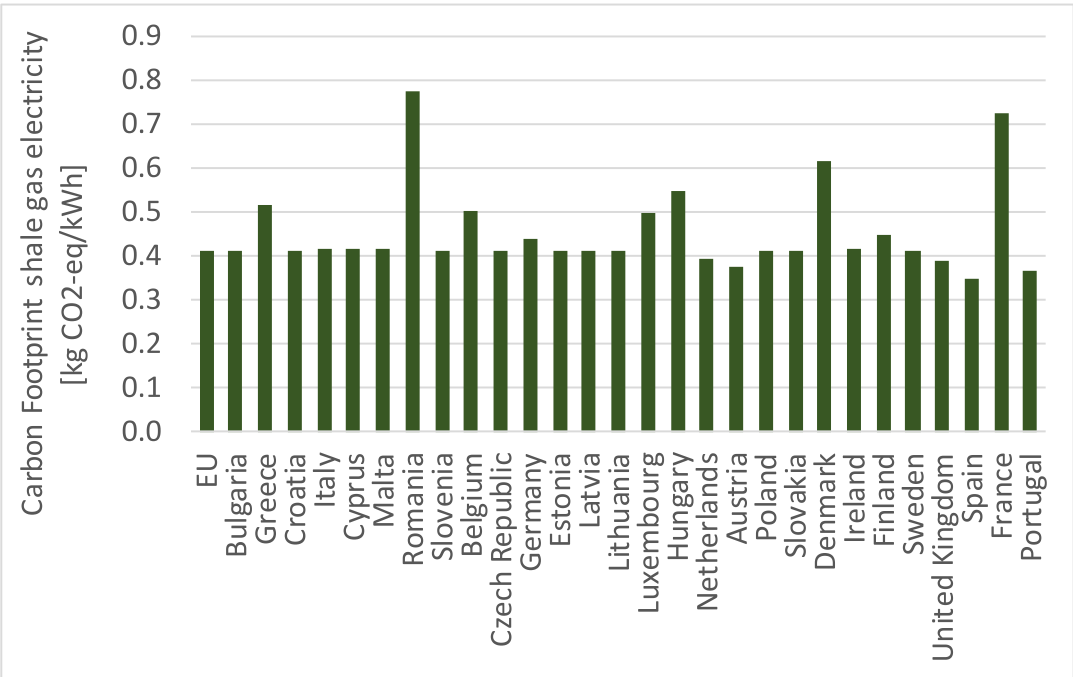

Figure 3

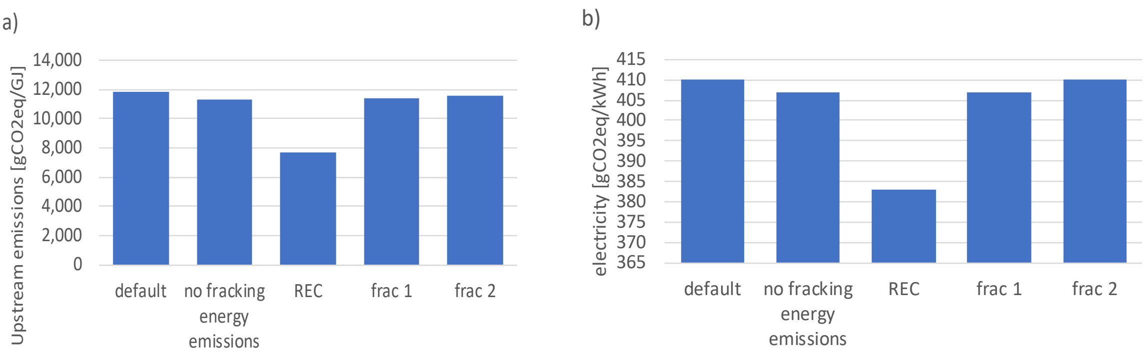

Figure 4

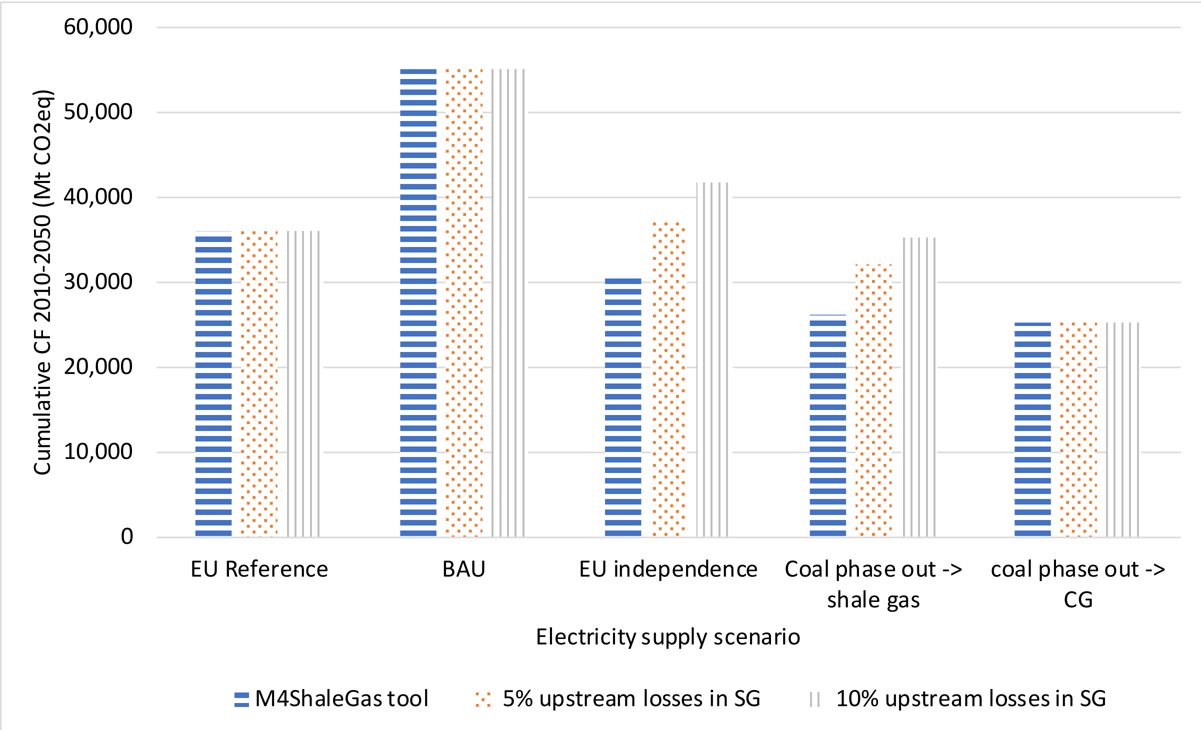

Figure 5

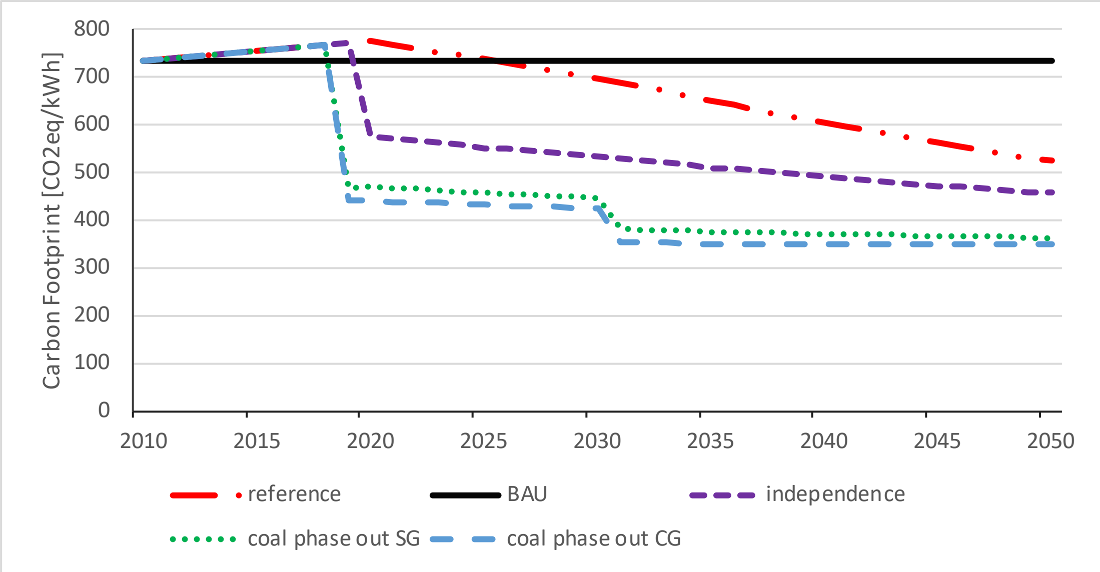

Figure 6

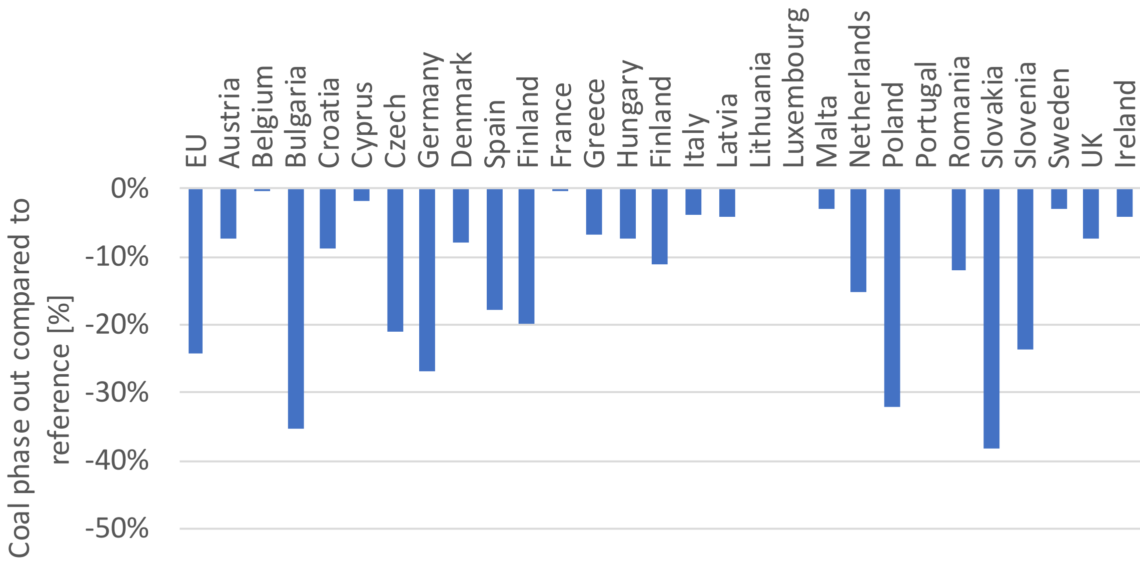

Figure 7

Figure captions

Figure 1. Flow of the carbon footprint calculations and system boundaries for upstream footprints, electricity generation and scenario comparison

Figure 2. Carbon Footprints [gCO_2-eq./MJ delivered] from shale gas produced in European plays (horizontal countries on x-axis), delivered to four European regions (vertical regions on x-axis). Contribution of life cycle stages is also shown (blue with dots: production, red filled: processing, green striped: transmission). Horizontal black line indicates conventional gas delivered to the consumption-weighted average of all European regions. Poland 1: Lublin Basin; Poland 2: Podlasie Basin; Poland 3: Baltic Basin.

Figure 3. Carbon footprints for electricity generation from shale gas in European countries including the combustion phase [kg CO_2eq/kWh].

Figure 4. Comparison of carbon footprints in original calculations ('default') and in additional scenarios: electric fracking ('no fracking energy emissions'); reduced emissions completions ('REC'); change in number of fracking events (1 ('frac 1') or 2 ('frac 2'); panel a) for gas production; panel b) for electricity generation for the European average.

Figure 5. Cumulative carbon footprints CF up to 2050 for the reference, business as usual (BAU), independence and two coal phase out scenarios (CG: conventional gas; SG: shale gas).

Figure 6. Development of carbon footprints of fossil electricity generation [kg CO_2eq/kWh] for the EU-28 in five scenarios (BAU: business as usual; CG: conventional gas; SG: shale gas).

Figure 7. Comparison of the coal phase out scenario to the reference scenario for EU countries.

Supplementary Information

GHGenius model calculations

GHGenius, a model for life cycle assessment of transportation fuels, was developed by (S&T)^2 Consultants Inc. commissioned by Natural Resources Canada. The carbon footprint of fuels used for heat and electricity generation can also be calculated. Emissions are taken into account for several GHGs (CO_2, CH_4, N_2O) and for pollutants. Details of the model are described in (S&T)^2 Consultants Inc (2013a). GHGenius[1] includes about 100 types of fossil and renewable fuels to be used in several regions of Canada and the United States. COWI (2015) adapted GHGenius for Europe and included Oil and conventional gas to be used in four European regions (North, Central, Southwest and Southeast Table S1). For Europe as a whole, a consumption weighted average is calculated. The production of fuels is modelled for all countries worldwide that export to these regions.

For fossil fuels used for electricity generation, the upstream life cycle stages recovery, transmission and treatment of the fuel are included. The energy use and GHG emissions for production and processing of fuels are estimated on a country level using national statistics, mainly energy balances and national GHG inventory reports. Transmission emissions have been calculated from transport distances (from operators) and energy consumption rates. Data sources are given by (S&T)^2 Consultants Inc (2013a,b) for the original GHGenius version and by COWI (2015) for the version including oil and gas imports to Europe. Origins of fuel consumption in regions reflects the current situation (2012 data as included in COWI, 2015).

Table S1 Countries per region of the EU as defined in the COWI (2015) modelling study.

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

EU South-West	EU North	EU Central	EU South-East
Spain	Denmark	Belgium	Bulgaria
France	Ireland	Czech Republic	Greece
Portugal	Finland	Germany	Croatia
	Sweden	Estonia	Italy
	United Kingdom	Latvia	Romania
		Lithuania	Slovenia
		Luxembourg	
		Hungary	
		Netherlands	
		Austria	
		Poland	
		Slovakia	

Calculations were performed with model version GHGenius 5.0 BETA 2c. The Model structure was kept in place as much as possible by replacing some existing production regions irrelevant for Europe with European shale gas plays. As a consequence the adapted model version used here should no longer be used for modeling emissions from fuel use in North America. Upstream emissions were calculated for ‘gas to power’. To transfer methane emissions to kg CO_2-equivalents (eq), a GWP of 30 was applied (IPCC, 2013). New data were added to allow for all shale plays to deliver to all European consumption regions. This means the estimation of transport distances that were not included yet. Transport distances influence gas leakage during transportation and are therefore included for emissions estimations. See below for details on estimation of additional transport distances.

Table S2. Emission factors applied to calculate emission from energy use for gas production.

	diesel engine	**NG boiler**	**NG turbine for compressor**	**NG engine forcompressor**
G CO2/GJ	67,989	50,840	50,874	49,035

Transport distances

Not all of the countries in Table S1 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 S2), applying the following lines of thought:

- For distances from a production country the countries in its own 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 other regions.

To assess the uncertainty associated with these estimations, we multiplied all transport distances newly derived by a factor of 1.5 and recalculated the specific upstream footprints. This lead to increases in the upstream footprint of a factor 1.1 at most. Hence, our modelling results are not very sensitive to these assumptions.

Table S3. Transport distances (km) between European production countries and consumption regions. Distances printed in normal font were already included in GHGenius. Distances in bold 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.

Carbon Footprint of coal electricity

Coal produced in Europe or imported to Europe was not included in GHGenius. Therefore, life cycle greenhouse gas emissions from coal combusted in Europe were modelled separately. The coal life cycle was modelled in three stages (see e.g. Steinmann et al., 2014): mining, transport and combustion for electricity generation. The total carbon footprint for a specific country and year was calculated as the sum over all these stages:

$$CF = \frac{\left(E_{mining} + E_{transport} + E_{combustion}\right) \cdot I_{combustion}}{O_{electricity}}$$

Where: CF = carbon footprint in kg CO_2eq/kWh; E_{mining} = emission from mining in kg CO_2eq/TJ; $E_{transport}$ = emission from transport in kg CO_2eq/TJ; $E_{combustion}$ = emission from combustion in kg CO_2eq/TJ; $I_{combustion}$ = total input into combustion (TJ); $O_{electricity}$ = electricity generated from that input (kWh). To derive electricity produced in 2015, efficiencies per country were calculated for 2014 (TJ_{out}/TJ_{in} from EIA Energy balances 2016) and applied to 2015 inputs from Eurostat. Emissions estimations per life cycle stage are described below. For Europe as a whole, the average weighted by electricity generation carbon footprint was applied.

Mining

Mining emissions were modelled as GHG emission per TJ mined. This includes methane emissions as fugitives from coalbeds and CO_2 emissions from combustion of fuels to support the mining activity. Amounts of coal produced as well as fuel consumption for mining were taken from the EIA energy balances 2016 as averages over the years 2010-2014. For countries (Colombia, Indonesia, South Africa, India, Greece) with no or incomplete (i.e. only one type of fuel) reported fuel consumption, the fraction of the world fuel consumption corresponding to the country's contribution to world coal production were applied. Methane emission factors were taken from country specific inventory reports as submitted to the UNFCCC (see Table S3 for the sources per country). If these were unavailable, default emission factors from the IPCC (2006) were applied. Emission factors from the provision and use of fuel (natural gas, oil, biodiesel, heat) were taken from ecoinvent (Wernet et al., 2016) with exception of emission factors for electricity that were taken from Brander et al. (2011) because not all countries were included in ecoinvent. Table S3 shows the sources of mining emission factors per country.

Transport

Transport emissions per transport route were calculated as the product of the amount transported, the transport distance and an emission factor per tkm. Emission factors per mode of transport (waterborn, railways, trucks) were taken from ecoinvent (Spielmann et al., 2007). Transport distances were estimated using Coal Gap Route and the following guidelines:

- Transport distances within mining countries were neglected;
- International transport distances were modelled from and to major ports;
- One average distance was applied for transport within consuming countries.

Transport emissions per route were recalculated to country-specific transport emissions per TJ by calculating the weighted sum over all transport routes divided by the total imports.

Sources of imports per country are given in Table S4.

Major coal ports were derived from several online sources (Carbon Brief, 2016; OpenSea.Org 2017a,b) and distances were derived from information of the Navigation Port of Rotterdam website *(https://navigate.portofrotterdam.com/search/connection?origin=ChIJMw1UiCPAfDYR3XGeyZyb5ko&destination=ChIJT608vzr5sUARKKacfOMyBqw*), since bulk routes mainly pass by it. If the distance from country A to B could not be found, it was calculated by Google maps or Coal Gap Route (*http://tsteven4.qwestoffice.net/BoulderRides/CoalGapRoute.html*).

Carbon Brief, 2016 Mapped: The global coal trade: https://www.carbonbrief.org/mapped-the-global-coal-trade. Visited May 2017.

OpenSea.Org 2017a. European Shipping: Commodities – Markets – Trade Flows: https://opensea.pro/blog/european-shipping Visited May 2017.

Opensea Org, 2017, Coal: The “Black Gold” of Dry Bulk Shipping: https://opensea.pro/blog/shipping-coal. Visited May 2017.

Combustion

Combustion phase emissions were calculated from total coal use (in TJ that go into combustion) for electricity generation in each country in 2015 (from eurostat 2016) and emission factors per TJ from IPCC (2006).

Table S4. Mining Emission Factors per country. All websites have been visited in May 2017. CRF: Common reporting format. Emission factors are given for underground and surface mining separately. Assuming that lignite is mined on surface and hard coal (all other types of coal) underground these emission factors were applied to the corresponding amounts (TJ) mined for each country. If the corresponding emission factors were not available, the intermediate IPCC default emission factors were used (IPCC, 2006).

Primary List	Country Specific CH4 Mining Emission Factors
Bulgaria	Bulgaria CRF (Table 1.B.1) http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/7383.php
Czech Republic	Czech Republic CRF (Table 1.B.1) http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/7383.php
Germany	Germany CRF (Table 1.B.1) http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/7383.php
Greece	Greece CRF (Table 1.B.1) http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/7383.php
Poland	Poland CRF (Table 1.B.1) http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/7383.php
Romania	Romania CRF (Table 1.B.1) http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/7383.php
Spain	Spain CRF (Table 1.B.1)

	http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/7383.php
United Kingdom	UK CRF (Table 1.B.1) http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/7383.php
Hungary	Hungary CRF (Table 1.B.1) http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/7383.php
Slovakia	Slovakia CRF (Table 1.B.1) http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/7383.php
Slovenia	Slovenia CRF (Table 1.B.1) http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/7383.php
Russia	Russia CRF (Table 1.B.1) http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/7383.php
Columbia	IPCC Guideline for Greenhouse Gases Inventories: « Draft 2006 IPCC Guidelines for National Greenhouse Gas Inventories », Volume 2: Energy, 2006.
USA	USA CRF (Table 1.B.1)

	http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/7383.php
Australia	Department of the Environment, 2014. http://www.environment.gov.au/system/files/resources/b24f8db4-e55a-4deb-a0b3-32cf763a5dab/files/national-greenhouse-accounts-factors-2014.pdf
South Africa	IPCC Guideline for Greenhouse Gases Inventories: « Draft 2006 IPCC Guidelines for National Greenhouse Gas Inventories », Volume 2: Energy, 2006.
Indonesia	http://www.ipcc-nggip.iges.or.jp/public/mtdocs/pdffiles/1407_Sofia/31_Indonesia_s_mitigation_potential_project-rohmadi_ridlo.pdf
Canada	CANADA CRF (Table 1.B.1) http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/8108.php
India	Singh & Kumar, 2016. Fugitive methane emissions from Indian coal mining and handling activities: estimates, mitigation and opportunities for its utilization to generate clean energy. Energy Procedia 90, 336 – 348, https://doi.org/10.1016/j.egypro.2016.11.201

Table S5. Sources of coal imports (total amounts imported [Mt]* and contributions per exporting country). All websites assessed in May 2017.

Country	Reference	Link
Bulgaria		Data sent from the Energy Organisation of Bulgaria
Czech Republic	International Energy Agency, 2016. Energy Policies of IEA countries. 2016 review. Czech Republic. Paris, France, 190p	https://www.iea.org/publications/freepublications/publication/Energy_Policies_of_IEA_Countries_Czech_Republic_2016_Review.pdf
Germany	VDKi (Verein der Kohlenimporteure), 2016. Annual Report 2016. Facts and Trends 2015/16., Hamburg, Germany, 120p.	http://english.kohlenimporteure.de/annual-reports-archive.html
Poland, Bulgaria	Euracoal, 2016. EURACOAL Market Report 1/2016. European Association for Coal and Lignite aisbl, 2017, 16p.	https://euracoal.eu/library/coal-market-reports/
Spain	International Energy	https://www.iea.org/publica

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	Agency, 2016. Energy Policies of IEA countries. 2016 review. Spain. Paris, France, 178p	tions/countryreviews/
United Kingdom	UK Government, Department of Energy & Climate Change, 2016. Coal in 2016.	https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/559572/Coal_in_2015.pdf
Romania, Hungary, Slovenia, Slovakia,, France, Netherland, Austria, Belgium, Portugal, Denmark, Finland, Italy, Ireland	AJG Simoes, CA Hidalgo. The Economic Complexity Observatory: An Analytical Tool for Understanding the Dynamics of Economic Development. Workshops at the Twenty-Fifth AAAI Conference on Artificial Intelligence.	https://atlas.media.mit.edu/en/
Croatia	REPUBLIC OF CROATIA MINISTRY OF ENVIRONMENT AND ENERGY, 2015. ANNUAL ENERGY	http://www.eihp.hr/wp-content/uploads/2016/12/Energija2015.pdf

	REPORT. ENERGY IN CROATIA, p.258	

* For recalculations of mass of coal to energy of coal, net calorific values (9,9000 kJ/kg for lignite and 19,100 kJ/kg for had coal) were taken from ecoinvent (Faist-Emenegger et al. 2007).

Details on Scenario calculations

In some cases, total (fossil) electricity production numbers in the reference scenario for reported years and those calculated via rate of change didn’t exactly match: In such cases, numbers calculated via rate of change prevailed. For Malta, however, changes were too radical to be modelled correctly (e.g. 1200 GWh in 2015 from oil to 0 in 2020), therefore 2015 and 2020 numbers were taken from the reference scenario, and the following steps applied:

- 2010-2104 as 2010
- 2015-2016 as 2015
- 2017-2020 as 2020

Rocha et al. (2017) provide two chronologies in phase out (with the same final reduction in capacity), the market and the regulator perspective. The regulator perspective was chosen in the scenario description to derive the maximum spread in scenarios.

Carbon footprints of shale gas from literature

Table S6 Carbon Footprints for electricity generation (CF, g CO_2-eq/kWh), domestic shale gas delivery to the plant (at plant, g CO_2-eq/MJ and as percentage of total carbon footprint (% total)), and domestic shale gas production (g CO_2-eq/$MJ_{produced}$) from literature.

Reference	Play	CF	low	high	Origin range	at plant	% total	Combustion Efficiency (%)	Production	Losses form well production (%)	Main contributors to CF	Compared to…/for…
Laurenzi & Jersey (2013)	Marcellus	466	450	567	80% CI	14	22	50.2 (HHV)	9		EUR, gas engines, need for processing	Coal
Stephenson et al. (2011)	general	499				6.8	11	47.6 (LHV), 43 (HHV)	2		EUR, fugitive production emissions, need for workovers	CG, coal
Burnham et al. (2012)	Marcellus, Barnett, Haynesville, Fayetteville, averaged EURs	700[F]	600[F]	850[F]	technology differences			33.1 (33.0-33.5) for boiler, 47 (39-55) for combined cycle		2.01 (0.71-5.23) (CH4 only)	EUR, venting well equipment, workover, recovery and processing efficiency, CH_4 content in raw gas[A]	CG, coal, gasoline, diesel, km (passenger car, bus)
Jiang et al. (2011)	Marcellus	490[B]	454	540	90% CI	20[F]	26[F]		2 (0.1-9)	2 (production only)	preproduction: production rate, well lifetime	CG, coal, LNG, none

Weber & Clavin (2012)	based on other		500[F]	674[F]	95%CI	15 (11-21)[F]	20-22	37-50 (LHV)	2 (0.2-5)		preproduction: well completion	
Heath et al. (2014a)	Barnett	440	420	510	high and low EUR	78	18	51 (HHV)	1	1.5 (0.8-2.5) + 5.6 (6.5-8.9)	EUR (from EIA averages), composition relevant if areas in field are largely deviating from average, second part consumption in engines	
Hultman et al. (2011)	generic	632	480	730	technology differences			33.7-50.5				CG, coal
Dale et al. (2013)	Marcellus		420	430				49				
Howarth et al. (2011)[D]	including tight sand, Haynesville, Uinta, others		528[B, F]	792[F]						3.6-7.9		CG, coal
Skone et al. (2011)						70			0.1			

Heath et al. (2014b)[E]	Based on other	470[F]	440[F]	750[F]	min-max of harmonized studies	270				0.66-6.2	EUR, emission reduction for (re)completion, well lifetime (recompletion), emission factor for liquids unloading	CG, coal

CI: confidence interval; CC: combined cycle; EUR: expected ultimate recovery

A: For Conventional gas liquids unloading was also found important, shale gas was assumed to be dry;

B: Results are reported per MJ burned and were calculated assuming 50% efficiency;

C: Weber& Clavin list the most important contributors to variation in CFs over the studies: 1. number of well workovers per well lifetime (primarily shale gas), 2. fugitive emissions rate at the wellhead (conventional and shale gas), 3. estimated ultimate recovery (i.e., total produced gas) of the well (primarily shale gas), 4. completion and workover emission factor (primarily shale gas), 5. liquid unloading emission factor (conventional gas), and 6. fugitive emissions at the gas processing plant (conventional and shale gas);

D: Howarth et al. use a GWP of methane of 33 in contrast to other studies

E: Heath et al. use GWPs from the IPCC's 5th Assessment Report, whereas other studies are based on AR4 numbers.

F: approximate numbers due to reading from figures.

Production loss percentages

Table S7. Gas lost during production as percentage of production output for countries delivering gas to Europe.

Country	Conventional gas lost of stage output	Country	Shale gas lost of stage output
Norway	0.005%	UK shale gas	1.392%
United Kingdom	0.622%	Poland Lublin	1.216%
Netherlands	0.030%	Poland Podlasie	1.216%
Denmark	0.040%	Denmark shale gas	1.002%
Germany	0.023%	Sweden shale gas	1.002%
Russia	0.500%	Germany shale gas	0.793%
Poland	0.446%	France shale gas	1.002%
Italy	0.220%	Poland Baltic	1.216%
Hungary	0.485%	NL shale gas	0.800%
Romania	0.443%		
Algeria	1.800%		
Libya	0.500%		

Carbon Footprints for electricity generation

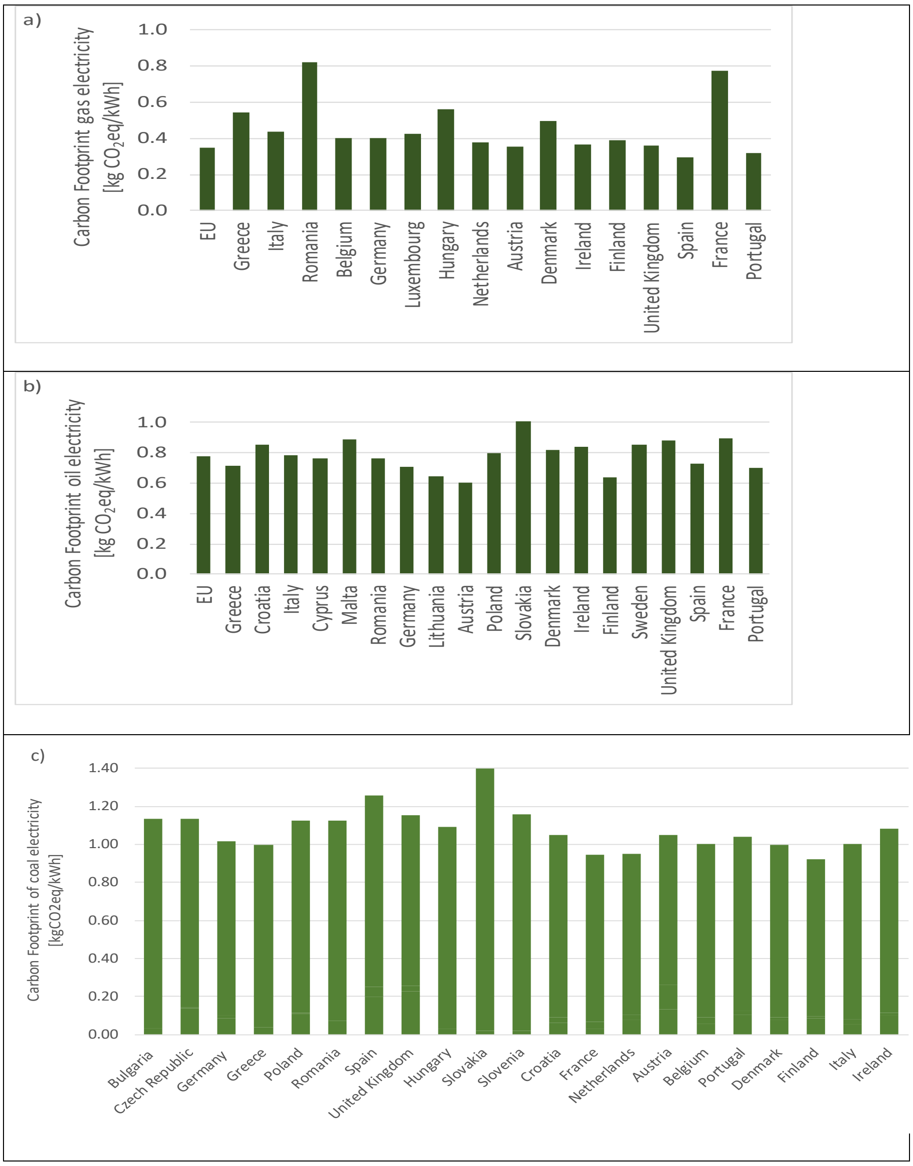
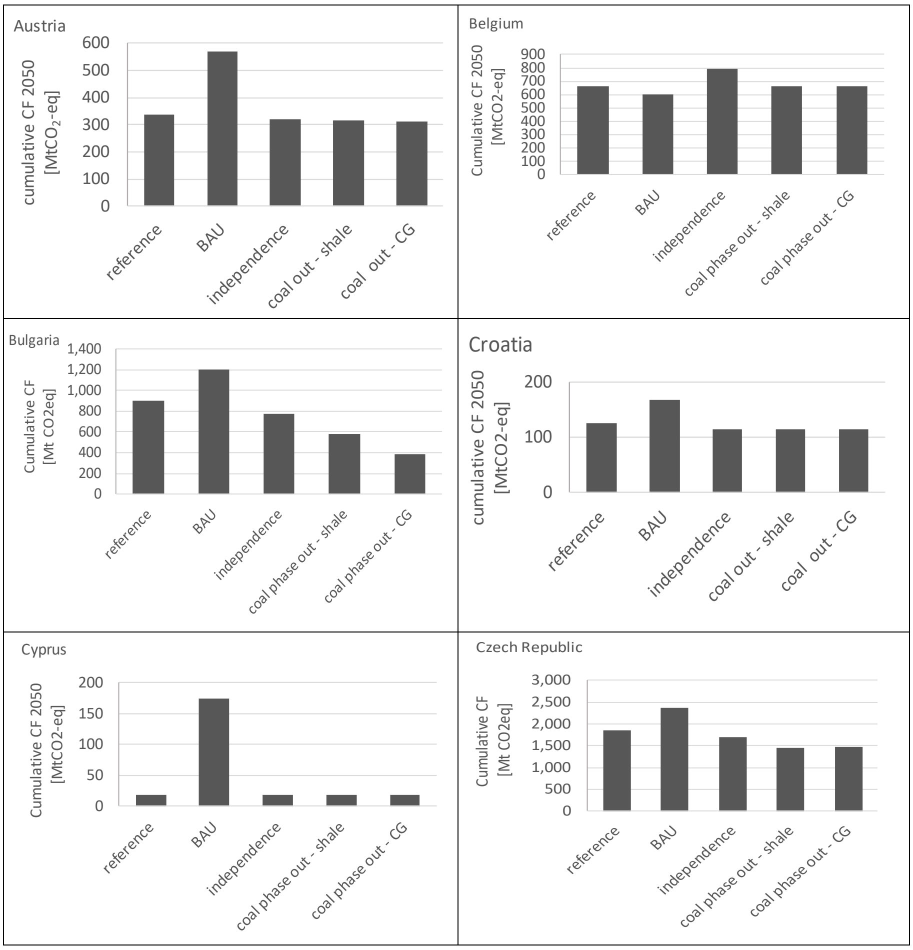
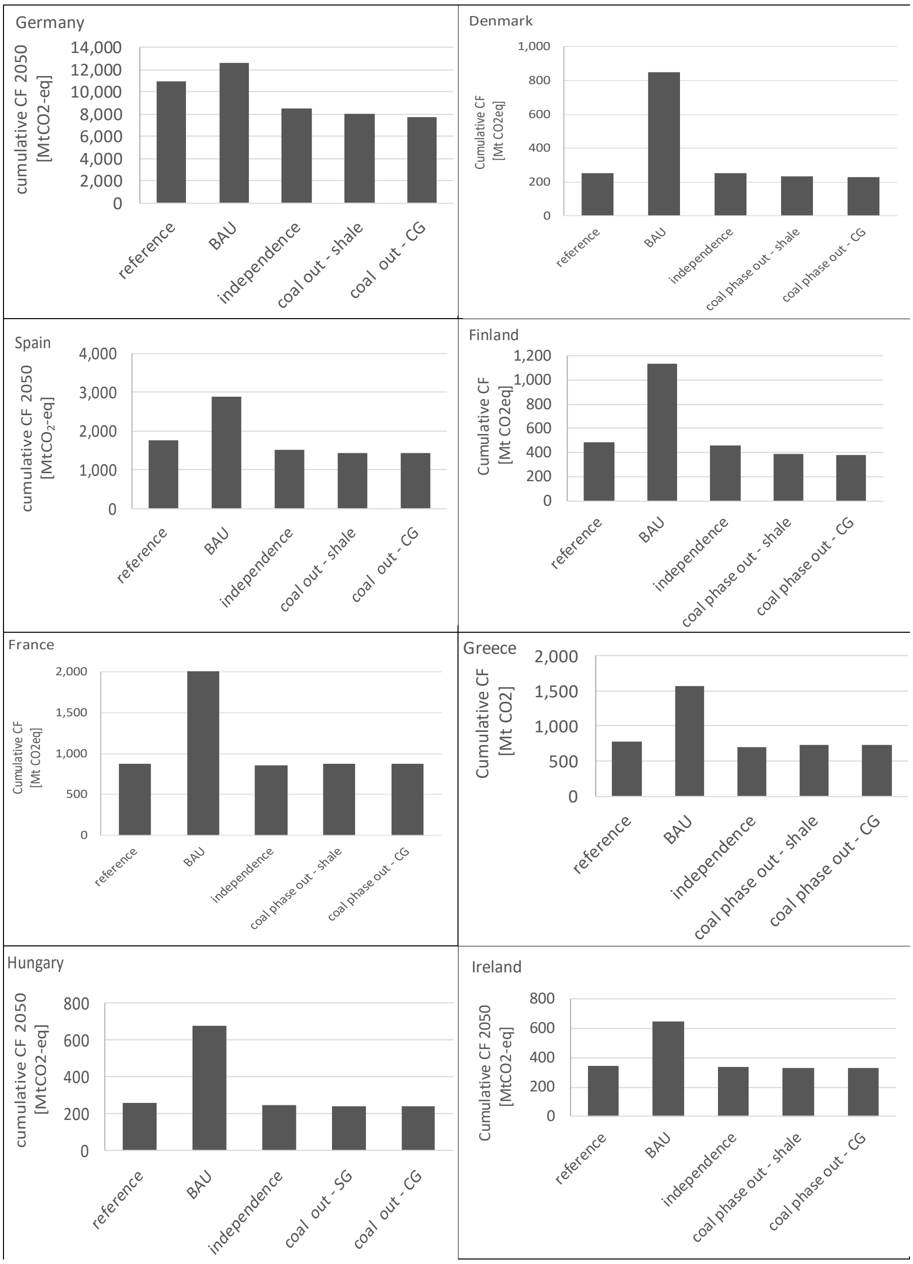


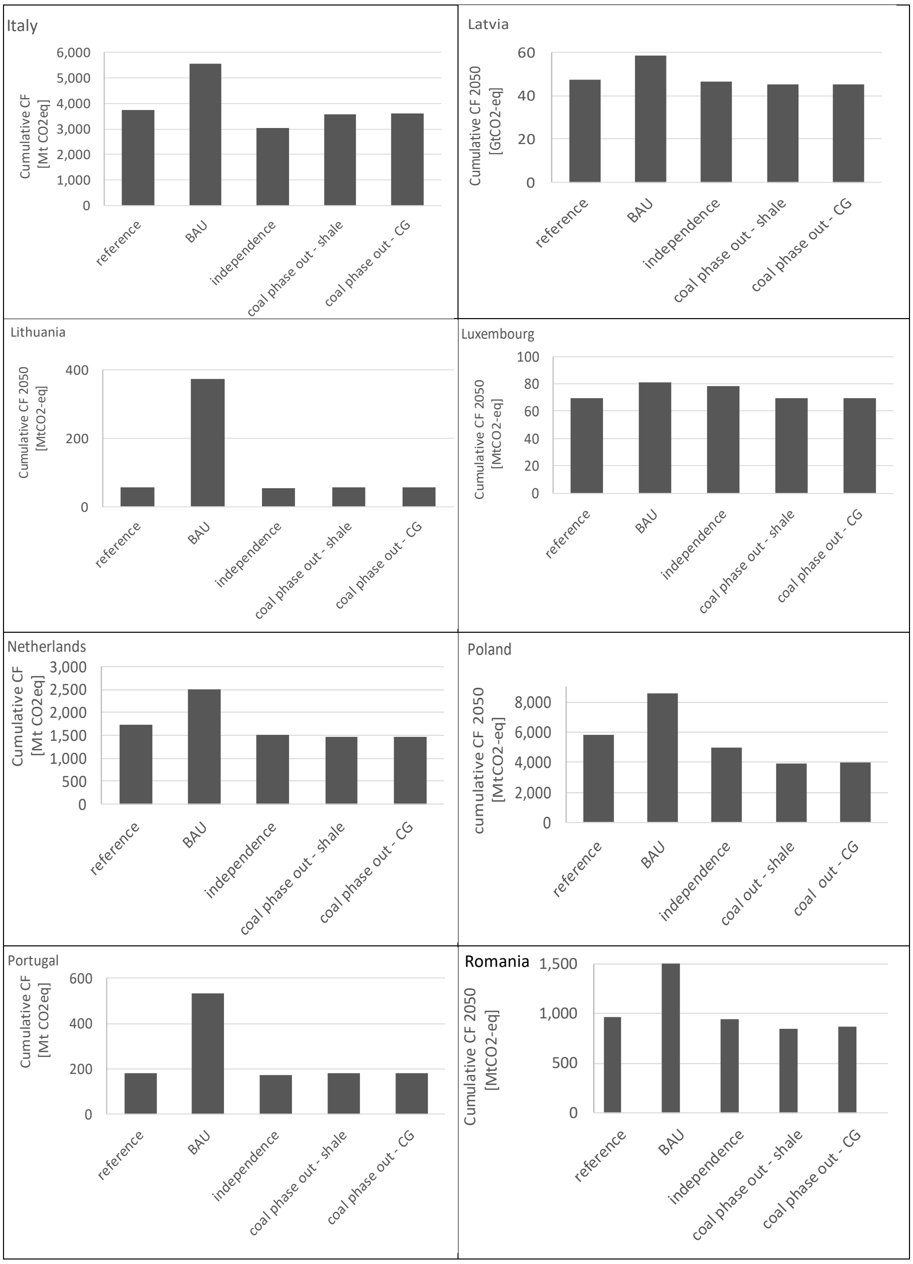
Figure S1. Carbon Footprints for electricity generation with a) conventional gas; b) oil and c) coal in EU countries that use the fuel (>10,000 TJ input; >1,000 TJ for oil) for electricity generation in the reference scenario 2010-2015, modelled with GHGenius and energy balance data. Slovakia has a very high coal footprint because the reported efficiency (ratio from out-and input over all power plants) was low. Oil footprint in Slovakia was higher than visible on the graph (1.6 kg CO2eq/kWh) due to very low efficiencies as derived from the energy balances.

Cumulative Carbon Footprint scenario comparison per country

Note: y-axis not the same




Germany
cumulative CF 2050 [MtCO2-eq]
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
reference
BAU
independence
coal out - shale
coal out - CG
Denmark
Cumulative CF [Mt CO2eq]
1,000
800
600
400
200
0
reference
BAU
independence
coal phase out - shale
coal phase out - CG
Spain
cumulative CF 2050 [MtCO2-eq]
4,000
3,000
2,000
1,000
0
reference
BAU
independence
coal out - shale
coal out - CG
Finland
Cumulative CF [Mt CO2eq]
1,200
1,000
800
600
400
200
0
reference
BAU
independence
coal phase out - shale
coal phase out - CG
France
Cumulative CF [Mt CO2eq]
2,000
1,500
1,000
500
0
reference
BAU
independence
coal phase out - shale
coal phase out - CG
Greece
Cumulative CF [Mt CO2]
2,000
1,500
1,000
500
0
reference
BAU
independence
coal phase out - shale
coal phase out - CG
Hungary
cumulative CF 2050 [MtCO2-eq]
800
600
400
200
0
reference
BAU
independence
coal out - SG
coal out - CG
Ireland
Cumulative CF 2050 [MtCO2-eq]
800
600
400
200
0
reference
BAU
independence
coal phase out - shale
coal phase out - CG


Italy
Cumulative CF [Mt CO2eq]
6,000
5,000
4,000
3,000
2,000
1,000
0
reference
BAU
independence
coal phase out - shale
coal phase out - CG
Latvia
Cumulative CF 2050 [GtCO2-eq]
60
40
20
0
reference
BAU
independence
coal phase out - shale
coal phase out - CG
Lithuania
Cumulative CF 2050 [MtCO2-eq]
400
200
0
reference
BAU
independence
coal phase out - shale
coal phase out - CG
Luxembourg
Cumulative CF 2050 [MtCO2-eq]
100
80
60
40
20
0
reference
BAU
independence
coal phase out - shale
coal phase out - CG
Netherlands
Cumulative CF [Mt CO2eq]
3,000
2,500
2,000
1,500
1,000
500
0
reference
BAU
independence
coal phase out - shale
coal phase out - CG
Poland
cumulative CF 2050 [MtCO2-eq]
8,000
6,000
4,000
2,000
0
reference
BAU
independence
coal out - shale
coal out - CG
Portugal
Cumulative CF [Mt CO2eq]
600
400
200
0
reference
BAU
independence
coal phase out - shale
coal phase out - CG
Romania
Cumulative CF 2050 [MtCO2-eq]
1,500
1,000
500
0
reference
BAU
independence
coal phase out - shale
coal phase out - CG

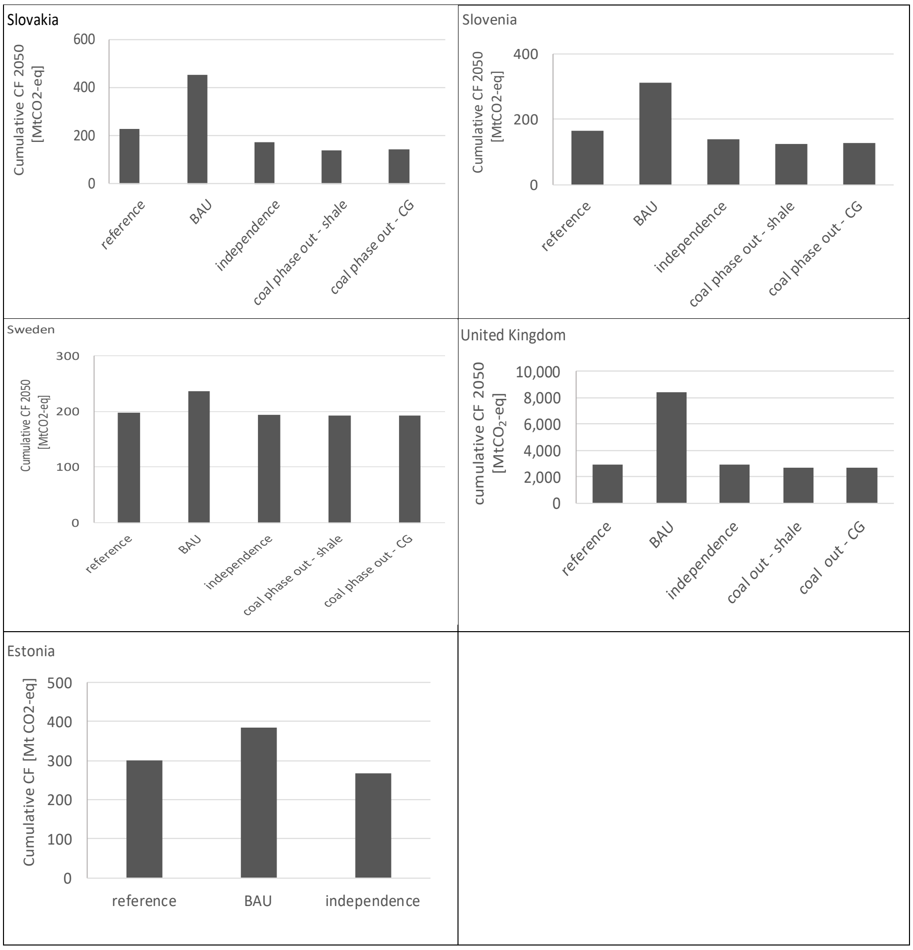


Figure S2. Comparison of scenarios for EU countries separately (SG: shale gas; CG: conventional gas).

In Belgium, the carbon footprint is lower in the BAU scenario, because in 2010 a large part of electricity generation comes from nuclear – which decreases in the reference scenario, while the fossil electricity generation increases. This comes almost 100% from gas – explaining small differences between reference and coal phase out scenarios. In the independence scenario on the other hand, conventional gas in the reference scenario gets replaced by shale gas – with a slightly higher carbon footprint.

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