A documentation of studies on the greenhouse gas balance of shale gas

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Introduction

Many studies have examined greenhouse gas (GHG) emissions from shale gas production and their possible impact on climate. The methodologies and assumptions of these studies differ, and have resulted in various conclusions on the potential emissions. Most studies explicitly state great uncertainty in some, or many, of their assumptions.

The GHG balance of shale gas has to take into account all GHG air emissions related to the production, transportation, and end-use of shale gas. GHG emissions related to end-use, i.e. electricity generation in gas-fired power plants, are reasonably well constrained and may be readily compared to other fossil fuels or renewables.

Production-related GHG emissions are much less well constrained and include: emissions from roads and well-pad construction; from diesel engines and compressors deployed during drilling and hydraulic fracturing; from well completion; and from venting/flaring during and after flowback. There is a strong variance in the quality of emission data on the production of shale gas, and also a variance in flow rate uncertainties and well lifetimes, and therefore in the eventual production volumes of individual shale gas plays.

2015

The impact of shale gas on the costs of climate policy

Kersting et al., 2015, report commissioned by German Federal Environment Agency

Abstract: "This report investigates the effects of an increased exploitation of shale gas reserves around the globe and the extent to which it can serve as a low-cost GHG mitigation option. We compare a scenario of global shale gas exploitation with a scenario in which shale gas use is very limited. Both scenarios are modelled with the global techno-economic POLES model and rely on a high regional disaggregation. The effects of shale gas production on the energy market and, consequently, on GHG emissions are analysed in a baseline case without additional climate policy and for mitigation targets compatible with the 2°C target. We find that shale gas should not be considered a cheap option to reduce global GHG emissions due to three reasons: the effects of global shale gas availability (a) are small in the short-term, (b) lead to higher baseline GHG emissions for most countries in the long-term due to lower energy prices and (c) result in higher costs of compliance with climate targets. Further, shale gas competes with renewable energy sources resulting in smaller cost reductions for renewable energy technologies. Lower energy prices also reduce the payoffs for energy efficiency measures, leading to shortened investment in such measures."

Allocating Methane Emissions to Natural Gas and Oil Production from Shale Formations
Zavala-Araiza et al., 2015

Abstract: "In this work, life cycle allocation methods have been used to assign methane emissions from production wells operating in shale formations to oil, condensate, and gas products from the wells. The emission allocations are based on a data set of 489 gas wells in routine operation and 19 well completion events. The methane emissions allocated to natural gas production are approximately 85% of total emissions (mass based allocation), but there is regional variability in the data and therefore this work demonstrates the need to track natural gas sources by both formation type and production region. Methane emissions allocated to salable natural gas production from shale formations, based on this work, are a factor of 2 to 7 lower than those reported in commonly used life cycle data sets."

2014

Methane leaks from North American natural gas systems
Brandt et al., 2014

From the abstract: "Natural gas (NG) is a potential "bridge fuel" during transition to a decarbonized energy system: It emits less carbon dioxide during combustion than other fossil fuels and can be used in many industries. However, because of the high global warming potential of methane (CH_4, the major component of NG), climate benefits from NG use depend on system leakage rates. Some recent estimates of leakage have challenged the benefits of switching from coal to NG, a large near-term greenhouse gas (GHG) reduction opportunity (1–3). Also, global atmospheric CH_4 concentrations are on the rise, with the causes still poorly understood (4). [....], we review 20 years of technical literature on natural gas emissions in the United States and Canada."

The authors conclude that "if natural gas is to be a "bridge" to a more sustainable energy future, it is a bridge that must be traversed carefully: Diligence will be required to ensure that leakage rates are low enough to achieve sustainability goals."

See **SHIP article**: "Official greenhouse gas inventories underestimate methane emissions" (Link)

Toward a better understanding and quantification of methane emissions from shale gas development
Caulton et al., 2014

From the abstract: "An instrumented aircraft platform was used to identify large sources of methane and quantify emission rates in southwestern PA in June 2012. A large regional flux, 2.0–14 g CH_4 s^{-1} km^{-2}, was quantified for a ∼2,800-km^2 area, which did not differ statistically from a bottom-up inventory, 2.3–4.6 g CH_4 s^{-1} km^{-2}. Large emissions averaging 34 g CH_4/s per well were observed from seven well pads determined to be in the drilling phase, 2 to 3 orders of magnitude greater than US Environmental Protection Agency estimates for this operational phase. The emissions from these well pads, representing ∼1% of the total number of wells, account for 4–30% of the observed regional flux. More work is needed to determine all of the sources of methane emissions from natural gas production, to ascertain why these emissions occur and to evaluate their climate and atmospheric chemistry impacts."

See **SHIP article** "Measurements taken using aircraft point to high emissions during the drilling phase in the Marcellus shale formation" (Link)

Harmonization of initial estimates of shale gas life cycle greenhouse gas emissions for electric power generation
Heath et al., 2014

From the abstract: "Through a meta-analytical procedure we call harmonization, we develop robust, analytically consistent, and updated comparisons of estimates of life cycle GHG emissions for electricity produced from shale gas, conventionally produced natural gas, and coal. On a per-unit electrical output basis, harmonization reveals that median estimates of GHG emissions from shale gas-generated electricity are similar to those for conventional natural gas, with both approximately half that of the central tendency of coal."

See **SHIP article** "Controversial studies on the impact of shale gas on climate" (Link)

Life cycle greenhouse gas emissions from Barnett shale gas used to generate electricity
Heath et al., 2014

From the abstract: "The data sources and approach used in this study differ significantly from previous efforts. The authors used inventories from the year 2009 tracking emissions of regulated air pollutants by the natural gas industry in the Barnett Shale play. [....] These data cover the characteristics and volatile organic compound (VOC) emissions of more than 16,000 individual sources in shale gas production and processing. Translating estimated emissions of VOCs into estimates of methane and carbon dioxide emissions was accomplished through the novel compilation of spatially heterogeneous gas composition analyses. Life cycle greenhouse gas emissions associated with electricity generated from Barnett Shale gas extracted in 2009 were found to be very similar to conventional natural gas and less than half those of coal-fired electricity generation."

Highlights (as presented on the article website):

- Central estimate for 2009 Barnett Shale life cycle GHG emissions is 440 g CO2e/kWh.
- Life cycle GHG emissions vary by well lifetime production, 420–510 g CO2e/kWh.
- The vast majority of GHG emissions are not affected by the type or origin of gas.
- Methane leakage comes mostly from potentially controllable sources.
- Gas composition variability can affect GHG estimation at fine spatial resolution.

A bridge to nowhere: methane emissions and the greenhouse gas footprint of natural gas
Howarth, 2014

From the abstract: "The best data available now indicate that our estimates [Howarth et al., 2011] of methane emission from both shale gas and conventional natural gas were relatively robust. Using these new, best available data and a 20-year time period for comparing the warming potential of methane to carbon dioxide, the conclusion stands that both shale gas and conventional natural gas have a larger GHG than do coal or oil, for any possible use of natural gas and particularly for the primary uses of residential and commercial heating."

See **SHIP article** "Controversial studies on the impact of shale gas on climate". (Link)

Mitigation of climate impacts of possible future shale gas extraction in the EU: available technologies, best practices and options for policy makers

ICF, 2014, report for European Commission, DG Climate Action

From the Executive Summary: "The specific objectives of the study are to analyse international experiences in minimising onsite fugitive GHG emissions to identify lessons and best practices; to provide an overview of the most advanced technologies and practices that could be promoted or enforced for minimizing these emissions; to provide an overview of different policy options for a possible regulatory framework for minimizing these emissions and to analyse the climate, environmental and economic impacts of key policy options."

Implications of Shale Gas Development for Climate Change

Newell and Raimi, 2014

From the abstract: "Most evidence indicates that natural gas as a substitute for coal in electricity production, gasoline in transport, and electricity in buildings decreases greenhouse gases, although as an electricity substitute this depends on the electricity mix displaced. Modeling suggests that absent substantial policy changes, increased natural gas production slightly increases overall energy use, more substantially encourages fuel-switching, and that the combined effect slightly alters economy wide GHG emissions; whether the net effect is a slight decrease or increase depends on modeling assumptions including upstream methane emissions. Our main conclusions are that natural gas can help reduce GHG emissions, but in the absence of targeted climate policy measures, it will not substantially change the course of global GHG concentrations. Abundant natural gas can, however, help reduce the costs of achieving GHG reduction goals."

Life cycle environmental impacts of UK shale gas

Stamford and Azapagic, 2014

The authors make "a first attempt at quantifying a range of overall lifecycle impacts of shale gas production in the UK. The results suggest that the impacts range widely, depending on the assumptions. It is suggested that shale gas is comparable or superior to conventional gas and low-carbon technologies for depletion of abiotic resources, eutrophication, and freshwater, marine and human toxicities.

Conversely, it has a higher potential for creation of photochemical oxidants (smog) and terrestrial toxicity than any other option considered. For acidification, shale gas is a better option than coal power but an order of magnitude worse than the other options. The impact on ozone layer depletion is within the range found for conventional gas, but nuclear and wind power are better options still.

The results of this research highlight the need for tight regulation and further analysis once typical UK values of key parameters for shale gas are established, including its composition, recovery per well, fugitive emissions and disposal of drilling waste."

Westaway et al., 2015 Comment on 'Life cycle environmental impacts of UK shale gas' by L. Stamford and A. Azapagic. Applied Energy, 134, 506–518, 2014

Link to Final Draft of the article.

The authors conclude: "Overall, we consider that through their combination of tacitly assuming that dirty environmental practices that are already illegal in the EU and UK will nevertheless be followed there, and their emphasis on worst-case scenarios in which wells are assumed to yield unrealistically low amounts of shale gas, Stamford and Azapagic have seriously exaggerated the potential environmental impact of a future UK shale gas industry."

2013

Measurements of methane emissions at natural gas production sites in the United States
Allen et al., 2013

This article focuses on methane emissions during the pre-production and production stages of hydraulically fractured shale gas wells. A main finding is that methane emissions from well completion flowbacks are significantly lower than the estimate in a report from U.S. EPA (2013). Methane emissions from pneumatic devices, however, were 60 % higher than estimated by U.S. EPA (2013). The authors make an important contribution towards a better understanding of methane emissions from natural gas production, and specifically for shale gas operations, towards a more general assessment of the greenhouse gas balance of the natural gas sector. A comment on the study on the SHIP website points out that more data are needed and that the published data from this study are not representative. Additionally, the sampling policy for this study has been critizised.

See **SHIP article** "Lower methane emissions than expected at selected shale gas production sites in the U.S." (Link)

Methane emissions estimate from airborne measurements over a western United States natural gas field.
Karion et al., 2013

Full Text

Abstract: "Methane (CH_4) emissions from natural gas production are not well quantified and have the potential to offset the climate benefits of natural gas over other fossil fuels. We use atmospheric measurements in a mass balance approach to estimate CH_4 emissions of $55 \pm 15 \times 10^3$ kg h^{-1} from a natural gas and oil production field in Uintah County, Utah, on 1 day: 3 February 2012. This emission rate corresponds to 6.2%–11.7% (1σ) of average hourly natural gas production in Uintah County in the month of February. This study demonstrates the mass balance technique as a valuable tool for estimating emissions from oil and gas production regions and illustrates the need for further atmospheric measurements to determine the representativeness of our single-day estimate and to better assess inventories of CH_4 emissions."

Life cycle greenhouse gas emissions and freshwater consumption of Marcellus shale gas
Laurenzi and Jersey, 2013

Abstract: "We present results of a life cycle assessment (LCA) of Marcellus shale gas used for power generation. The analysis employs the most extensive data set of any LCA of shale gas to date, encompassing data from actual gas production and power generation operations. Results indicate that a typical Marcellus gas life cycle yields 466 kg CO2eq/MWh (80% confidence interval: 450–567 kg CO2eq/MWh) of greenhouse gas (GHG) emissions and 224 gal/MWh (80% CI: 185–305 gal/MWh) of freshwater consumption. Operations associated with hydraulic fracturing constitute only 1.2% of the life cycle GHG emissions, and 6.2% of the life cycle freshwater consumption. These results are influenced most strongly by the estimated ultimate recovery (EUR) of the well and the power plant efficiency: increase in either quantity will reduce both life cycle freshwater consumption and GHG emissions relative to power generated at the plant. We conclude by comparing the life cycle impacts of Marcellus gas and U.S. coal: The carbon footprint of Marcellus gas is 53% (80% CI: 44–61%) lower than coal, and its freshwater consumption is about 50% of coal. We conclude that substantial GHG reductions and freshwater savings may result from the replacement of coal-fired power generation with gas-fired power generation."

Potential Greenhouse Gas Emissions Associated with Shale Gas Extraction and Use

MacKay and Stone, 2013

This study gathers available evidence on the potential greenhouse gas emissions (GHG) from shale gas production and use in the UK and discusses the compatibility of shale gas production and use with UK and global climate change targets.

Main findings about the carbon footprint of shale gas are, among others: The carbon footprint (emissions intensity) of shale gas extraction and use is likely to be in a range which makes it comparable to gas extracted from conventional sources. When shale gas is used for electricity generation, its carbon footprint is likely to be significantly lower than the carbon footprint of coal.

Extraction and use of shale gas does produce emissions, and therefore the authors conclude that any increase in emissions associated with domestic shale gas operations would have to be offset by emissions cuts elsewhere in the economy, if UK's carbon budgets are binding constraints. With regard to global GHG emissions rates and cumulative emissions, the authors state that the production of shale gas could increase global cumulative GHG emissions if the fossil fuels displaced by shale gas are used elsewhere. The potential increase could be counteracted if equivalent and additional emissions-reduction measures are made. Recommendations given include the use of the best available technology, careful monitoring programs, and research into improved technologies.

Anthropogenic emissions of methane in the United States

Miller et al., 2013

From the abstract: "Existing state regulations in California and Massachusetts require ∼15% greenhouse gas emissions reductions from current levels by 2020. However, government estimates for total US methane emissions may be biased by 50%, and estimates of individual source sectors are even more uncertain. This study uses atmospheric methane observations to reduce this level of uncertainty. We find greenhouse gas emissions from agriculture and fossil fuel extraction and processing (i.e., oil and/or natural gas) are likely a factor of two or greater than cited in existing studies. Effective national and state greenhouse gas reduction strategies may be difficult to develop without appropriate estimates of methane emissions from these source sectors."

See **SHIP article** "Methane emissions are underestimated by the U.S. Environmental Protection Agency (EPA)" (Link)

A Dilemma of Abundance: Governance Challenges of Reconciling Shale Gas Development and Climate Change Mitigation

Stephensons and Shaw, 2013

The authors argue that governance challenges are both more pressing and more profound as compared to the technical feasibility of reconciling shale gas development with climate action. It is pointed out that policy measures prove challenging, particularly in jurisdictions that stand to benefit economically from unconventional fuels. This dilemma is illustrated through a case study of shale gas development in British Columbia, Canada, a global leader on climate policy that is nonetheless struggling to manage gas development for mitigation.

Methane leaks erode green credentials of natural gas

Tollefson, 2013

This editorial in Nature magazine summarizes the current scientific debate on fugitive emissions of the natural gas industry. It includes reports on high methane leakage rates, measured at natural gas fields in the US, which were presented at an American Geophysical Union (AGU) meeting in December, 2012. “Whether the high leakage rates claimed in Colorado and Utah are typical across the US natural-gas industry remains unclear. The NOAA data represent a “small snapshot” of a much larger picture that the broader scientific community is now assembling”, says Steven Hamburg, chief scientist at the Environmental Defense Fund (EDF) in Boston, Massachusetts.

2012

Greater focus needed on methane leakage from natural gas infrastructure

Alvarez et al., 2012

This study addresses the potential climate implications of an increased use of natural gas (conventional and unconventional) in the U.S., instead of coal or oil in different sectors (e.g., electricity generation and transportation). Results show that using natural gas instead of coal in electric power plants can reduce radiative forcing immediately, and reducing CH_4 losses from the production and transportation of natural gas would produce even greater benefits.

The article includes a discussion on the upstream GHG emissions of shale gas. The authors explain that their "... conclusion that natural gas produces net climate benefits relative to certain types of coal reaches the opposite conclusion of Howarth et al. [2011] for three principal reasons. The main difference is that Howarth et al. [2011] assume much greater methane emissions than we do. As described above, we estimate that 2.1% of natural gas produced is lost annually between the well and the power plant (including the local distribution system, we estimate that the natural gas emitted is 2.4% of gross natural gas production). Howarth et al. [2011] used a range of 3.6–7.9% for shale gas and 1.7–6.0% for conventional gas (as a percentage of the CH_4 produced over the lifecycle of a well—also a different metric than we used)."

Has US Shale Gas Reduced CO_2 Emissions?

Broderick and Anderson, 2012

This report from the Tyndall Centre for Climate Change Research calls for a meaningful cap on global carbon emissions in order to take full advantage of the potential benefits from a coal-to-gas switch in power generation.

The authors examine the recent emissions savings in the US power sector, influenced by shale gas, and the concurrent trends in coal exports that may increase emissions in Europe and Asia.

“US CO_2 emissions from domestic energy have declined by 8.6% since a peak in 2005, the equivalent of 1.4% per year. Part of this decline is related to the switch from coal to gas in US power generation.

During this time, there has been a substantial increase in coal exports from the US (2008-2011) and globally, coal consumption has continued to rise. The calculations presented in the report suggest that more than half of the emissions avoided in the US power sector may have been exported as coal."

The report states that "... without a meaningful cap on global carbon emissions, the exploitation of shale gas reserves is likely to increase total emissions. For this not to be the case, consumption of displaced fuels must be reduced globally and remain suppressed indefinitely; in effect displaced coal must stay in the ground."

Life-Cycle Greenhouse Gas Emissions of Shale Gas, Natural Gas, Coal, and Petroleum.

Burnham et al., 2012

This study discusses the key sources of GHG emissions in conventional and shale gas, as well as in coal and petroleum, to estimate the level of GHG emissions and to understand the uncertainties involved in calculating their life-cycle GHG impacts. Current data gaps are identified and discussed. Life-Cycle Analysis results show "… that shale gas life-cycle emissions are 6% lower than conventional natural gas, 23% lower than gasoline, and 33% lower than coal." The sensitivity analysis shows that estimated ultimate recovery of gas wells contributes the most uncertainty to the shale gas model results.

Assessing the greenhouse impact of natural gas

Cathles, 2012

This study investigates the impact of a coal-to-gas switch on global warming and concludes that "the substitution of natural gas for coal and some oil would realize ~40% of the greenhouse benefits that could be had by replacing fossil fuels with low carbon energy sources such as wind, solar, and nuclear." This estimate however, will only be reached when methane leakage in natural gas production is further reduced in the future, below todays level.

Cathles discusses published leakage rates of natural gas production, as these are a major input parameter in his calculations. Especially he argues that the leakage rate estimated by Howarth et al. (2011) is about five times higher than published results, thereby challenging their conclusions that the climate impact of shale gas might be worse than that of coal.

A commentary on "The greenhouse-gas footprint of natural gas in shale formations" by R.W. Howarth, R. Santoro, and Anthony Ingraffea.

Cathles et al., 2012

These authors criticized the assumptions made by Howarth et al. 2011: "... they significantly overestimate the fugitive emissions associated with unconventional gas extraction, undervalue the contribution of "green technologies" to reducing those emissions to a level approaching that of conventional gas, base their comparison between gas and coal on heat rather than electricity generation (almost the sole use of coal), and assume a time interval over which to compute the relative climate impact of gas compared to coal that does not capture the contrast between the long residence time of CO_2 and the short residence time of methane in the atmosphere." These authors concluded that "Using more reasonable leakage rates and bases of comparison, shale gas has a GHG footprint that is half and perhaps a third that of coal."

Climate impact of potential shale gas production in the EU

Forster and Perks, 2012

Report for European Commission DG CLIMA

From the Executive Summary:

"A hypothetical analysis has been carried out of the potential lifecycle GHG [greenhouse gas] emissions that may arise from shale gas exploitation within Europe. In our base case, which does not represent a preferred scenario, we have estimated the GHG emissions per unit of electricity generated from shale gas to be around 4% to 8% higher than for electricity generated by conventional pipeline gas from within Europe."

"These additional emissions arise in the pre-combustion stage, predominantly in the well completion phase when the fracturing fluid is brought back to the surface together with released methane. If emissions from well completion are mitigated, through flaring or capture, and utilized then this difference is reduced to 1% to 5%. This finding is broadly in line with those of other U.S. studies which found that generation from shale gas had emissions about 2% to 3% higher than conventional pipeline gas generation."

The report also provides a review of the current legislative framework in the EU for the control of GHG emissions from shale gas operations. Additionally, the report examines the current GHG emissions reporting framework and explores the extent to which emissions from shale gas operations would be captured within the existing reporting requirements.

Venting and leaking of methane from shale gas development: response to Cathles et al.

Howarth et al., 2012

In a response to the above comment, Howarth et al. 2012 stood by their approach and findings: "… we conclude that for most uses, the GHG footprint of shale gas is greater than that of other fossil fuels on time scales of up to 100 years. When used to generate electricity, the shale-gas footprint is still significantly greater than that of coal at decadal time scales but is less at the century scale. We reiterate our conclusion from our April 2011 paper that shale gas is not a suitable bridge fuel for the 21st Century."

Effects of New Fossil Fuel Developments on the Possibilities of Meeting 2°C Scenarios

Meindertsma and Block, 2012

This report, commissioned by Greenpeace International, investigates the impact of new fossil fuel production on mankind´s ability to mitigate climate change. New fossil fuels include tar sands and shale gas, fossil fuels from remote locations, and fossil fuels with a very large increase in production in the near future.

The report concludes that "...in a scenario where the new fossil fuels are developed, we need to embark on a rapid emission reductions pathway at the latest in 2019 in order to meet the 50% probability carbon budget. Avoiding the development of new fossil fuels will give us until 2025 to start further rapid emission reductions."

Shale gas production: potential versus actual greenhouse gas emissions

O’Sullivan and Paltsev, 2012

The findings of this study reiterate what many recent studies have suggested; greenhouse gas (GHG) emissions of shale gas wells are slightly, and not extensively, higher than the emissions of conventional natural gas wells. The MIT - Massachusetts Institute of Technology authors calculate that the total fugitive GHG emissions from U.S. shale gas related hydraulic fracturing in 2010 represent 3.6% of the estimated fugitive emissions from all natural gas production-related sources in that year. They state that, “… the production of shale gas and specifically, the associated hydraulic fracturing operations, have not materially altered the total GHG emissions from the natural gas sector. At the same time the authors state that, “… fugitive emissions from the overall natural gas sector are a proper concern”.

Hydrocarbon emissions characterization in the Colorado Front Range: A pilot study

Pétron et al., 2012

The authors "... focus on describing and interpreting the measured variability in CH_4 and C3–5 alkanes observed in the Colorado Northern Front Range. We use data from daily air samples collected at a NOAA tall tower located in Weld County as well as continuous CH_4 observations and discrete targeted samples from an intensive mobile sampling campaign in the Colorado Northern Front Range."

The study suggests that methane emissions from natural gas production may be much higher than indicated by industry data and some of the recently published studies.

The paper by Pétron et al. was questioned and an alternative data interpretation was provided by**Levi, 2012**: Comment on “Hydrocarbon emissions characterization in the Colorado Front Range—A pilot study (Link to Final Draft of the paper)

Reply to Levis´ comment by **Pétron et al., 2013**: Reply to comment on “Hydrocarbon emissions characterization in the Colorado Front Range—A pilot study” by Michael A. Levi

Levi, 2013: Reply to “Reply to ‘Comment on “Hydrocarbon emissions characterization in the Colorado Front Range – A Pilot Study”’ by Michael A. Levi” by Gabrielle Pétron et al. (Link to Final Draft of the paper)

Air Sampling Reveals High Methane Emissions from Natural Gas Field.

Tollefson, 2012

This article briefly reviews the current debate on methane emissions as of February 2012 and features a new study from Pétron et al. (2012) (see above) which suggests that methane emissions from natural gas production may be much higher than indicated by industry data and some of the recently published studies.

Results are based on analyzed air samples from a region where hydraulic fracturing of gas wells is applied at large scale. According to Tollefson, the strength of the study by Pétron et al. is that it uses independent, original data and not data from industry reports or conceptual models. Interpretation of these data is, as usual, based on assumptions and models, however, and the authors readily point out substantial uncertainties in their calculations.

"Pétron says that more studies are needed using industry inventories and measurements of atmospheric concentrations. "We will never get the same numbers," she says, "but if we can get close enough that our ranges overlap in a meaningful way, then we can say we understand the process.""

Life Cycle Carbon Footprint of Shale Gas: Review of Evidence and Implications

Weber and Clavin, 2012

These authors review several recent studies of the shale gas carbon footprint and provide a Monte Carlo uncertainty analysis of the footprint of both shale and conventional natural gas production. The results show that the most likely upstream carbon footprints of both types of gas production are largely similar.

The study also modeled an alternative scenario that provides for the use of RECs (Reduced Emissions Completions), as regulated for in future U.S. shale gas wells by the U.S. Environmental Protection Agency (EPA). This resulted in a substantial reduction of both the mean shale gas upstream carbon footprint and the uncertainty range.

The authors emphasize that the upstream carbon footprint represents less than 25% of the total carbon footprint of natural gas. When identifying emission reduction opportunities in the energy and transportation sector, it is of equal or greater importance that the efficiency of producing heat, electricity and other functions is considered.

2011

Methane and the greenhouse-gas footprint of natural gas from shale formations.

Howarth et al., 2011

This was the first study published on that topic in peer-reviewed literature. It gained a lot of public attention, partly due to its novelty, but foremost because it challenged the belief that natural gas is the cleanest of all fossil fuels in terms of GHG emissions. This had up until then been taken for granted. The authors argued that GHG emissions during shale gas production may be so high that the climate impact of natural gas from shale could be as bad, or even worse, than that of coal. The authors pointed out great uncertainties in some crucial model input data, however, and concluded that further studies with better input data would be needed.

The industry-sponsored 'Energy-In-Depth' group have in turn presented a critical appraisal, a collection of challenging reactions to this study, and documentation of subsequent studies with more positive conclusions on shale gas GHG balances. Howarth and his co-workers defend their positions with updated background information and FAQs here.

The greenhouse impact of unconventional gas for electricity generation.

Hultmann et al., 2011

Concerning methodology, the authors point out uncertainties due to the scarcity of reliable data on fugitive emissions from unconventional gas production and the lack of documentation of the equipment and practices most commonly used by these wells. They also elaborate on the selection criteria of Global Warming Potential time horizons and calculation factors and discuss the assumptions made by Howarth et al. 2011.

Taking into account the uncertainties, this study draws the conclusion "... that for electricity generation the GHG impacts of shale gas are 11% higher than those of conventional gas, and only 56% that of coal for standard assumptions."

The authors estimate that due to the future increased application of available and new technologies in shale gas development, the GHG balance of shale gas may be substantially improved and the difference between this and the impact of coal will continually widen. For this reason, the study recommends that "... any regulatory standard that classifies conventional gas as a source of 'clean energy' should therefore consider shale gas in this context; arguments that shale gas is more polluting than coal are largely unjustified."

Life cycle greenhouse gas emissions of Marcellus shale gas.

Jiang et al., 2011

Looking specifically at Marcellus shale gas production, the authors identify emissions from well completion to be the largest source of GHG during gas production. This includes the natural gas associated with hydraulic fracturing flowback water, which is flared and/or vented. The authors point out that these emissions could be reduced significantly by using Reduced Emission Completions, which capture gas emissions.

Production-related emissions are not substantial contributors to the overall GHG balance, however, when looking at Life Cycle Analysis. This is dominated by the emissions of gas combustion. Overall, the authors find that natural gas from the Marcellus shale has 20–50% lower life cycle GHG emissions than coal for the production of electricity, depending upon plant efficiencies and natural gas emissions variability. According to this study, Marcellus shale gas adds only 3 % more emissions when used for electricity generation, as compared with the average from conventional gas.

Life Cycle Greenhouse Gas Inventory of Natural Gas Extraction, Delivery and Electricity Production

Skone et al., 2011

This study compared life-cycle GHG emissions for baseload power production with different types of natural gas and coal on different climate impact timescales. They found that "... using unconventional natural gas, from tight sands, shale and coal beds, and compared with a 20-year global warming potential (GWP), natural gas-fired electricity has 39 percent lower greenhouse gas emissions than coal per delivered megawatt-hour (MWh) using current technology."

"Additionally, "cradle to gate" GHG emission assessments (for raw material acquisition and transport) are modeled for different coal and natural gas types, including shale gas. These data are useful as input data when modeling life cycle analyses (LCAs) with end uses different from electricity generation in power plants.

An early draft version of Skone et al. 2011 was compared with Howarth et al. 2011 in a study by David Hughes 2011: Hughes critically examined the assumptions made by Skone et al. and supported the conclusions made by Howarth et al. 2011.

Modeling the Relative GHG Emissions of Conventional and Shale Gas Production.

Stephenson et al., 2011

With this modeling study, the authors compare GHG Life Cycle Analysis results for shale gas and conventional gas. They conclude "... that shale gas typically has a WtW ["well-to-wire"] emissions intensity about 1.8-2.4 % higher than conventional gas, arising mainly from higher methane releases upon well completion. Even using extreme assumptions, it was found that WtW emissions from shale gas need be no more than 15 % higher than conventional gas, if flaring or recovery measures are used. In all cases considered, the WtW emissions of shale gas power generation are significantly lower than those of coal."