How to quantify uncertainty and variability in life cycle assessment: the case of greenhouse gas emissions of gas power generation in the United States

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S1 Simple cycle vs. combined cycle gas power plants

Life cycle greenhouse gas (GHG) emission calculations of gas power require special consideration of distinct classes of gas power generation technologies, which constitute an extreme case of technological variability. The first class uses a “simple cycle” to generate power: In this process, gas is burned to directly generate high pressure steam from boiler feed water. This steam then flows through steam turbines, dropping in pressure as power is generated. The second class of gas power generation technology utilizes a “combined cycle”: In this process, gas is combusted in a turbine to directly generate power. The hot combustion products (mainly CO_2, H_2O and air) are then utilized to generate high pressure steam as in the simple cycle. The combined cycle is more efficient than the simple cycle, requiring less gas to generate an equivalent amount of electricity. Both technologies yield hot combustion products that may be used for heating, i.e. cogeneration. Therefore, there are two distinct scenarios possible for gas power, via combined cycle and via simple cycle. We did not consider cases associated with cogeneration, as the amount of heat produced was not always reported on a plant-specific level (EIA, 2011). In some cases, a facility may have both SC and CC plants. If the power output and heat input to the SC and CC plants can be discerned (e.g. in the EIA 923 Data File), then the SC or CC plants were included in their respective system boundaries. We report life cycle GHG emissions of CC power plants (239 plants in 2009) and SC power plants (69 plants in 2009).

S2 Modeling approach and equations

Table S1. Losses and uses of gas in the production phase. Combustive emissions may be calculated by multiplying the combustive methane use by $H_i \kappa_i(44/12)$ where H_i is the high heating value of the produced gas (Btu HHV/scf NG), and κ_i is the carbon content (kg C/Btu, HHV basis). Activity factors (A_{ji}) and Emission factors (E_{ji}) reported in the Appendices of the EPA GHGI already account for regional composition. If regional composition is not explicitly accounted for in the emission factors, they should be divided by the average methane content of the gas from which they were estimated (e.g. 78.8%, for the emission factors from the EPA/GRI study of 1996) and multiplied by x_i, the methane content of the gas (mol%). Similar accounting was employed for naturally-occurring CO_2 in the raw gas. Other variables reported: t: lifetime of well (years), ξ = combustion efficiency (flaring), ε: heat rate of gas engines or turbines (Btu/Hphr, HHV-basis), $\Xi_{Prod,i:}$ correction factor to account for decreased methane emissions due to governmental regulations and incentives (dimensionless) that came into force after the development of the original EPA/GRI emission factors. $\Xi_{Prod,i:} = 1-(R_{STAR}+R_{NESHAP})/E_{excl}$, where R_{STAR} is the methane emission reductions due to the EPA GAS STAR program in 2011, R_{NESHAP} is an additional reduction due to governmental regulation in 2011, and E_{excl} are the actual methane emissions in 2011 excluding reductions due to regulations and the GAS STAR program.

Region	Activity	Activity Data	Emission Factor	Methane Emission
i	Non-associated Gas Wells without Hydraulic Fracturing	$A_{1i} = A_{1i,EPA}$	E_{1i}	$m_{1i} = A_{1,i}E_{1i}$
i	Gas Wells with Hydraulic Fracturing	$A_{2i} = A_{2i,EPA}$	$E_{2i} = 0$	$m_{2i} = A_{2,i}E_{2i}$
i	Heaters	$A_{3i} = A_{3i,EPA}\frac{A_{1i}}{A_{1i}+A_{2i}}$	E_{3i}	$m_{3i} = A_{3,i}E_{3i}$
i	Separators	$A_{4i} = A_{4i,EPA}\frac{A_{1i}}{A_{1i}+A_{2i}}$	E_{4i}	$m_{4i} = A_{4,i}E_{4i}$
i	Dehydrators	$A_{5i} = A_{5i,EPA}\frac{A_{1i}}{A_{1i}+A_{2i}}$	E_{5i}	$m_{5i} = A_{5,i}E_{5i}$
i	Meters/Piping	$A_{6i} = A_{6i,EPA}\frac{A_{1i}}{A_{1i}+A_{2i}}$	E_{6i}	$m_{6i} = A_{6,i}E_{6i}$
i	Small Reciprocating Compressors	$A_{7i} = A_{7i,EPA}\frac{A_{1i}}{A_{1i}+A_{2i}}$	E_{7i}	$m_{7i} = A_{7,i}E_{7i}$
i	Large Reciprocating Compressors	$A_{8i} = A_{8i,EPA}\frac{A_{1i}}{A_{1i}+A_{2i}}$	E_{8i}	$m_{8i} = A_{8,i}E_{8i}$
i	Large Reciprocating Stations	$A_{9i} = A_{9i,EPA}\frac{A_{1i}}{A_{1i}+A_{2i}}$	E_{9i}	$m_{9i} = A_{9,i}E_{9i}$
i	Pipeline Leaks	$A_{10i} = A_{10i,EPA}\frac{A_{1i}}{A_{1i}+A_{2i}}$	E_{10i}	$m_{10i} = A_{10,i}E_{10i}$
i	Pneumatic Device Vents	$A_{11i} = A_{11i,EPA}\frac{A_{1i}}{A_{1i}+A_{2i}}$	E_{11i}	$m_{11i} = A_{11,i}E_{11i}$
i	Chemical Injection Pumps	$A_{12i} = A_{12i,EPA}\frac{A_{1i}}{A_{1i}+A_{2i}}$	E_{12i}	$m_{12i} = A_{12,i}E_{12i}$
i	Kimray Pumps	$A_{13i} = A_{13i,EPA}\frac{A_{1i}}{A_{1i}+A_{2i}}$	E_{13i}	$m_{13i} = A_{13,i}E_{13i}$
i	Dehydrator Vents	$A_{14i} = A_{14i,EPA}\frac{A_{1i}}{A_{1i}+A_{2i}}$	E_{14i}	$m_{14i} = A_{14,i}E_{14i}$
i	Condensate Tanks without Control Devices	$A_{15i} = A_{15i,EPA}\frac{A_{1i}}{A_{1i}+A_{2i}}$	E_{15i}	$m_{15i} = A_{15,i}E_{15i}$
i	Condensate Tanks with Control Devices	$A_{16i} = A_{16i,EPA}\frac{A_{1i}}{A_{1i}+A_{2i}}$	E_{16i}	$m_{16i} = A_{16,i}E_{16i}$
i	Gas Engines	$A_{17i} = A_{17i,EPA}\frac{A_{1i}}{A_{1i}+A_{2i}}$	E_{17i}	$m_{17i} = A_{17,i}E_{17i}$
i	Workovers without hydraulic fracturing	$A_{18i} = A_{18i,EPA}\frac{A_{1i}}{A_{1i}+A_{2i}}$	E_{18i}	$m_{18i} = A_{18,i}E_{18i}$
i	Liquids Unloading (with plunger lifts)	$A_{19i} = A_{19i,EPA}\frac{A_{1i}}{A_{1i}+A_{2i}}$	E_{19i}	$m_{19i} = A_{19,i}E_{19i}$
i	Liquids Unloading (without plunger lifts)	$A_{20i} = A_{20i,EPA}\frac{A_{1i}}{A_{1i}+A_{2i}}$	E_{20i}	$m_{20i} = A_{20,i}E_{20i}$
i	Vessel Blowdown	$A_{21i} = A_{21i,EPA}\frac{A_{1i}}{A_{1i}+A_{2i}}$	E_{21i}	$m_{21i} = A_{21,i}E_{21i}$
i	Pipeline Blowdown	$A_{22i} = A_{22i,EPA}\frac{A_{1i}}{A_{1i}+A_{2i}}$	E_{22i}	$m_{22i} = A_{22,i}E_{22i}$
i	Compressor Blowdown	$A_{23i} = A_{23i,EPA}\frac{A_{1i}}{A_{1i}+A_{2i}}$	E_{23i}	$m_{23i} = A_{23,i}E_{23i}$
i	Compressor Starts	$A_{24i} = A_{24i,EPA}\frac{A_{1i}}{A_{1i}+A_{2i}}$	E_{24i}	$m_{24i} = A_{24,i}E_{24i}$
i	Pressure Relief Valves	$A_{25i} = A_{25i,EPA}\frac{A_{1i}}{A_{1i}+A_{2i}}$	E_{25i}	$m_{25i} = A_{25,i}E_{25i}$
i	Mishaps	$A_{26i} = A_{26i,EPA}\frac{A_{1i}}{A_{1i}+A_{2i}}$	E_{26i}	$m_{26i} = A_{26,i}E_{26i}$
i	Produced Water from CBM	$A_{27i} = A_{27i,EPA}\frac{A_{1i}}{A_{1i}+A_{2i}}$	E_{27i}	$m_{27i} = A_{27,i}E_{27i}$
i	Shallow Water Gas Platforms	$A_{28i} = A_{28i,EPA}\frac{A_{1i}}{A_{1i}+A_{2i}}$	E_{28i}	$m_{28i} = A_{28,i}E_{28i}$
i	Deepwater Gas Platforms	$A_{29i} = A_{29i,EPA}\frac{A_{1i}}{A_{1i}+A_{2i}}$	E_{29i}	$m_{29i} = A_{29,i}E_{29i}$
i	Well Drilling	$A_{30i} = A_{1i,EPA}$	$E_{30i} = E_{30i}/t$	$m_{30i} = A_{30,i}E_{30i}$
i	Gas Well Completions without Hydraulic Fracturing	$A_{31i} = A_{1i,EPA}$	$E_{31i} = E_{31i}/t$	$m_{31i} = A_{31,i}E_{31i}$
i	Regional Subtotal, noncombustive loss (scf/yr)	$m_{\mathsf{Prod},i} = \Xi_{\mathsf{Prod},i}\sum_j m_{ji}$		
i	Regional Subtotal, combustive consumption (scf/yr)	$f_{\mathsf{Production},i} = m_{31}\frac{\xi}{1-\xi} + A_{17}\frac{1}{H_i\epsilon}$		

Table S2. Accounting of gas from well to power plant. Production, losses and transferred gas in scf/yr. The EPA GHG Inventory separates the U.S. into six regions (N=6): Northeast, Midcontinent, Rocky Mountain, Southwest, West Coast and Gulf Coast. It does not account for processing and transmission plants by region, as it does for the Production facilities. Therefore, we lump all production facilities to track methane – the primary constituent of natural gas, through the supply chain, and obtain an estimate of the total amount of methane delivered from the gas transmission system, $S_{trans} = \sum_{i=1}^{N} s_i - (f_{\mathrm{Proc}} + m_{\mathrm{Proc}} + f_{\mathrm{Trans}} + m_{\mathrm{Trans}})$. Noncombustive methane losses were summed to obtain the total methane emission, and multiplied by the GWP of methane. Similar accounting was employed for noncombustive CO_2 emissions due to the presence of CO_2 in natural gas. Combustive upstream GHG emissions were calculated from the amounts of gas consumed as fuel (*f*), and summed to get the total combustive GHG emissions for processing and transmission. The combustive and non-combustive GHG emissions were then summed to obtain the total upstream emission (kg CO_2eq). The upstream carbon footprint was then calculated by dividing the total upstream GHG emission by S_{trans} (kg CO_2eq/scf delivered to power plant).

Region	1	2	···	N
Methane Production Rate	Q_1	Q_2	···	Q_N
Combustive Losses, Production	$f_{\mathsf{Prod},1}$	$f_{\mathsf{Prod},2}$	···	$f_{\mathsf{Prod},N}$
Noncombustive Losses, Production	$m_{\mathsf{Prod},1}$	$m_{\mathsf{Prod},2}$	···	$m_{\mathsf{Prod},N}$
Methane to Processing	$s_1 = Q_1 - f_{\mathsf{Prod},1} - m_{\mathsf{Prod},1}$	$s_2 = Q_2 - f_{\mathsf{Prod},2} - m_{\mathsf{Prod},2}$	···	$s_N = Q_N - f_{\mathsf{Prod},N} - m_{\mathsf{Prod},N}$
Total Methane to Processing	$\sum_{i=1}^{N} s_i$			
Combustive Losses, Processing	f_{Proc}			
Noncombustive Losses, Processing	m_{Proc}			
Total Methane to Transmission	$\sum_{i=1}^{N} s_i - (f_{\mathsf{Proc}} + m_{\mathsf{Proc}})$			
Combustive Losses, Transmission	f_{Trans}			
Noncombustive Losses, Transmission	m_{Trans}			

Life Cycle Emissions

The upstream GHG emissions in kg CO_2/scf and kg CH_4/scf, thus defined, can be combined with the information on plant-specific fuel use and electricity generation reported in the EIA-923 Data File to yield the life cycle GHG emissions for all systems terminating at unique power plants. EIA reports both the gas input to each power plant as well as the net power output. Using this information, the life cycle GHG emissions (kg CO_2eq/kWh) were calculated for each system π using the following formula

$$y_\pi = 3412\left(C_{\text{upstream},\pi}\frac{1}{H_\pi \epsilon_\pi} + \frac{44\kappa_\pi^*}{12\epsilon_\pi} + E_{CH_4} \cdot \frac{G}{\epsilon_\pi}\right) \tag{S1}$$

here ε_π is the power plant efficiency (HHV basis), *H* is the heating value of the fuel content of the gas burned (Btu/scf NG, HHV basis), E_{CH4} is the emission factor for CH_4 emission during combustion (kg CH_4/Btu, HHV, G is the GWP of methane, the κ_π∗ is the carbon content (kg C/Btu, HHV basis) corrected for the unburned fraction:

$$\kappa_\pi^* = \kappa_\pi - \frac{12}{16}E_{CH_4} \tag{S2}$$

Where κ_π is the carbon content (kg C/Btu, HHV basis), E_{CH4} is the emission factor for CH_4 emission during combustion (kg CH_4/Btu, HHV).

The weighted average life cycle GHG emissions for the gas-fired power plants in the US (simple cycle and combined cycle) were calculated from the individual power plant life cycle GHG emissions as follows:

$$Y = \frac{\sum_{\pi} y_{\pi} P_{\pi}}{\sum_{\pi} P_{\pi}} \quad \text{(S3)}$$

Where y_{π} are the individual life cycle emissions, and p_{π} the net production of the individual power plants.

Figure S1. National Energy Modeling System (NEMS) oil and gas supply module regions from the EIA (EIA, 2013). Production activity and emission factors are provided by EPA at this level as stated in EPA, 2013.

S3 Uncertainty distributions

Uncertainty in the model parameters was taken into account by means of Monte Carlo simulation. To that purpose, probability distributions were defined as described below.

EPA does not report how it adjusts emission estimates, thus, uncertainty in the correction factor Ξ_v (see Table S1) is unknown, and possibly unknowable – in contrast to physical measures. Hence, we do not estimate uncertainty for this parameter.

Uniform distribution for well lifetime estimation

Well life times were distributed uniformly between 25 and 40 years, following the approach of Laurenzi and Jersey (2013).

Lognormal distributions from the EPA/GRI studies

The EPA/GRI study reports 90% confidence limits for activity factors and emission factors as "±100δ%". EPA reports some activity factors and emission factors as having values of δ that exceed unity, i.e. their distributions are extremely asymmetric. To account for this, and the impossibility of negative activities or emissions, we modeled all activity factors and emission factors as lognormal distributions with averages ($\bar{x}$) specified by the reported activity factors and emission factors and standard errors of the mean (se). Standard errors were approximated from the reported mean and 95th percentile by the following formula (EPA/GRI, 1996c):

$$se = \bar{x}\frac{\delta\%}{100\%}Z^{-1} \quad \text{(S4)}$$

Where the Z-value is 1.645.

Data in the table below includes data from the EPA's 2013 GHG Inventory, which characterizes emissions in the 2011 calendar year.

Table S3. Characteristics of the lognormal distributions for activity factors and emission factors from the EPA/GRI studies.

PRODUCTION ACTIVITY DATA	Unit	mean	95p	se
North East				
NE - Non-associated Gas Wells (less wells with hydraulic fracturing)	number of wells	1.1E+05	1.2E+05	3.5E+03
Field Separation Equipment				
Heaters	number of heaters	2.3E+02	6.8E+02	2.7E+02
Separators	number of separators	8.2E+04	1.0E+05	1.1E+04
Dehydrators	number of dehydrators	1.6E+04	1.9E+04	1.9E+03
Meters/Piping	number of meters	5.7E+03	1.1E+04	3.5E+03
Gathering Compressors				
Small Reciprocating Compressors	number of compressors	1.2E+02	1.5E+02	2.3E+01
Large Reciprocating Compressors	number of compressors	1.8E+01	3.6E+01	1.1E+01
Large Reciprocating Stations	number of stations	2.3E+00	4.5E+00	1.4E+00
Pipeline Leaks	miles	5.7E+04	6.3E+04	3.5E+03
Normal Operations				
Pneumatic Device Vents	number of controllers	5.6E+04	8.3E+04	1.6E+04
Chemical Injection Pumps	number of active pumps	5.8E+02	1.4E+03	5.0E+02
Kimray Pumps	MMscf/yr	4.7E+06	7.6E+06	1.8E+06
Dehydrator Vents	MMscf/yr	5.3E+06	8.5E+06	2.0E+06
Condensate Tank Vents				
Condensate Tanks without Control Devices	MMbbl/yr	3.8E-01	4.3E-01	3.4E-02
Condensate Tanks with Control Devices	MMbbl/yr	3.8E-01	4.3E-01	3.4E-02
Well Workovers				
Workovers without hydraulic fracturing	Workovers / yr	5.0E+03	1.8E+04	7.8E+03
Liquids Unloading				
Liquids Unloading (with plunger lifts)	Number of wells	6.6E+03	5.3E+03	1.5E+02
Liquids Unloading (without plunger lifts)	Number of wells	1.7E+04	1.4E+04	3.9E+02
Blowdowns				
Vessel Blowdown	number of vessels	9.8E+04	1.2E+05	1.5E+04
Pipeline Blowdown	miles (gathering)	5.7E+04	6.3E+04	3.5E+03

Compressor Blowdown	number of compressors	1.2E+02	1.8E+02	3.6E+01
Compressor Starts	number of compressors	1.2E+02	1.8E+02	3.6E+01
Upsets				
Pressure Relief Valves	number of pressure relief valves	2.7E+05	4.2E+05	8.8E+04
Mishaps	Miles	1.4E+04	1.6E+04	8.6E+02
Midcontinent				
MC - Non-associated Gas Wells (less wells with hydraulic fracturing)	number of wells	6.9E+04	7.2E+04	2.1E+03
Field Separation Equipment				
Heaters	number of heaters	2.8E+04	8.2E+04	3.3E+04
Separators	number of separators	3.0E+04	3.7E+04	4.2E+03
Dehydrators	number of dehydrators	9.6E+03	1.1E+04	1.2E+03
Meters/Piping	number of meters	9.0E+04	1.8E+05	5.5E+04
Gathering Compressors				
Small Reciprocating Compressors	number of compressors	7.8E+03	1.2E+04	2.5E+03
Large Reciprocating Compressors	number of compressors	1.2E+01	2.4E+01	7.4E+00
Large Reciprocating Stations	number of stations	1.5E+00	3.0E+00	9.2E-01
Pipeline Leaks	miles	5.3E+04	5.9E+04	3.2E+03
Normal Operations				
Pneumatic Device Vents	number of controllers	1.1E+05	1.6E+05	3.1E+04
Chemical Injection Pumps	number of active pumps	9.7E+03	2.4E+04	8.5E+03
Kimray Pumps	MMscf/yr	2.8E+06	4.5E+06	1.1E+06
Dehydrator Vents	MMscf/yr	3.1E+06	5.1E+06	1.2E+06
Condensate Tank Vents				
Condensate Tanks without Control Devices	MMbbl/yr	1.2E+01	1.4E+01	1.1E+00
Condensate Tanks with Control Devices	MMbbl/yr	1.2E+01	1.4E+01	1.1E+00
Compressor Exhaust Vented				
Gas Engines	MMHPhr/yr	1.3E+04	3.9E+04	1.6E+04
Well Workovers				
Workovers without Hydraulic	Workovers / yr	3.0E+03	1.1E+04	4.7E+03

Fracturing				
Liquids Unloading				
Liquids Unloading (with plunger lifts)	Number of wells	2.1E+03	1.7E+03	4.9E+01
Liquids Unloading (without plunger lifts)	Number of wells	3.7E+03	3.0E+03	8.6E+01
Blowdowns				
Vessel Blowdown	number of vessels	6.7E+04	8.5E+04	1.1E+04
Pipeline Blowdown	miles (gathering)	5.3E+04	5.9E+04	3.2E+03
Compressor Blowdown	number of compressors	7.8E+03	1.2E+04	2.5E+03
Compressor Starts	number of compressors	7.8E+03	1.2E+04	2.5E+03
Upsets				
Pressure Relief Valves	number of pressure relief valves	1.6E+05	2.5E+05	5.2E+04
Mishaps	Miles	1.3E+04	1.5E+04	8.1E+02
Rocky Mountain				
RM - Non-associated Gas Wells (less wells with hydraulic fracturing)	number of wells	2.3E+04	2.4E+04	7.0E+02
Field Separation Equipment				
Heaters	number of heaters	1.0E+04	2.0E+04	6.1E+03
Separators	number of separators	1.1E+04	1.8E+04	4.0E+03
Dehydrators	number of dehydrators	3.2E+03	3.8E+03	3.9E+02
Meters/Piping	meters	2.7E+04	5.4E+04	1.6E+04
Gathering Compressors				
Small Reciprocating Compressors	number of compressors	2.6E+03	3.9E+03	8.1E+02
Large Reciprocating Compressors	number of compressors	8.8E+00	1.8E+01	5.3E+00
Large Reciprocating Stations	number of stations	1.1E+00	2.2E+00	6.7E-01
Pipeline Leaks	Miles	3.0E+04	3.3E+04	1.8E+03
Normal Operations				
Pneumatic Device Vents	number of controllers	3.4E+04	5.0E+04	9.8E+03
Chemical Injection Pumps	number of active pumps	4.1E+03	9.9E+03	3.6E+03
Kimray Pumps	MMscf/yr	9.4E+05	1.5E+06	3.5E+05
Dehydrator Vents	MMscf/yr	1.1E+06	1.7E+06	4.0E+05

Condensate Tank Vents				
Condensate Tanks without Control Devices	MMbbl/yr	3.4E+00	3.9E+00	3.1E-01
Condensate Tanks with Control Devices	MMbbl/yr	3.4E+00	3.9E+00	3.1E-01
Compressor Exhaust Vented				
Gas Engines	MMHPhr/yr	4.4E+03	1.3E+04	5.4E+03
Well Workovers				
Workovers without Hydraulic Fracturing	Workovers / yr	1.0E+03	3.6E+03	1.6E+03
Liquids Unloading				
Liquids Unloading (with plunger lifts)	Number of wells	1.1E+04	1.1E+04	3.3E+02
Liquids Unloading (without plunger lifts)	Number of wells	1.3E+03	1.3E+03	3.9E+01
Blowdowns				
Vessel Blowdown	number of vessels	2.5E+04	3.2E+04	4.0E+03
Pipeline Blowdown	miles (gathering)	3.0E+04	3.3E+04	1.8E+03
Compressor Blowdown	number of compressors	2.6E+03	3.9E+03	8.1E+02
Compressor Starts	number of compressors	2.6E+03	3.9E+03	8.1E+02
Upsets				
Pressure Relief Valves	number of pressure relief valves	5.4E+04	8.3E+04	1.8E+04
Mishaps	Miles	7.4E+03	8.2E+03	4.5E+02
South West				
SW - Non-associated Gas Wells (less wells with hydraulic fracturing)	number of wells	2.2E+04	2.3E+04	6.6E+02
Field Separation Equipment				
Heaters	number of heaters	5.9E+03	1.2E+04	3.4E+03
Separators	number of separators	1.2E+04	1.9E+04	4.2E+03
Dehydrators	number of dehydrators	3.0E+03	3.7E+03	3.7E+02
Meters/Piping	number of meters	2.6E+04	5.2E+04	1.6E+04
Gathering Compressors				
Small Reciprocating Compressors	number of compressors	3.0E+03	4.5E+03	9.4E+02
Large Reciprocating Compressors	number of compressors	8.4E+00	1.7E+01	5.1E+00
Large Reciprocating Stations	number of stations	1.1E+00	2.1E+00	6.4E-01

Pipeline Leaks	Miles	3.2E+04	3.5E+04	1.9E+03
Normal Operations				
Pneumatic Device Vents	number of controllers	2.9E+04	4.3E+04	8.5E+03
Chemical Injection Pumps	number of active pumps	1.3E+03	3.2E+03	1.2E+03
Kimray Pumps	MMscf/yr	8.9E+05	1.4E+06	3.4E+05
Dehydrator Vents	MMscf/yr	1.0E+06	1.6E+06	3.8E+05
Condensate Tank Vents				
Condensate Tanks without Control Devices	MMbbl/yr	1.3E+01	1.5E+01	1.2E+00
Condensate Tanks with Control Devices	MMbbl/yr	1.3E+01	1.5E+01	1.2E+00
Compressor Exhaust Vented				
Gas Engines		4.2E+03	1.3E+04	5.1E+03
Well Workovers	MMHPhr/yr			
Workovers without Hydraulic Fracturing	Workovers / yr	9.5E+02	3.4E+03	1.5E+03
Liquids Unloading				
Liquids Unloading (with plunger lifts)	Number of wells	1.4E+03	1.4E+03	4.2E+01
Liquids Unloading (without plunger lifts)	Number of wells	8.1E+03	8.5E+03	2.5E+02
Blowdowns				
Vessel Blowdown	number of vessels	2.1E+04	2.7E+04	3.4E+03
Pipeline Blowdown	miles (gathering)	3.2E+04	3.5E+04	1.9E+03
Compressor Blowdown	number of compressors	3.0E+03	4.5E+03	9.4E+02
Compressor Starts	number of compressors	3.0E+03	4.5E+03	9.4E+02
Upsets				
Pressure Relief Valves	number of pressure relief valves	5.2E+04	7.9E+04	1.7E+04
Mishaps	Miles	8.0E+03	8.8E+03	4.9E+02
West Coast				
WC - Non-associated Gas Wells (less wells with hydraulic fracturing)	number of wells	2.1E+03	2.2E+03	6.4E+01
Field Separation Equipment				
Heaters	number of heaters	2.1E+03	4.1E+03	1.2E+03
Separators	number of separators	1.5E+03	2.4E+03	5.4E+02
Dehydrators	number of	3.0E+02	3.5E+02	3.6E+01

	dehydrators			
Meters/Piping	Number of meters	4.0E+03	8.0E+03	2.4E+03
Gathering Compressors				
Small Reciprocating Compressors	number of compressors	2.5E+03	3.7E+03	7.8E+02
Large Reciprocating Compressors	number of compressors	8.0E+00	1.6E+01	4.9E+00
Large Reciprocating Stations	number of stations	1.0E+00	2.0E+00	6.1E-01
Pipeline Leaks	Miles	1.7E+04	1.8E+04	1.0E+03
Normal Operations				
Pneumatic Device Vents	number of controllers	2.1E+03	3.1E+03	6.2E+02
Chemical Injection Pumps	number of active pumps	1.4E+03	3.5E+03	1.2E+03
Kimray Pumps	MMscf/yr	8.6E+04	1.4E+05	3.3E+04
Dehydrator Vents	MMscf/yr	9.7E+04	1.6E+05	3.6E+04
Compressor Exhaust Vented				
Gas Engines	MMHPhr/yr	4.1E+02	1.2E+03	4.9E+02
Well Workovers				
Workovers without Hydraulic Fracturing	Workovers / yr	9.2E+01	3.3E+02	1.4E+02
Liquids Unloading				
Liquids Unloading (with plunger lifts)	Number of wells	1.6E+02	1.7E+02	4.9E+00
Liquids Unloading (without plunger lifts)	Number of wells	1.4E+02	1.5E+02	4.4E+00
Blowdowns		0.0E+00		0.0E+00
Vessel Blowdown	number of vessels	4.0E+03	5.0E+03	6.3E+02
Pipeline Blowdown	miles (gathering)			
Compressor Blowdown	number of compressors	2.5E+03	3.7E+03	7.8E+02
Compressor Starts	number of compressors	2.5E+03	3.7E+03	7.8E+02
Upsets		0.0E+00		0.0E+00
Pressure Relief Valves	number of pressure relief valves	5.0E+03	7.7E+03	1.6E+03
Mishaps	Miles	4.2E+03	4.6E+03	2.5E+02
Gulf Coast				
GC - Non-associated Gas Wells (less wells with hydraulic fracturing)	number of wells	3.8E+04	3.9E+04	1.1E+03
Field Separation Equipment				

Heaters	number of heaters	8.4E+03	1.6E+04	4.9E+03
Separators	number of separators	2.5E+04	3.9E+04	8.6E+03
Dehydrators	number of dehydrators	5.2E+03	6.3E+03	6.4E+02
Meters/Piping	number of meters	4.3E+04	8.7E+04	2.6E+04
Gathering Compressors				
Small Reciprocating Compressors	number of compressors	3.0E+03	4.6E+03	9.6E+02
Large Reciprocating Compressors	number of compressors	1.6E+01	3.2E+01	9.6E+00
Large Reciprocating Stations	number of stations	2.0E+00	3.9E+00	1.2E+00
Pipeline Leaks	Miles	4.9E+04	5.4E+04	3.0E+03
Normal Operations				
Pneumatic Device Vents	number of controllers	2.6E+04	3.9E+04	7.6E+03
Chemical Injection Pumps	number of active pumps	1.2E+03	3.0E+03	1.1E+03
Kimray Pumps	MMscf/yr	1.5E+06	2.5E+06	5.8E+05
Dehydrator Vents	MMscf/yr	1.7E+06	2.8E+06	6.5E+05
Condensate Tank Vents				
Condensate Tanks without Control Devices	MMbbl/yr	1.6E+01	1.8E+01	1.4E+00
Condensate Tanks with Control Devices	MMbbl/yr	1.6E+01	1.8E+01	1.4E+00
Compressor Exhaust Vented				
Gas Engines	MMHPhr/yr	7.2E+03	2.2E+04	8.8E+03
Well Workovers				
Workovers without Hydraulic Fracturing	Workovers / yr	1.6E+03	5.9E+03	2.6E+03
Liquids Unloading				
Liquids Unloading (with plunger lifts)	Number of wells	1.8E+03	1.9E+03	5.4E+01
Liquids Unloading (without plunger lifts)	Number of wells	5.4E+03	5.7E+03	1.6E+02
Blowdowns				
Vessel Blowdown	number of vessels	3.8E+04	4.8E+04	6.1E+03
Pipeline Blowdown	miles (gathering)	4.9E+04	5.4E+04	3.0E+03
Compressor Blowdown	number of compressors	3.0E+03	4.6E+03	9.6E+02
Compressor Starts	number of compressors	3.0E+03	4.6E+03	9.6E+02
Upsets				

Pressure Relief Valves	number of pressure relief valves	8.9E+04	1.4E+05	2.9E+04
Mishaps	Miles	1.2E+04	1.4E+04	7.5E+02
Offshore Platforms				
Shallow water Gas Platforms (GoM and Pacific)	Number of platforms	2.0E+03	2.2E+03	1.2E+02
Deepwater Gas Platforms (GoM and Pacific)	Number of platforms	4.1E+01	4.5E+01	2.5E+00
PRODUCTION EMISSION FACTORS				
Gas Wells				
Non-associated conventional Gas Wells NE, MC	scf/d/well	7.1E+00	9.0E+00	1.2E+00
Non-associated conventional Gas Wells RM, SW, WC, GC	scf/d/well	3.6E+01	4.5E+01	5.3E+00
Field Separation Equipment				
Heaters NE, MC	scf/d/equipment	1.4E+01	2.0E+01	3.7E+00
Heaters RM, SW, WC, GC	scf/d/equipment	5.8E+01	8.1E+01	1.4E+01
Separators NE, MC	scf/d/equipment	9.0E-01	1.1E+00	1.5E-01
Separators RM, SW, WC, GC	scf/d/equipment	1.2E+02	1.6E+02	2.4E+01
Dehydrators NE	scf/d/equipment	2.2E+01	2.9E+01	4.6E+00
Dehydrators MC, RM, SW, WC, GC	scf/d/equipment	9.1E+01	1.1E+02	1.4E+01
Meters/Piping NE, MC	scf/d/equipment	9.0E+00	1.2E+01	1.6E+00
Meters/Piping RM, SW, Wc, GC	scf/d/equipment	5.3E+01	6.9E+01	9.6E+00
Gathering Compressors				
Small Reciprocating Compressors	scf/d/equipment	2.7E+02	4.5E+02	1.1E+02
Large Reciprocating Compressors	m3/equipment/d	1.5E+04	2.5E+04	1.1E+02
Large Reciprocating Stations	m3/equipment/d	8.2E+03	1.4E+04	3.3E+03
Pipeline Leaks	scf/d/mile	5.3E+01	1.1E+02	3.5E+01
Drilling and Well Completion				
Completion Flaring	scf/completion	7.3E+02	2.2E+03	8.9E+02
Well Drilling NE[a]	scf/well	2.7E+03	2.7E+03	2.7E+03
Well Drilling MC[a]	scf/well	2.7E+03	2.7E+03	2.7E+03
Well Drilling RM[a]	scf/well	2.5E+03	2.5E+03	2.5E+03
Well Drilling SW[a]	scf/well	2.6E+03	2.6E+03	2.6E+03
Well Drilling WC[a]	scf/well	3.0E+03	3.0E+03	3.0E+03
Well Drilling GC[a]	scf/well	2.9E+03	2.9E+03	2.9E+03
Normal Operations				
Pneumatic Device Vents	scf/d/device	3.5E+02	4.8E+02	8.4E+01
Chemical Injection Pumps	scf/d/pump	2.5E+02	4.5E+02	1.3E+02

Kimray Pumps	scf CH_4/MMscf	9.9E+02	1.8E+03	4.7E+02
Dehydrator Vents	scf/MMscf	2.8E+02	7.0E+02	2.6E+02
Condensate Tank Vents				
Condensate Tanks without Control Devices NE, RM, WC, GC[b]	scf/bbl	2.2E+01	4.4E+01	9.0E+00
Condensate Tanks without Control Devices MC, SW[b]	scf/bbl	3.0E+02	6.1E+02	1.2E+02
Compressor Exhaust Vented				
Gas Engines	scf/HPhr	2.4E-01	2.5E-01	7.3E-03
Well Workovers				
Workovers without hydraulic fracturing	scf/workover	2.5E+03	1.4E+04	6.8E+03
Liquids Unloading				
Liquids Unloading (with plunger lifts) NE	scf/bbl	2.5E+05	1.4E+06	5.6E+05
Liquids Unloading (without plunger lifts) NE	scf/bbl	1.7E+04	9.6E+04	3.8E+04
Liquids Unloading (with plunger lifts) MC	scf/bbl	1.2E+06	6.6E+06	1.3E+01
Liquids Unloading (without plunger lifts) MC	scf/bbl	2.0E+05	1.1E+06	4.3E+05
Liquids Unloading (with plunger lifts) RM	scf/bbl	1.2E+05	6.7E+05	2.6E+05
Liquids Unloading (without plunger lifts) RM	scf/bbl	2.0E+06	1.1E+07	4.4E+06
Liquids Unloading (with plunger lifts) SW	scf/bbl	2.9E+03	1.6E+04	6.3E+03
Liquids Unloading (without plunger lifts) SW	scf/bbl	7.8E+04	4.4E+05	1.7E+05
Liquids Unloading (with plunger lifts) WC	scf/bbl	3.2E+05	1.8E+06	7.0E+05
Liquids Unloading (without plunger lifts) WC	scf/bbl	2.8E+05	1.6E+06	6.1E+05
Liquids Unloading (with plunger lifts) GC	scf/bbl	6.2E+04	3.5E+05	1.0E+01
Liquids Unloading (without plunger lifts) GC	scf/bbl	2.7E+05	1.5E+06	5.9E+05
Blowdowns				
Vessel BD	scf/yr/vessel	7.8E+01	2.9E+02	1.3E+02
Pipeline BD	scf/yr/mile	3.1E+02	4.1E+02	6.0E+01
Compressor BD	scf/yr/compressor	3.8E+03	9.3E+03	3.4E+03

Compressor Starts	scf/yr/compressor	8.4E+03	2.2E+04	8.1E+03
Upsets				
Pressure Relief Valves	scf/PRV	3.4E+01	1.2E+02	5.2E+01
Mishaps	scf/mile	6.7E+02	1.4E+04	7.9E+03
Offshore Platforms				
Gulf of Mexico Platform	scf/d/platform	2.9E+03	3.7E+03	4.8E+02
Pacific Platform	scf/d/platform	1.2E+03	1.6E+03	2.6E+02
PROCESSING ACTIVITY DATA				
gas plants	number of plants	5.9E+02	6.0E+02	7.1E+00
reciprocal compressors	number of comp	5.4E+03	7.9E+03	1.6E+03
centrifugal compressors (wet seals)[c]	number of comp	6.5E+02	1.2E+03	3.1E+02
centrifugal compressors (dry seals)[c]	number of comp	2.1E+02	3.7E+02	9.9E+01
Compressor exhaust				
gas engine	MMHPhr/yr	3.9E+04	9.0E+04	3.1E+04
gas turbine	MMHPhr/yr	4.6E+04	1.0E+05	3.4E+04
AGR vents	AGR units	3.0E+02	3.6E+02	3.6E+01
Kimray Pumps	MMscf/yr	1.4E+06	4.1E+06	1.6E+06
Dehydrator Vents	MMscf/yr	1.3E+07	1.5E+07	1.7E+06
PROCESSING EMISSION FACTORS				
gas plants	scf/d/plant	7.9E+03	1.2E+04	2.3E+03
reciprocal compressors	scf/d/compressor	1.1E+04	1.9E+04	5.0E+03
centrifugal compressors (wet seals)	scf/d/compressor	5.1E+04	7.1E+04	1.2E+04
centrifugal compressors (dry seals)	scf/d/compressor	2.5E+04	3.5E+04	6.0E+03
Compressor exhaust				
gas engine	scf CH_4 /HPhr	2.4E-01	2.5E-01	7.3E-03
gas turbine[d]	scf CH_4 /HPhr	5.7E-03	7.4E-03	1.0E-03
AGR vents	scf/d/AGR	6.1E+03	1.2E+04	3.9E+03
Kimray Pumps	scf/MMscf	1.8E+02	2.8E+02	6.2E+01
Dehydrator Vents	scf/MMscf	1.2E+02	3.7E+02	1.5E+02
Pneumatic devices	scf/yr/plant	1.6E+05	3.8E+05	1.3E+05
Blowdowns/Venting	Mscf/yr/plant	4.1E+03	1.5E+04	6.5E+03
TRANSMISSION ACTIVITY DATA				
transmission pipeline	Miles	3.0E+05	3.2E+05	9.3E+03
Compressor Station Transmission				
station	number of stations	1.8E+03	2.0E+03	1.1E+02
reciprocal compressor	number of comp	7.3E+03	8.5E+03	7.5E+02
centrifugal compressor (wet seals)	number of comp	6.6E+02	8.4E+02	1.0E+02

centrifugal compressor (dry seals)	number of comp	6.6E+01	8.3E+01	1.0E+01
Compressor Station Storage				
station	number of stations	3.9E+02	4.1E+02	1.2E+01
reciprocal compressor	number of comp	1.1E+03	1.8E+03	4.0E+02
centrifugal compressor (wet seals)	number of comp	8.3E+01	1.8E+02	6.0E+01
centrifugal compressor (dry seals)	number of comp	2.9E+01	6.4E+01	2.1E+01
wells (storage)	number of wells	1.8E+04	1.9E+04	5.5E+02
M&R (Trans Co Interconnect)	number of stations	2.7E+03	2.4E+04	1.3E+04
M&R (Farm Taps + Direct Sales)	number of stations	8.0E+04	7.1E+05	3.8E+05
dehydrator vents (transmission)	MMscf/year	1.2E+06	2.8E+06	1.0E+06
dehydrator vents (storage)	MMscf/year	2.0E+06	2.5E+06	3.1E+05
Compressor exhaust				
transmission (engines)	MMHPhr/yr	4.9E+04	5.7E+04	5.0E+03
transmission (turbines)	MMHPhr/yr	1.2E+04	1.5E+04	2.3E+03
storage (engines)	MMHPhr/yr	5.0E+03	6.3E+03	8.1E+02
storage (turbines)	MMHPhr/yr	1.7E+03	1.3E+04	6.6E+03
generators (engines	MMHPhr/yr	2.4E+03	1.7E+04	9.0E+03
generators (turbines	MMHPhr/yr	2.8E+01	4.0E+02	2.2E+02
Pneumatic devices				
Pneumatic devices (transmission)	number of devices	7.1E+04	9.8E+04	1.6E+04
Pneumatic devices (storage)	number of devices	1.5E+04	2.1E+04	3.5E+03
Routine Maintenance and Upsets				
pipeline venting	Miles	3.0E+05	3.2E+05	9.3E+03
Station venting				
station venting transmission	number of compressor stations	1.8E+03	2.0E+03	1.1E+02
station venting storage	number of compressor stations	3.9E+02	4.1E+02	1.2E+01
TRANSMISSION EMISSION FACTORS				
transmission pipeline	scf/d/mile	1.6E+00	2.9E+00	8.4E-01
Compressor Station Transmission				
station	scf/d/station	8.8E+03	1.8E+04	5.4E+03
reciprocal compressor	scf/d/compressor	1.5E+04	2.8E+04	7.9E+03
centrifugal compressor (wet seals)	scf/d/compressor	5.0E+04	6.7E+04	1.0E+04
centrifugal compressor (dry seals)	scf/d/compressor	3.2E+04	4.3E+04	6.7E+03
Compressor Station Storage				
station	scf/d/station	2.2E+04	4.3E+04	1.3E+04
reciprocal compressor	scf/d/compressor	2.1E+04	2.8E+04	4.4E+03
centrifugal compressor (wet seals)	scf/d/compressor	4.5E+04	6.7E+04	1.3E+04

centrifugal compressor (dry seals)	scf/d/compressor	3.2E+04	4.7E+04	9.3E+03
wells (storage)	scf/d/compressor	1.2E+02	2.0E+02	5.5E+01
M&R (Trans Co Interconnect)	scf/d/station	4.0E+03	7.2E+03	1.9E+03
M&R (Farm Taps + Direct Sales)	scf/d/station	3.1E+01	5.6E+01	1.5E+01
dehydrator vents (transmission)	scf/MMscf	9.4E+01	2.9E+02	1.2E+02
dehydrator vents (storage)	scf/MMscf	1.2E+02	3.3E+02	1.3E+02
Compressor exhaust				
transmission (engines)	scf/HPhr	2.4E-01	2.5E-01	7.3E-03
transmission (turbines) [d]	scf/HPhr	5.7E-03	7.4E-03	1.0E-03
storage (engines)	scf/HPhr	2.4E-01	2.5E-01	7.3E-03
storage (turbines) [d]	scf/HPhr	5.7E-03	7.4E-03	1.0E-03
generators (engines	scf/HPhr	2.4E-01	2.5E-01	7.3E-03
generators (turbines	scf/HPhr	5.7E-03	7.4E-03	1.0E-03
Pneumatic devices				
Pneumatic devices (transmission)	scf/yr/device	1.6E+05	2.3E+05	4.3E+04
Pneumatic devices (storage)	scf/yr/device	1.6E+05	2.3E+05	4.3E+04
Routine Maintenance and Upsets				
pipeline venting	Mscf/yr/mile	3.2E+01	1.1E+02	4.6E+01
Station venting				
station venting transmission	Mscf/yr/station	4.4E+03	1.7E+04	7.5E+03
station venting storage	Mscf/yr/station	4.4E+03	1.7E+04	7.5E+03

a: Uncertainty assumed based on other well completion values, EPA does not report a CI for these EFs.
b: EPA does not report a CI for these EFs. We use a CI of ±101% with respect to the mean based on (API, 2009).
c: No distinction in uncertainty between dry and wet seals in EPA/GRI (1996b).
d: Turbine emission factors are reported in the GHG Inventory Tables as 0.01, whereas the actual EF from the GRI study is 0.0057.

Beta-pert distribution

For parameters that were defined by a most likely value, minimum and maximum, beta-pert distributions were used. CH_4 emission factors from the IPCC (IPCC, 2006) for combustion in power plants were described by these characteristics and modelled as beta-pert distributions. We modeled the combustion efficiency for all upstream life cycle phases and regions by treating it as a “Beta Pert” random variable ranging from 98% to 100%, with a median defined by the EPA assumption of 99.5% (API, 2009).

Table S4. Characteristics of uncertainty distributions modeled as beta-pert distributions

Parameter	unit	most likely	minimum	maximum	Source
heat content pipeline natural gas	Btu/scf	1,031	970	1,100	(EPA, 2013)
carbon content of pipeline natural gas	Tg Carbon/Qbtu	14.46	14.42	14.48	(EPA, 2013)
combustion efficiency flaring	-	0.995	0.980	1.000	(API, 2009; EPA, 2013)
Pipeline CO_2 content	mol% (vol%)	2.0	1.0	3.0	(API, 2009)
CH_4 emission factor combustion at power plant	kg TJ LHV	1.0	0.3	3.0	(IPCC, 2006)

Lognormal distribution for volume fractions in natural gas and absolute global warming potentials

IPCC (IPCC, 2007) reports 90% confidence limits for AGWPs as "±δ%". For CH_4 and CO_2 fraction, uncertainty ranges were reported as percentages of the mean (EPA, 2013). We modelled these as lognormal distributions with non-transformed averages ($\bar{x}$) specified by the reported means and by non-transformed standard deviations (sd) derived from the reported uncertainty ranges. To derive the standard deviations of the non-transformed values, the log-based standard deviations (σ, equation S5) and log-based means (μ, Equation S6) were derived (Burmaster and Hull, 1997; Strom and Stansbury, 2000):

$$\sigma = Z - \sqrt{Z^2 + 2\ln\frac{\bar{x}}{95p}} \qquad (S5)$$

where $Z = 1.645$ is the critical standard normal variable for a 90% confidence interval and $Z = 1.96$ for a 95% confidence interval

$$\mu = \bar{x}e^{\sigma^2/2} \qquad (S6)$$

From these, the non-transformed standard deviations for were calculated (Burmaster and Hull, 1997):

$$sd = e^{\mu}\sqrt{e^{\sigma^2}\left(e^{\sigma^2} - 1\right)} \qquad (S7)$$

Table S5 Characteristics (mean, 95th percentile (95p) and standard deviation (sd)) of uncertainty distributions for Absolute Global Warming Potentials (AGWPs) from IPCC, 2007

	Unit	Average	95 p	sd
AGWP CH_4 100	W m^-2yr (kg CO_2)^-1	2.2E-12	2.9E-12	4.3E-13
AGWP CO_2 100	W m^-2yr (kg CO_2)^-1	8.7E-14	1.0E-13	7.6E-15
AGWP CH_4 20	W m^-2yr (kg CO_2)^-1	1.8E-12	2.4E-12	3.5E-13
AGWP CO_2 20	W m^-2yr (kg CO_2)^-1	2.5E-14	2.8E-14	2.2E-15

AGWP CH_4 500	W m^-2yr (kg CO_2)^-1	2.2E-12	2.9E-12	4.3E-13
AGWP CO_2 500	W m^-2yr (kg CO_2)^-1	2.9E-13	3.3E-13	2.5E-14

Table S6 Characteristics (mean, 97.5th percentile (97.5p) and standard deviation (sd)) of uncertainty distributions for heat content, carbon content and volume fractions of CH_4 and CO_2 in natural gas in different life cycle stages from (API, 2009; EPA, 2013).

	Unit	Average	97.5p	sd
heat content produced natural gas	Btu/scf	1240.2	1302.2	43.9
carbon content produced natural gas	Tg Carbon/Qbtu	15.3	16.2	0.6
CH_4 content in natural gas transmission	%	93.4	95.1	1.205
CH_4 content in natural gas processed	%	86.8	92.5	4.001
CO_2 content produced gas, NE	%	0.92	0.96	0.019
CO_2 content produced gas, MC	%	0.79	0.82	0.016
CO_2 content produced gas, RM	%	7.95	8.27	0.160
CO_2 content produced gas, SW	%	3.81	3.96	0.077
CO_2 content produced gas, WC	%	0.16	0.17	0.003
CO_2 content produced gas, GC	%	2.17	2.26	0.044

NE = north east ; MC = mid continent; RM = rocky mountains; SW = south west; WC = west coast; GC = gulf coast

Lognormal distributions derived from data fitting

Heat rates of gas turbines and gas engines during processing and transmission were taken from measured data for several types of turbines and engines. From these data, means and standard deviations were calculated to characterize a lognormal distribution.

Table S7 Characteristics of uncertainty distributions for heat rates derived from data from (Caterpillar, 2013; SolarTurbines, 2013).

Heat rates	**Unit**	**Average**	**Standard deviation**
Gas turbine heat rate	Btu/HPhr, HHV	8772	798
Gas engine production heat rate	Btu/HPhr, HHV	7410	303
Gas engine processing & transmission heat rate	Btu/HPhr, HHV	6824	39

Lognormal distributions from engineering judgement

Uncertainty in the expected ultimate recovery of wells was set as having a 5th percentile value of 0.5 Bcf/well and a 95th percentile value of 5 Bcf/well.

Lognormal distributions for infrastrucuture

Ecoinvent (Frischknecht et al., 2007) reports geometric means and squared geometric standard deviations. We employed these figures to make estimates of uncertainty in infrastructure, which were then employed in MC simulations.

S4 Contribution to variance

The contribution of uncertainties in individual parameters to the range in impacts associated with the life cycle GHG emissions of the comprehensive system (*Y*) was also assessed. This analysis consisted of a Monte Carlo simulation in combination with a Rank correlation (expressed as percentage of total variance). Crystal Ball is equipped with a routine to calculate the Spearman rank correlation coefficients between the output and each of the input parameters. These rank correlation coefficients are valued between -1 and +1. We individually squared the correlation coefficient for each input variable. These squares of the correlation coefficients were summed, and the contribution of each input variable was derived by dividing its individual coefficient by this total sum. Multiplying these individual contributions by 100 yielded percentages representing an approximation of the relative contributions of the input variables to the variance of the life cycle GHG emissions of the comprehensive system (Equation S8). The contribution to variance is a combination of the model's sensitivity to a parameter and the uncertainty range of the parameter. The resulting statistics may then be interpreted as the percentage of variance that is explained by each uncertain input parameter.

$$V_a = \frac{rc_a^2}{\sum_a rc_a^2} \cdot 100 \qquad \text{(S8)}$$

Where: V_a = contribution of variable 'a' to output (life-cycle GHG emissions of comprehensive system), rc_a^2 = Spearman rank correlation coefficient between variable 'a' and output.

Table S8. Life cycle and upstream GHG emissions for electricity from conventional natural gas, estimated in this study and recent publications.

Reference	measured range	life cycle GHG emissions	range	upstream GHG emissions	range	upstream contribution	range	efficiency	range
		kg CO_2-eq/kWh		kg CO_2-eq/MJ (HHV)		%		MJ/MJ (HHV)	
our study CC	95% CI due to uncertainty	0.49 0.58 (GWP20) 0.46 (GWP500)	0.47-0.53 0.52-0.67 (GWP20) 0.44-0.49 (GWP500)	0.012 0.023 (GWP20) 0.008 (GWP500)	0.009-0.017 0.016-0.035 (GWP500) 0.006-0.011 (GWP500)	19% 31% (GWP20) 13% (GWP500)	15%-25% 24%-41% (GWP500) 11%-18% (GWP500)		
	95% CI due to variability		0.46-0.66 0.54-0.76 (GWP20) 0.43-0.61 (GWP500)					0.34-0.49	
	95% CI due to total variance		0.45-0.66 0.51-0.79 (GWP20) 0.42-0.62 (GWP 500)						
our study SC	95% CI due to uncertainty	0.75 0.88 (GWP20) 0.70 (GWP500)	0.71-0.81 0.80-1.02 (GWP500) 0.68-0.74 (GWP500)	Equal to CC	Equal to CC	Equal to CC	Equal to CC		
	95% CI due to variability		0.66-0.89 0.78-1.05 (GWP20) 0.62-0.83 (GWP500)					0.25-0.44	
	95% CI due to total variance		0.60-0.91 0.72-1.11 (GWP20) 0.56-0.84 (GWP500)						
Ecoinvent (Faist	Min-max of NERC regions	0.68	0.56 - 0.92	0.006				0.25-0.35	

Emmenegger et al., 2007)									
Venkatesh et al. (2011)	90%CI	0.48[a]		0.015		23%		0.5 (efficient CC plant)	0.2-0.48 (all plants) 0.25-0.49 (>500MW)
NETL (NETL, 2013)		0.5		0.007				50.2%[b]	
Stephenson et al. (2011)	min-max		0.488-0.490		0.0040-0.0041	14%		0.43	
Burnham et al. (2011)	min-max (CC)	0.57						0.43	0.35-0.5[c]
Jiang et al. (2011)		0.48[d]						0.5[h]	
Alvarez et al., (2012)		0.48[e]		0.016		24%[f]		CC	
Weber & Clavin (2012)[g]	95%CI			0.014	0.011-0.176		20%-22%		
	min-max							0.33 - 0.5[c]	

a: calculated with 50% efficiency as used by (Venkatesh et al., 2011) for comparison with coal
b: from (NETL, 2010)
c: LHV, HHV conversion by assuming 10% difference
d: calculated based on Jiang et al. (2011)
e: calculated based on GWP100
f: calculated based on data in Alvarez et al. (2012)
g: based on (Jiang et al., 2011), (Draucker et al., 2010), (Stephenson et al., 2011), (Burnham et al., 2011) amongst others
h: CC based on Venkatesh et al. (2011)

Table S9 Contribution to overall variance in life cycle GHG emissions by uncertain parameters that contributed more than 1% for at least one of the three time horizons. Results are shown for national weighted average life cycle GHG emissions from CC plants.

	20 year time horizon	100 year time horizon	500 year time horizon
Absolute GWP CH_4 (W m^{-2}yr/kg)	59%	41%	12%
Activity factor, Gas turbines, processing (MMHPhr/yr)	5%	19%	45%
Activity factor, Gas engine, processing (MMHPhr/yr)	6%	14%	26%
Absolute GWP CO_2 (W m^{-2}yr /kg)	11%	8%	2%
Emission Factor, Reciprocating compressor for compressor station, transmission (scf/d/compressor)	6%	4%	1%
CO_2 content in pipeline natural gas (%)	<1%	2%	4%
Emission Factor, Reciprocating compressors, processing (scf/d/compressor)	2%	1%	<1%
Emission Factor, pipeline venting, transmission (Mscf/yr/mile)	<1%	1%	<1%
Emission Factor, station venting, transmission, (Mscf/yr/station)	1%	1%	<1%
Gas turbine heat rate, processing and transmission (Btu/HPhr HHV)	1%	1%	2%
Activity Factor, compressor engine exhaust, transmission (MMHPhr/yr)	1%	1%	1%

Table S10 Contribution to overall variance in life cycle GHG emissions by uncertain parameters that contributed more than 1% for at least one of the three time horizons. Results are shown for national weighted average life cycle GHG emissions from SC plants.

	20 year time horizon	100 year time horizon	500 year time horizon
Absolute GWP CH_4 (W m^{-2}yr/kg)	58%	40%	11%
Activity factor, Gas turbines, processing (MMHPhr/yr)	5%	20%	45%
Activity factor, Gas engine, processing (MMHPhr/yr)	6%	15%	27%
Absolute GWP CO_2 (W m^{-2}yr /kg)	11%	8%	2%
Emission Factor, Reciprocating compressor for compressor station, transmission (scf/d/compressor)	6%	4%	1%
CO_2 content in pipeline natural gas (%)	<1%	1%	4%
Emission Factor, Reciprocating compressors, processing (scf/d/comp)	2%	1%	<1%
Emission Factor, pipeline venting, transmission (Mscf/yr/mile)	1%	1%	<1%
Emission Factor, station venting transmission,	1%	1%	<1%

(Mscf/yr/station)			
Gas turbine heat rate, processing and transmission (Btu/HPhr HHV)	<1%	1%	1%
Activity Factor, compressor engine exhaust, transmission (MMHPhr/yr)	<1%	1%	1%

S5 Additional Analysis with updated GWPs

Global Warming Potentials of methane, including uncertainty estimates, have been updated by the latest Assessment Report of the IPCC for the 20 and 100 year time horizons (Myhre *et al.*, 2013) and are reported in Table S11. An additional analysis was performed replacing GWPs from Assessment Report No. 4 with these updated values, the same way as described for AGWPs in section S3. This slightly increased carbon footprints: to 0.50 kg CO_2-eq/kWh (100 year time horizon) and 0.60 kg CO_2-eq/kWh (20 year time horizon) for CC plants, and to 0.76 kg CO_2-eq/kWh (100 year time horizon) and 0.92 kg CO_2-eq/kWh (20 year time horizon) for SC plants. Uncertainty and variability factors did not change. The variation in life cycle GHG emissions of CC and SC power plants are reported in Figure S2 and Figure S3. Figure S2 gives an overview of ranges due to uncertainty and variability respectively. Figure S3 shows the variation due to uncertainty for individual power plants. Table S12 and S13 show the contribution to variance for parameters that contributed more than 1% to overall variance when using the updated GWP for methane for CC and SC plants.

Table S11. Characteristics (mean, 95th percentile (95p) and standard deviation (sd)) of uncertainty distributions for Global Warming Potentials (GWPs) (Myhre *et al.*, 2013).

	Unit	mean	95 p	sd
GWP CH_4 100	kg CO_2eq/kg CH_4	30	42	7
GWP CH_4 20	kg CO_2eq/kg CH_4	85	111	14

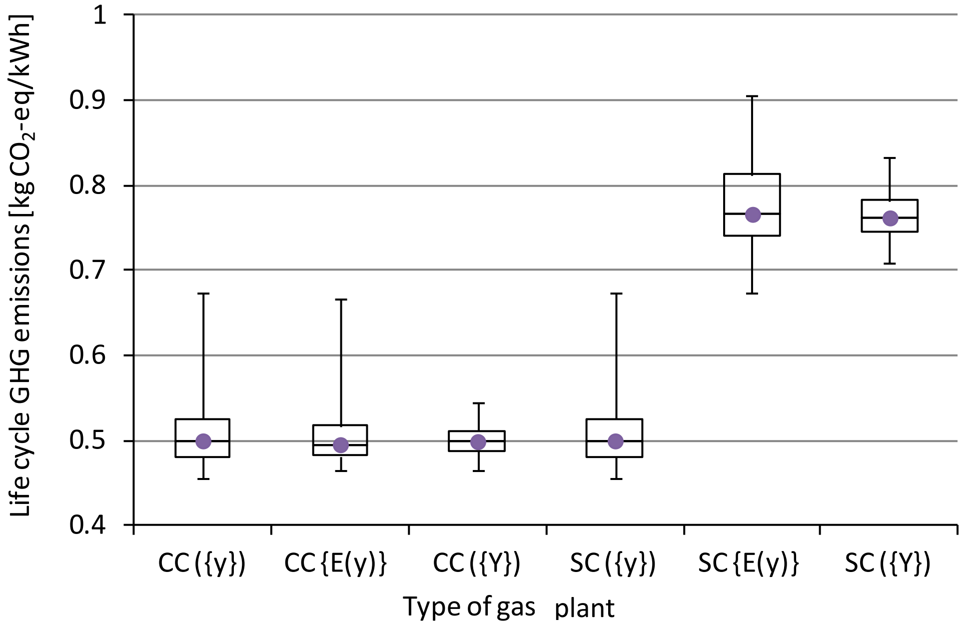
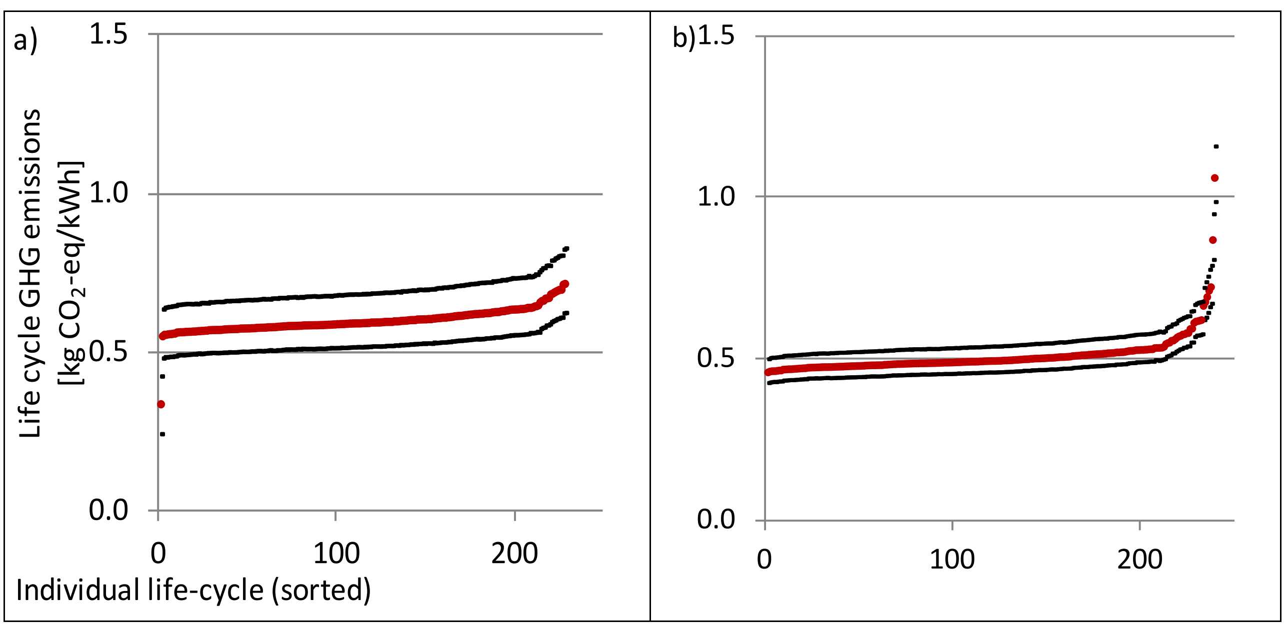


Figure S2. Life cycle GHG emissions associated with natural gas power generation (CC 239 plants, SC 69 plants) for a 100 year time horizon with updated GWP for methane. Model results accounting for uncertainty and variability are denoted by y, for variability only by E(y), those accounting only for uncertainty (by way of the use of a national-level system boundary) are denoted by Y.



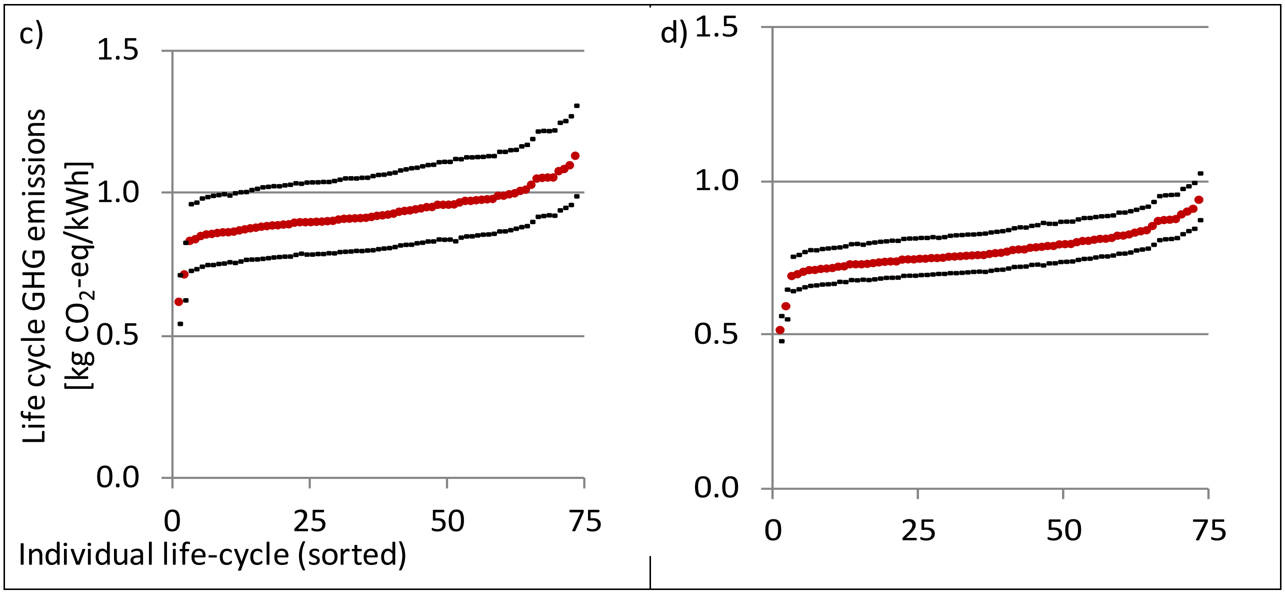


Figure S3. Variability and uncertainty in the life cycle of conventional natural gas for, a) CC power generation 20 year time horizon, b) CC power generation 100 year time horizon, c) SC power generation 20 year time horizon, d) SC power generation 100 year time horizon with updated GWP for methane.

Table S12. Contribution to overall variance in life cycle GHG emissions by uncertain parameters that contributed more than 1% for at least one of the two time horizons from (Myhre *et al.*, 2013). Results are shown for national weighted average life cycle GHG emissions from CC plants.

	20 year time horizon	100 year time horizon
GWP CH_4 (AR5) (-)	61%	55%
Activity factor, Gas turbines, processing (MMHPhr/yr)	6%	16%
Activity factor, Gas engine, processing (MMHPhr/yr)	7%	12%
Emission Factor, Reciprocating compressor for compressor station, transmission (scf/d/compressor)	9%	5%
Emission Factor, Reciprocating compressors, processing (scf/d/compressor)	2%	1%
CO_2 content in pipeline natural gas (%)	<1%	1%
Emission Factor, station venting tranmsission, (Mscf/yr/station)	2%	1%
Activity Factor, Reciprocating compressors, processing (number of compressors)	1%	1%

Table S13. Contribution to overall variance in life cycle GHG emissions by uncertain parameters that contributed more than 1% for at least one of the two time horizons from (Myhre *et al.*, 2013). Results are shown for national weighted average life cycle GHG emissions from SC plants.

	20 year time horizon	100 year time horizon
GWP CH4 (AR5) (-)	61%	55%
Activity factor, Gas turbines, processing (MMHPhr/yr)	6%	16%
Activity factor, Gas engine, processing (MMHPhr/yr)	7%	12%
Emission Factor, Reciprocating compressor for compressor station, transmission (scf/d/compressor)	9%	5%
Emission Factor, Reciprocating compressors, processing (scf/d/compressor)	2%	1%
CO_2 content in pipeline natural gas (%)	<1%	1%
Emission Factor, station venting transmission, (Mscf/yr/station)	2%	<1%
Activity Factor, Reciprocating compressors, processing (number of compressors)	1%	<1%
Emission Factor, pipeline venting transmission, (Mscf/yr/station)	2%	<1%

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