Paper #4-2
LIFE-CYCLE EMISSIONS OF NATURAL GAS AND COAL IN THE POWER SECTOR

Prepared by the Life-Cycle Analysis Team
of the
Carbon and Other End-Use Emissions Subgroup

On September 15, 2011, The National Petroleum Council (NPC) in approving its report, *Prudent Development: Realizing the Potential of North America's Abundant Natural Gas and Oil Resources*, also approved the making available of certain materials used in the study process, including detailed, specific subject matter papers prepared or used by the study's Task Groups and/or Subgroups. These Topic and White Papers were working documents that were part of the analyses that led to development of the summary results presented in the report's Executive Summary and Chapters.

These Topic and White Papers represent the views and conclusions of the authors. The National Petroleum Council has not endorsed or approved the statements and conclusions contained in these documents, but approved the publication of these materials as part of the study process.

The NPC believes that these papers will be of interest to the readers of the report and will help them better understand the results. These materials are being made available in the interest of transparency.

The attached paper is one of 57 such working documents used in the study analyses. Also included is a roster of the Team that developed or submitted this paper. Appendix C of the final NPC report provides a complete list of the 57 Topic and White Papers and an abstract for each. The full papers can be viewed and downloaded from the report section of the NPC website (www.npc.org).

Life-Cycle Analysis Team		
Lead		
Fiji C. George	Director, Carbon Strategies	El Paso Corporation
Members		
Ramon Alvarez	Senior Scientist	Environmental Defense Fund
Grover Campbell	Manager Regulatory Affairs – Air Regulations	Chesapeake Energy Corporation
Ronald Edelstein	Director, Regulatory and Government Relations	Gas Technology Institute
Christopher J. Freitas	Senior Program Manager, Office of Oil and Natural Gas, Office of Fossil Energy	U.S. Department of Energy
Bryan J. Hannegan	Vice President, Environment and Renewable	Electric Power Research Institute
Paul D. Holtberg	Acting Director, Office of Integrated and International Energy Analysis, Energy Information Administration	U.S. Department of Energy
David E. Rogers	General Manager, Climate Change, Strategic Planning	Chevron Corporation

I. Abstract

This paper reviews the life-cycle analysis (LCA) of emissions from natural gas and coal in the power sector in the U.S using updated 2009 EPA greenhouse gas (GHG) emissions inventory, global warming potential for methane from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4). The NPC finds that the life cycle GHG emissions (expressed as lb. CO_2e/million Btu) for natural gas are about 35% lower than coal on a heat input basis. For efficiencies typical of new coal- and natural gas-fired plants in the United States, the natural gas-fired plants are about 50% -60% lower in GHGs (expressed as lb. CO_2e/MWh) than a coal plant on a life-cycle basis. The NPC estimates the total methane emissions from the US natural gas systems to be 2.2% of the total gross production. Other studies have shown that a natural gas combined cycle (NGCC) plants have 99% lower SO_2 and mercury emissions and about 82% lower NO_x emissions relative to a pulverized coal unit on a life-cycle basis. Greater penetration and applications of various EPA Gas STAR technologies provide a proven avenue to reduce methane emissions.

II. Introduction:

This paper reviews the life-cycle analysis (LCA) of emissions from natural gas and coal in the power sector in the U.S using updated EPA DRAFT greenhouse gas (GHG) emissions inventory for 2009[1]. The NPC project is based on a principle of "study of studies". Review by the NPC Carbon & End-Use team of existing research and associated analysis indicates that an average of 58 GW of inefficient coal plants may retire as a result of upcoming EPA rules with significant portion of the retired capacity being replaced by efficient natural gas combined cycle (NGCC) plants. The EPA DRAFT inventory now indicates an increase of over 120 million tonnes (mm tonnes) of methane emissions from its 2008 official inventory to the current draft[2]. Most of the existing LCA literature in the public domain does not reflect the higher methane emissions estimated by the EPA in the recent DRAFT inventory. Hence, the aim for this paper is to review the impact of potential increased methane emissions on the life-cycle use of natural gas in the power sector relative to coal. The starting point for this analysis is the Paulina Jaramillo et al paper[3]. **The use of the Jaramillo methodology or even adoption of the new revised EPA emissions in this report should not be viewed as an endorsement but rather an attempt to place the analysis in the context of recent public discussions surrounding the impact of new EPA emissions data for the natural gas production sector and its impact on the overall natural gas life cycle emission.**

[1] U.S. EPA, "Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2009". http://www.epa.gov/climatechange/emissions/usinventoryreport.html

[2] In 2010, the EPA's official estimate of the 2008 methane emissions from natural gas systems was 96.4 mm tonnes. In the DRAFT 2011 inventory, the EPA estimates the 2009 methane emissions at 221 million tonnes.

[3] Jaramillo, P.; Griffin, W.M; Matthews; H. S. "Comparative Life Cycle Air Emissions of Coal, Domestic Natural Gas, LNG, and SNG for Electricity Generation." Environmental Science & Technology. 2007; 41(17); 6290-6296. Additional clarifications were provided by P. Jaramillo on February 5 and 7, 2011

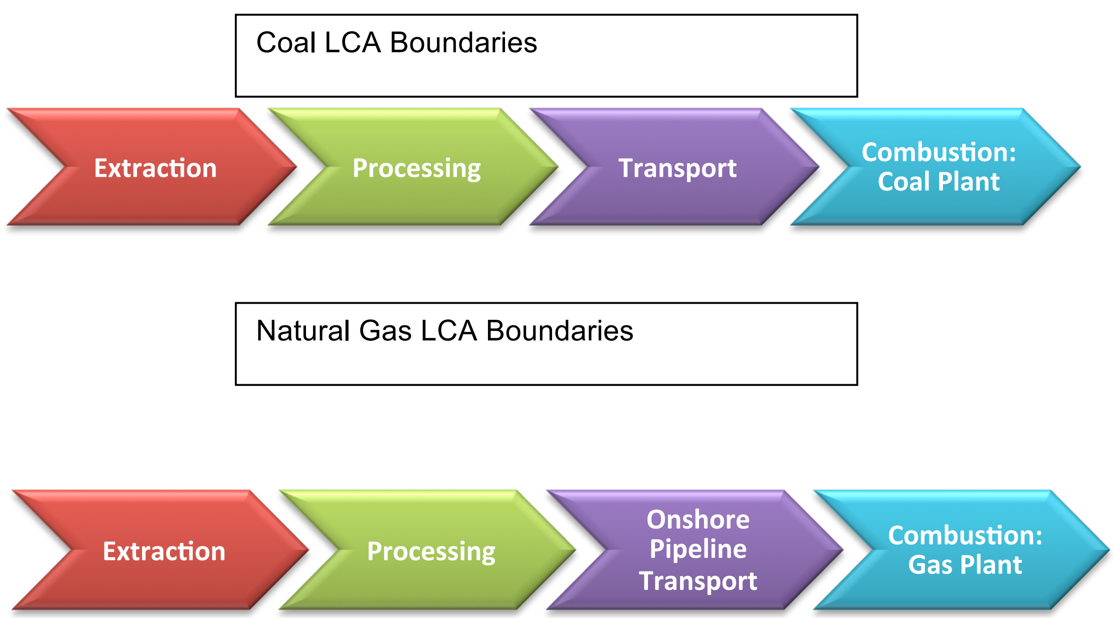
It should be noted that comprehensive emissions LCA is quite complex and requires a variety of methodological and data assumptions. Therefore, while there are published reports from both private and governmental agencies related to emissions, the uncertainties, process changes and lack of comprehensive measurement in the value chain make it difficult to draw definitive conclusions related to emission contributions especially from the fuel value chain prior to the power plants. These results should be viewed as a simplified, ***relative*** comparison of the total LCA between the fuel and technology alternatives.

III. Methodology:

To establish an "apples to apples" comparison of the past studies, it is important to draw the boundaries of the LCA.

1. Direct combustion and fugitive and vented emissions from the production/extraction, processing and transportation of coal and gas are included;
2. To ensure a fair representation of the current power production sector, promising technologies like carbon capture and sequestration (CCS) or integrated gas combined cycle (IGCC) are not included; and
3. Emissions related to construction and decommissioning of the facilities are not included.

Figure 1 - LCA Boundaries



IV. Life-Cycle Analysis of Natural Gas and Coal

This section estimates the fuel-based LCA for natural gas and coal as depicted by Jaramillo, et al. and was updated with more recent information. Two papers from the Jaramillo group address gas and coal LCA[4]. Both are fairly brief analyses and are not sufficiently detailed to allow a full assessment of the results. They are slightly different in their assumptions and results and some cases rely on outdated information[5]. Most significant for this discussion, there is new information on the methane emissions from natural gas production and transportation from the EPA that can be used to update the analysis. **In addition, this paper uses a global warming potential (GWP)[6] of 25 for methane rather than 21 which was used by Jaramillo and the EPA which was based on the Intergovernmental Panel on Climate Change (IPCC)'s Second Assessment Report (SAR).** The concept of GWP has been developed as a simplified way to compare the climate effects of different pollutants on a pound for pound basis relative to CO_2. The GWP accounts for a chemical's ability to absorb heat and varies with the time-horizon examined due to differing atmospheric lifetimes. Methane's atmospheric lifetime is roughly a little over a decade, compared to roughly a century for CO_2.

Natural Gas

As noted above, the key segments of the natural gas production process are extraction, processing, transportation and end-use combustion. From a GHG perspective, the major emitting components are:

- End-use combustion – the CO_2 released from the end-use combustion of the natural gas
- Upstream CO_2 from combustion – compressors and process equipment used to produce, process and transport the gas, including indirect emissions from electricity consumption
- Fugitive and vented methane emissions from these processes
- Non-combustion CO_2 released from the processes – CO_2 that is removed from the raw natural gas and vented

[4] Comparative Life Cycle Carbon Emissions of LNG Versus Coal and Gas for Electricity Generation, Paulina Jaramillo, W. Michael Griffin, H. Scott Matthews. http://www.ce.cmu.edu/~gdrg/readings/2005/10/12/Jaramillo_LifeCycleCarbonEmissionsFromLNG.pdf

[5] Emissions from the transportation of coal were calculated using the EIO-LCA tool developed at CMU (www.eiolca.net). The latest year for which the EIO-LCA tool has data is 1997; therefore, this 1997 date drove the entire coal life-cycle analysis. CMU used 1997 data for the majority of the analysis.

[6] 100-year time horizon GWP value from 2007 Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4). For methane, the GWPs range from 72 (for 20 year time horizon) to 7.6 (500 year time horizon). See Table 2.14 (http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter2.pdf). 100-year time horizon is the commonly adopted for various regulations (e.g. AB32, EPA Reporting Rule) and legislative proposals (e.g. 111th Congress). The 100-year time horizon is also the estimate employed by the EPA and EIA in its emissions estimates and projections.

This NPC analysis updates the Jaramillo analysis with updated natural gas emissions and production data[7] for 2009. It should be noted that Jaramillo uses 2003 natural gas data but employs 1997 coal data for comparison. Our attempt here is to employ the Jaramillo methodology and employ the updated EPA emissions data for natural gas as noted below and assess the impact of potential increased methane emissions from the upstream natural gas sector on its LCA in the power sector. Each of the emission categories is addressed below.

- **End-use combustion:** Jaramillo uses a value of 120 lb. CO_2e/MMBtu of gas. This is referenced to the EPA Clean Air Markets Division. The value used by the U.S. EIA and by the U.S. Inventory of GHG emissions is 117 lb. CO_2e/MMBtu.
- **Upstream CO_2 from combustion**: Jaramillo uses data from the U.S. EIA on natural gas consumption for gas production, processing, transmission and distribution and for electricity consumption, which was used to calculate indirect emissions. Using the same methodologies for 2009, we estimate the emissions to be approximately 113.5 $MMTCO_2$e. See Appendix A.
- **Non-combustion CO_2** – Jaramillo does not seem to include these values in the estimate but the most recent EPA inventory estimate of 32.2 $MMTCO_2$e for 2009 is added for the NPC estimate developed here.
- **Fugitive and vented emissions:** Jaramillo uses percentage factors[8] of the total gas production for the amount of fugitive and vented natural gas from the natural gas sector. Updating for the higher 25 GWP for methane, we arrive at a total of 165.5 $MMTCO_2$e for the Jaramillo methodology. This NPC study employs updated DRAFT EPA emissions inventory data for 2009 yielding a value of 229 $MMTCO_2$e. The distribution sector is not included because most electric generators do not receive gas via a local distribution company. Both calculations employ a 96% methane percentage in the natural gas for computing the emissions. See Attachment A for further details.

EPA has recently revised its estimate of fugitive and vented methane emissions from the gas industry for 2009. The largest changes are attributed by the EPA to changes in the estimate of methane released during well liquid unloading. This is a practice in which the well is vented to remove liquids that are choking the well. This applies only to conventional production (i.e., not shale gas).

The second largest increase is related to unconventional gas production with hydraulic fracturing. According to the EPA, fracking has the potential to produce higher methane emissions than conventional production due to the methane that is released during the flow-back after the fracturing. The first EPA adjustment on this topic increases the share of production that is accomplished through fracturing, which had not been recently updated in previous EPA's calculations. Second, EPA had previously assumed that most of the methane emissions from unconventional gas completions were being flared. However, through various industry sources,

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[7] Energy Information Administration (EIA). 2009 total natural gas gross withdrawals 26 tcf and consumption 22.8 tcf. See http://www.eia.gov/dnav/ng/ng_prod_sum_dcu_NUS_a.htm

[8] Table 2, Comparative Life Cycle Carbon Emissions of LNG Versus Coal and Gas for Electricity Generation, Paulina Jaramillo, W. Michael Griffin, H. Scott Matthews. http://www.ce.cmu.edu/~gdrg/readings/2005/10/12/Jaramillo_LifeCycleCarbonEmissionsFromLNG.pdf

EPA has now determined that some of the gas is not being flared but is vented. In addition, EPA updated the emission factor for wet compressor seals, which is a change from the old GRI factor based on more recent measurements.

Table 1 and 2 summarize the total upstream emissions from the Jaramillo study and the NPC update. Because some of these values were not shown explicitly in the Jaramillo study, they had to be reconstructed and may differ slightly from the values actually used, though in aggregate, they are within the final range of values presented in the Jaramillo paper. Because of the new, revised EPA estimate of fugitive and methane emissions and the inclusion of non-combustion CO_2, the NPC estimate for the natural gas emissions is 409 $MMTCO_2e$ compared to the Jaramillo estimate of 279, or 47% higher

Table 1 - Upstream GHG Emissions (2003) for Natural Gas as Calculated by Jaramillo, et al. (in $MMTCO_2e$)

Sector	Methane	Upstream Combustion	Non-Combustion CO_2	Total
Production	44.3	59.1		103.4
Processing	18.6	19.8		38.5
Transportation & Storage	61.8	34.5		96.3
Distribution	40.8			40.8
Total	165.5	113.45	0.00	**279**

Table 2 - Upstream GHG Emissions (2009) for Natural Gas as Calculated for NPC (in MMTCO2e)

Sector	Methane	Upstream Combustion	Non-Combustion CO_2	Total
Production	155.1	59.1	10.9	225.1
Processing	20.8	19.8	21.2	61.9
Transportation & Storage	52.9	34.5	0.1	87.5
Distribution	3.5	0.0	0.0	34.5
Total	263.3	113.5	32.2	**409**

Coal

The Jaramillo estimates of upstream coal emissions were more difficult to back out from the paper but there have been no significant changes to the estimate proposed by this NPC analysis. One important note is that the paper uses 1997 data for coal production in order to take advantage of a life cycle model of the coal industry for which the most recent available version was for that year. So in essence, Jaramillo compares 1997 coal data with 2003 natural gas data.

The supporting document that accompanied the Jaramillo paper provides information on fuel and electricity consumed for coal mining[9] and we compute yielding direct and indirect CO_2 emissions from combustion for mining of 35 $MMTCO_2e$. Coal mine emissions of methane gas of 81 $MMTCO_2e$ were computed by using the 1997 EPA inventory (68.4 $MMTCO_2e$) and the higher GWP of 25 for methane. Similarly, the emissions for coal transportation were calculated using the EIO-LCA model for 1997 and were estimated at 37 $MMTCO_2e$[10]. The total emissions are estimated at 153.7 $MMTCO_2e$. See Appendix A.

Table 3 - Upstream GHG Emissions for Coal (1997) as Calculated Using Data or Computed by Jaramillo et al. ($MMTCO_2e$)

	Methane	Upstream Combustion	Total
Production	81.4	35.2	116.6
Transportation	--	37.1	37.1
Total	81.4	72.3	153.7

The values for methane were estimated from the 2009 EPA estimates (71 $MMTCO_2e$) and updated for the higher GWP of methane and mining energy consumption were updated to 2007 (most recent available data) for the NPC assessment and are summarized in Table 5. Emissions from Abandoned Coal Mines of approximately 6.5 $MMTCO_2e$ were not included in the LCA.

Table 4 - Upstream GHG Emissions for Coal (1997) as Calculated for NPC ($MMTCO_2e$)

	Methane	Upstream Combustion	Total
Production	84.5	14.0	98.6
Transportation	--	37.1	37.1
Total	84.5	51.2	135.7

[9] Table 5S, Supporting Information, Comparative Life-cycle Air Emissions of Coal, Domestic Natural Gas, LNG, and SNG for Electricity Generation

[10] Rail+Water+Transport Emissions

In order to compare the gas and coal emissions, it is useful to normalize them to lb. CO_2e/MMBtu. Table 5 summarizes the normalized natural gas emissions calculated by Jaramillo (not adjusted for the GWP of 25 for methane). The distribution sector is not included because most electric generators do not receive gas via a local distribution company. Jaramillo does not show a similar breakdown of the coal emissions.

Table 5 – Normalized Life-cycle Emissions for Natural Gas as Calculated by Jaramillo, et al.[11]

Segment	Lbs. CO_2e/MMBtu
Production	7.7 – 8.7
Processing	3.7
Transmission and Storage	3.9 – 7.8
Upstream Total	15.3 – 20.1

The summary comparison of gas and coal emissions (adjusted for the GWP of 25 for methane) is shown in Table 6. The ranges of values are the result of a variety of uncertainties in data or assumptions, such as the effect of the EPA Gas STAR program or the amount of fuel consumed by gas transmission systems versus local distribution companies.

Table 6 - Comparison of LCA Emissions as Calculated by Jaramillo, et al. (lb. CO_2e/MMBtu)

	North American Natural Gas		Coal	
	Minimum	Maximum	Minimum	Maximum
Upstream	16.5	22.2	8.4	18.2
Fuel Combustion	120	120	205	205
Total	136.5	142.2	213.4	223.2

Table 7 compares the normalized LCA emissions calculated by using updated values calculated in this NPC report. The coal values are unchanged except for the value for final combustion is changed from the value used by Jaramillo and referenced to the EPA Clean Air Markets Division, to a slightly higher value used by the EPA GHG inventory and the EIA. There is a similar change to the final combustion emission factor for natural gas. In addition, the NPC version uses the new, higher EPA value for fugitive and vented methane emissions and includes the non-combustion CO_2 emissions. The revised LCA for natural gas is 6% higher than

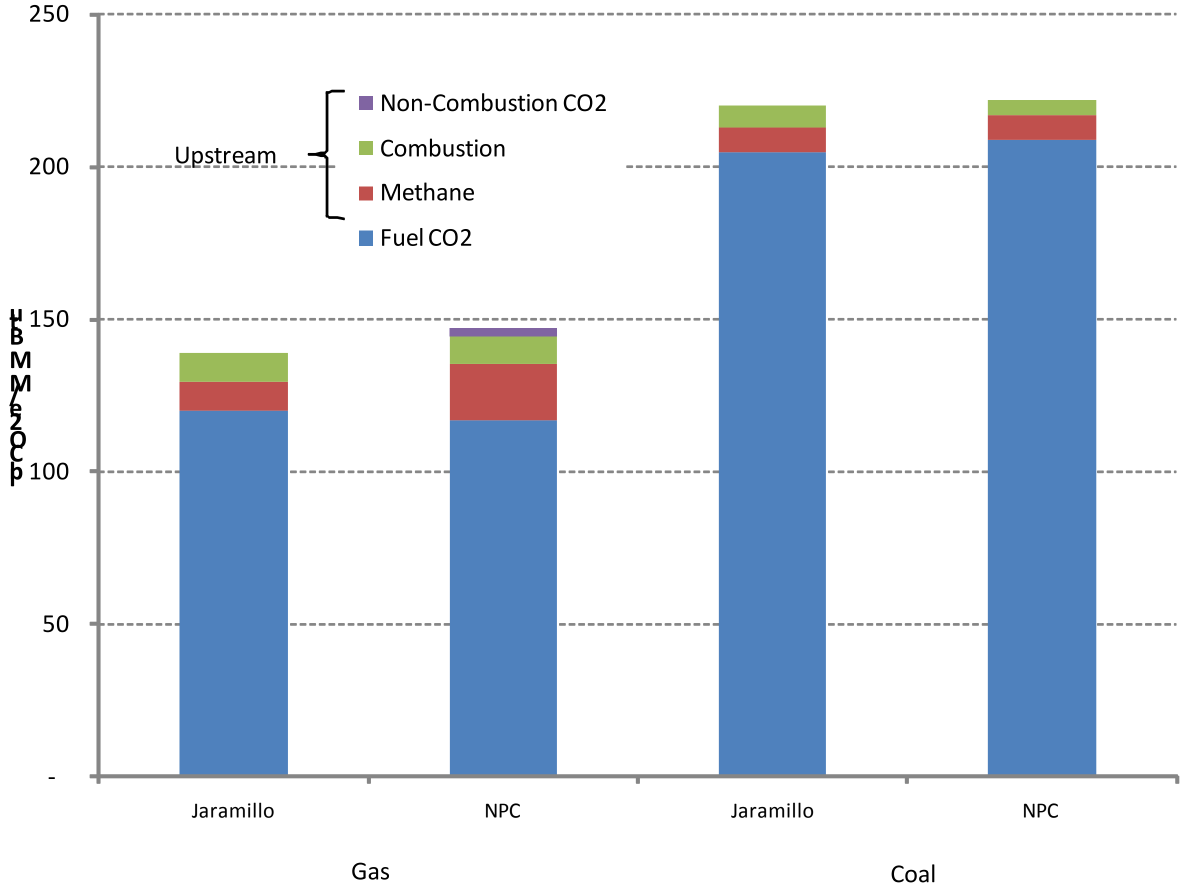
[11] Jaramillo 2007, Figure 6S in Comparative Life Cycle Carbon Emissions of LNG Versus Coal and Gas for Electricity Generation, Paulina Jaramillo, W. Michael Griffin, H. Scott Matthews. http://www.ce.cmu.edu/~gdrg/readings/2005/10/12/Jaramillo_LifeCycleCarbonEmissionsFromLNG.pdf and Table 10S, Supporting Information, Comparative Life-cycle Air Emissions of Coal, Domestic Natural Gas, LNG, and SNG for Electricity Generation

the Jaramillo value. The change in emission factor for coal increases that value by 1%. Figure 2 shows the same information graphically.

Table 7 – Comparison of Fuel and Upstream Emissions (lb. CO_2e/MMBtu)

	Natural Gas		Coal	
	Jaramillo	NPC	Jaramillo	NPC
Methane Emissions (Fugitive and Vented)	9.1	18	7.9	7.9
Upstream combustion	9.1	9.1	7.0	5.0
Non-Combustion CO2	--	2.6	--	--
Fuel CO_2	120	117	205	209
Total	139	147	220	222
Increase		6.1%		0.9%

Figure 2 - Comparison of Fuel and Upstream Emissions (lb. CO_2e/MMBtu)



The primary observation from this analysis is that changing to the much higher EPA methane factors for the natural gas value chain increases the total gas LCA emissions by only 6%.

Electricity Emissions Analysis

The second phase of the analysis is to calculate the emissions from generation of electricity. This requires an assessment of the efficiency of electric power plants. Jaramillo uses the EPA eGRID database and selects a range of efficiencies that account for the generators that produce between 5% and 95% of total generation for each fuel. The efficiency range is from 30% to 37% for coal and from 28% to 58% for gas. Table 8 shows the range of electricity emission factors for the various LCA fuel factors and power plant efficiencies. The same information is shown graphically in Figure 3. The triangles in Figure 3, represents the LCA emission rates computed by the updated Jaramillo methodology and the NPC at heat rates of 7000 Btu/kWh for natural gas combined cycle plant and 9000 Btu/Kwh for a coal fired power plant.

Figure 3 also shows an uncertainty range for the methane emissions from operations of natural gas systems. This is based on EPA's uncertainty estimate from the DRAFT GHG inventory of -19% to +30% for methane and from non-combustion CO_2. Uncertainty ranges[12] from coal mining operations or combustion of coal (-4% to +10%) or natural gas (-3 to +5%); and uncertainties from coal mine operations (-12.7% to +16.1)[13] are not illustrated in Figure 3. Table 9 illustrates these uncertainty values on the range of heat rates for the NPC analysis. Further review of uncertainties and incorporation of the same into this report is beyond the scope of this paper.

Table 8 - Comparison of LCA Electricity Emission Rates

Natural Gas			Coal		
Heat Rate (Btu/kWh)[14]	Jaramillo (lb. CO_2e/MWh)	NPC (lb. CO_2e/MWh)	Heat Rate (Btu/kWh)[15]	Jaramillo (lb. CO_2e/MWh)	NPC (lb. CO_2e/MWh)
5,884	814	866	9,224	2029	2047
12,189	1686	1794	11,377	2502	2524
7000	968	1030	9,000	1980	1997

[12] http://www.epa.gov/climatechange/emissions/downloads11/US-GHG-Inventory-2011-Chapter-3-Energy.pdf, Table 3-16

[13] http://www.epa.gov/climatechange/emissions/downloads11/US-GHG-Inventory-2011-Chapter-3-Energy.pdf (Table 3-31)

[14] Based on 58% and 28% efficiency for natural gas power plants.

[15] Based on 37% and 30% efficiency for coal plants

Figure 3 - Life-cycle Electricity Emission Rate (lb. CO_2e/MWh)

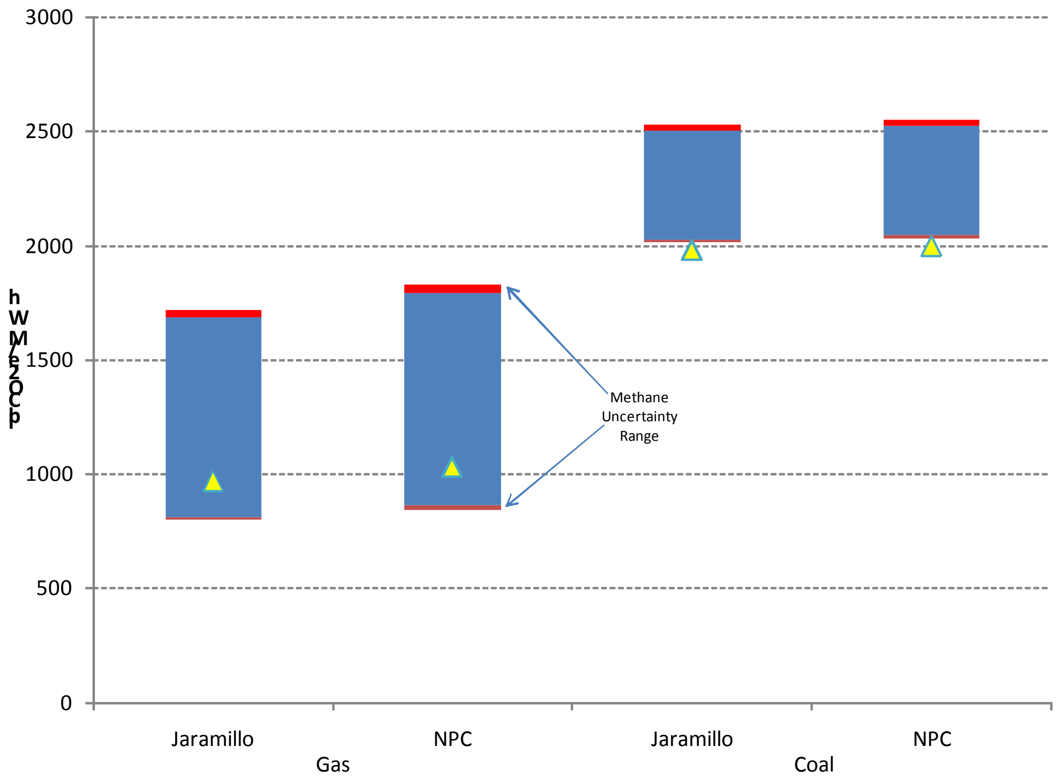


Table 9 – Impact of uncertainties in methane estimates

LCA Emission Rates (lbs. CO2e/MWh)				
Methane Uncertainty Range	NGCC Plant Heat Rate 7000 Btu/kWh		Coal Power Plant Heat Rate 9000 Btu/Kwh	
	Jaramillo- Gas	NPC- Gas	Jaramillo-Coal	NPC-Coal
30%	987	1051	2001	2018
	968	**1030**	**1980**	**1997**
-19%	956	1002	1966	1984

Implications of methane's global warming potential: As mentioned in Section III, the life-cycle emission estimates presented in this paper employed a 100-year global warming potential for methane of 25 (unless otherwise noted).
Although most regulations and policy discussions consider the 100-year time horizon, this practice may not fully compare the impact of short-lived GHGs like methane versus longer lived GHGs like CO_2. Conversely, considering a shorter time-horizon can give a more complete understanding of the near-term effects of shorter-lived species. As discussed in footnote 6, the IPCC's current estimate of methane's 20-year GWP is 72. Using a 20-year GWP for methane would result in larger emissions estimates for the upstream portions of both coal's and natural gas' life cycles in Table 8 and Figure 3, although natural gas still produces lower overall equivalent CO_2 emissions than coal. For example, using a 20-year GWP of 72 for methane yields 1273 lbs. of CO_{2e}/MWh and 2131 lbs./MWh for the heat rates of 7000 Btu/kWh and 9000 Btu/kWh in Table 8 for natural and

The wide range of values seen in the final results is the result of the broad power plant efficiency range, not the life-cycle emissions. The wide range of efficiency values and very low efficiency for the gas plants is somewhat surprising. It may be that Jaramillo has not differentiated between the different kinds of natural gas-fueled generators, which include gas steam plants, simple cycle peakers, and cogeneration plants of various designs and combined cycle plants. Not all of these are comparable to coal plants. As noted in Table 8, the highest heat rate for a coal fired power plant employed in the LCA is 11,377 versus a heat rate of 12,189 for a natural gas powered plant. It is not the lifecycle emissions from natural gas, but use of a very low efficiency gas plant compared to a new coal plant efficiency, which makes the Jaramillo LCA data for power production appear closer than it really is. One would draw a similar conclusion using only the end use fuel emissions based on these plant efficiencies. This seems particularly out of place since the real focus going forward will be on new, combined cycle gas plants versus either existing or new coal plants. The efficiency range for this comparison is much smaller, with combined cycle plants in the range of 49% efficient and coal plants in the 38% range[16]. Within this range (shown by the triangles in

Figure 3), the gas plant consistently has GHG emissions roughly half those of the coal plants.

V. Crossover Analysis

Some entities have computed a "break-even" point analysis to compare natural gas versus coal as a source of electricity assuming "leakage" rates for methane in the natural gas value chain[17]. In effect, the question is: "How much gas would have to be released by the natural gas system for

[16] Assumptions for EIA Annual Energy Outlook. http://www.eia.gov/oiaf/aeo/excel/aeo2010%20tab8%202.xls
Efficiency of a natural gas combined cycle (NGCC) plant computed based on 7000 Btu/Kwh. Using EIA's estimate of an average heat rate of the first and nth of kind (6543 Btu/kWh), the efficiency of a NGCC is at about 52%. Coal Plant efficiency computed based on average heat rate of 8970 Btu/kWh for the first and nth of a kind "Scrubbed New Coal Plant".

[17] Use of a 100-year GWP, break-even estimates have been between 6-13%. Using of a 20 year GWP time horizon, estimates have been between 4-6%. See Appendix B.

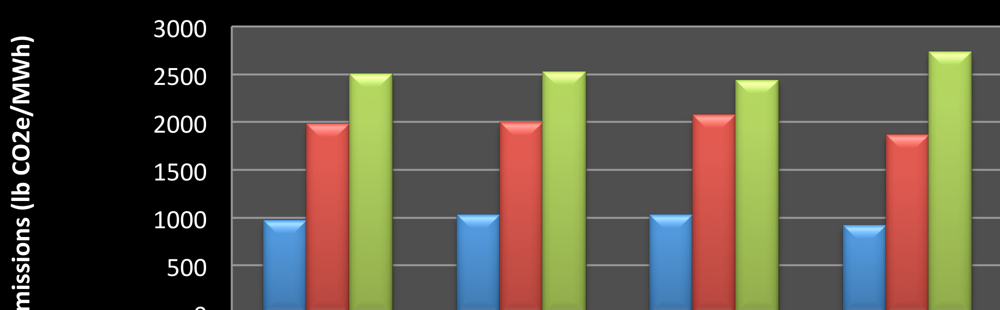
the use of gas to have the same life-cycle emissions as coal?" This can be calculated from the information discussed below based on 2009 data.

- The answer must be on an lb./MMBtu basis in order to be comparable.
- The difference between the total life-cycle emissions from coal and natural gas is 222 – 147 = 75 lb. CO_2e/MMBtu
- This already includes 18 lb. CO_2e/MMBtu of emissions from methane
- The methane total to "break even" would be the sum of these two 75 + 18 = 93 lb. CO_2e/MMBtu
- This is equal to 1,156 $MMTCO_2e$ of total GHG emissions from methane based on total gas production.
- Using a conversion factor of 0.46 $MTCO_2e$/Mcf of methane (GWP=25) and 96% methane content, the total breakeven gas quantity is about 2.5 Tcf of fugitive and vented methane or about 10% of gross gas withdrawals in 2009.

VI. Other LCAs

Figure 4 provides a comparative analysis of the LCA as reported by Jaramillo et al., NPC, NETL and the Pace analysis for the Center for LNG (CLNG)[18]. After accounting for higher GWPs from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report for methane and also higher EPA emission factors, the NPC estimates for natural gas combined cycle (NGCC) were at about 1030 lbs. of CO2e/MWh and were comparable to estimates from NETL (1027-1043 lbs. CO_2e/MWh). The Jaramillo estimates were not adjusted for the new EPA emissions but were adjusted to account for the higher GWPs. The Pace/CLNG had the lowest estimates for NGCC and employed GWPs from the IPCC second assessment report.

Figure 4- LCA Comparisons



	Jaramillo	NPC	NETL	Pace
Natural Gas	968	1030	1027	918
Coal(SCPC/USC)	1980	1997	2075	1868
Coal (PC)	2502	2524	2440	2731

[18] Multi-Scenario Carbon Lifecycle Analysis (LCA) Preliminary Assumptions Review Prepared for: Center for Liquefied Natural Gas, Pace, August 1, 2008

In addition to GHG benefits, NETL estimates the non-GHG benefits of natural gas has over 99% lower SO_2 and mercury life-cycle intensities and about 82% lower NO_x relative to a pulverized coal unit (Figures 5 through 7).

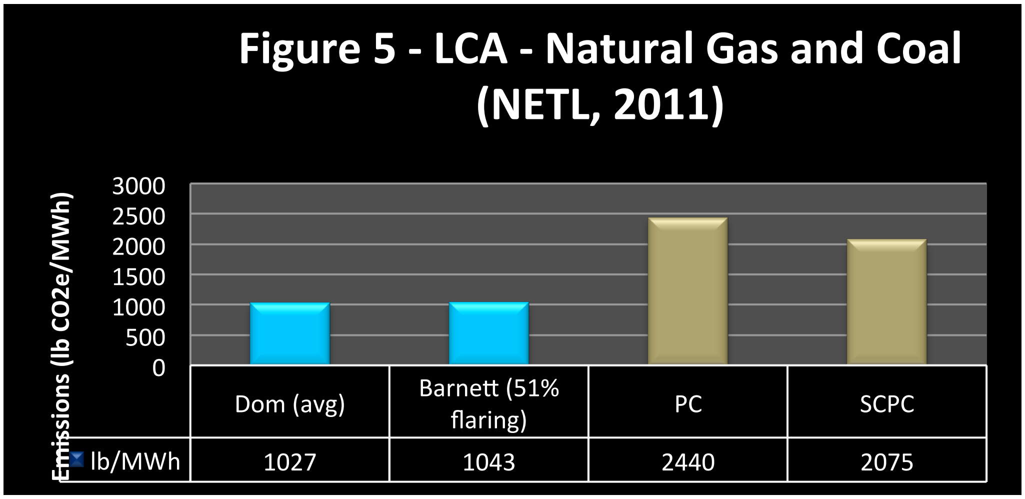


Figure 5 - LCA - Natural Gas and Coal (NETL, 2011)

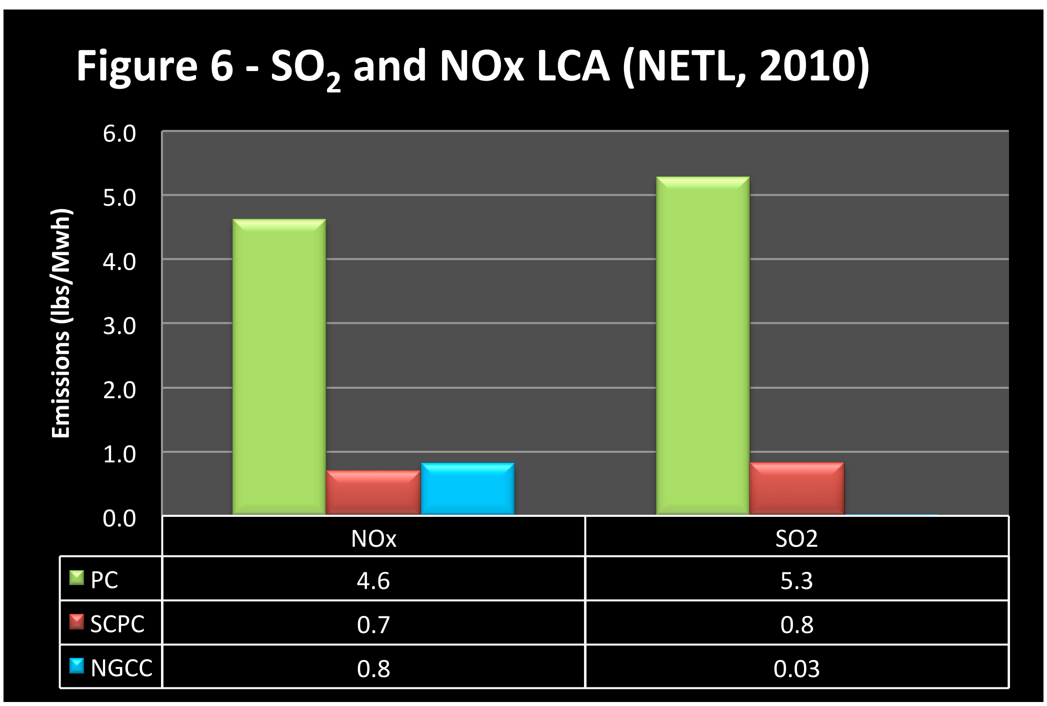
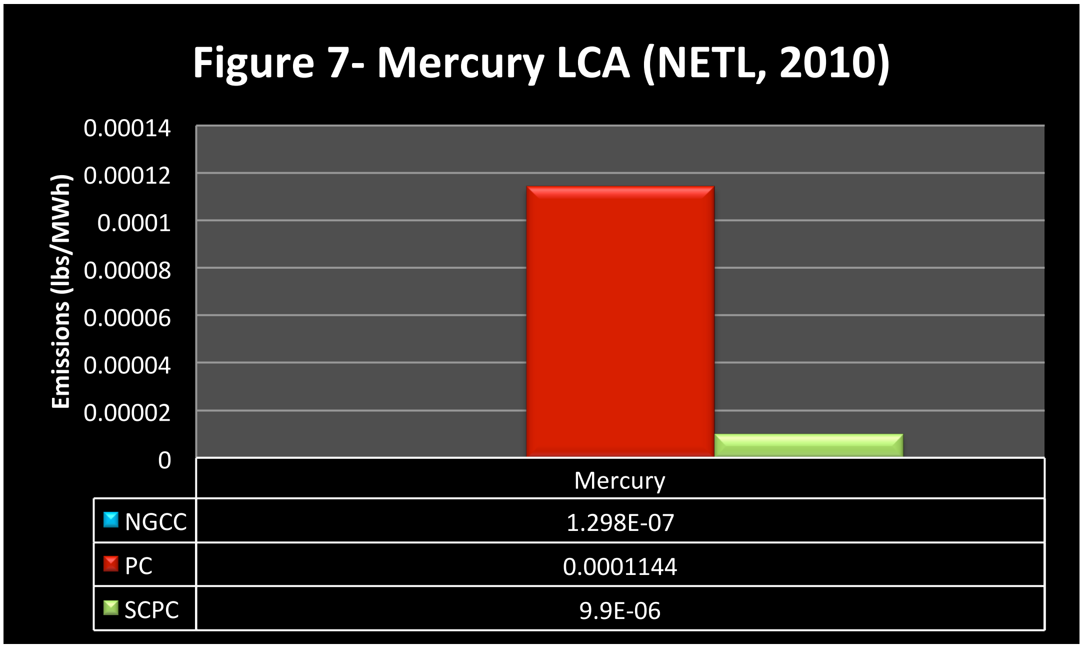


Figure 6 - SO_2 and NOx LCA (NETL, 2010)



VII. Conclusions

- The EPA has revised its projections of methane emissions from the gas industry, which has significantly increased the estimated emissions from some parts of the sector. At this time it is impossible to discern the EPA methodology and assess its accuracy at arriving at these higher emissions estimates. It should be noted that these estimates have not undergone public review and may change in its final form.

- Applying the increased EPA methane projection factors to the Jaramillo LCA increases the gas life-cycle emissions by about 6%. Under both scenarios, the LCA for natural gas is about 35% lower than coal on a heat input basis.

- The wide range of final LCA values in the Jaramillo paper is primarily due to a wide range of assumed power plant efficiencies. The use of a very low efficiency gas power plant is the driver for the small difference between gas and coal-fired power plants in some cases.

- For efficiencies typical of new coal and gas-fired plants, the gas-fired plants are about 50% lower in GHGs than coal plants on life cycle basis with an efficient super critical pulverized coal plant and about 60% lower relative to an inefficient pulverized coal plant.

- Other estimates have shown that NGCCs have 99% lower SO2 and Mercury emissions and about 82% lower NOx emissions relative to a pulverized coal unit on a life cycle basis.

VIII. Recommendations:

Life cycle analysis is complex undertaking that requires many assumptions and inputs. The LCA of natural gas and coal is no exception. While the NPC analysis contained in this report provides an upper bound life-cycle estimate for natural gas, we recommend that a more rigorous analysis be completed making use of the most recent EPA and EIA information on emissions and natural gas supplies and also incorporating robust uncertainties in the emissions estimated.

While EPA data does show increased natural gas emissions from the value chain, further refinements and improvements are already underway, including comprehensive nationwide measurements that are currently being undertaken by facilities subject to EPA reporting rules before adoption to any meaningful policy focus on natural gas[19]. EPA should analyze these comprehensive compliance measurement data to develop future factors for use in LCA analysis. The DRAFT inventory indicates that the Processing, Transmission and Storage and Distribution sectors have seen approximately 3%, 10% and 13% reduction in methane emissions respectively from 1990 levels[20]. The Production sector has seen a 46% increase over the same period.

263 MMT CO_{2e} of methane emissions in the natural gas life cycle (Table 2) equates to roughly 0.6 tcf of loss of natural gas. Assuming roughly a $4/MCF value, these emissions roughly equates to a loss of $2.4billion. Granted significant amount of the emissions in the natural gas value chain occur to facilitate safe and reliable operations (e.g. operations of actuators and relief valves), the industry should, regardless of the uncertainty with the emissions estimates and measurements, continue to adopt and employ EPA Gas STAR technologies to reduce methane emissions along the natural gas value chain while maintaining safety and reliability.

The EPA Gas STAR[21] data shows that the industry has reduced over 904 billion cubic feet (bcf) of methane emissions (or over 400 MMT CO_{2e}) through implementation of cost-effective technologies. In addition, the California Air Resources Board (CARB) has compiled a clearinghouse of non-CO2 Greenhouse Gas Emissions Control Technologies, which mostly based on EPA Gas STAR program[22]. The analysis provides details on technology description, market penetration and costs. Barriers to adoption of these technologies should be evaluated and the industry and government must work to overcome these barriers.

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[19] http://www.epa.gov/climatechange/emissions/downloads11/US-GHG-Inventory-2011-Chapter-3-Energy.pdf. See Page 48 (Planned Improvements)

[20] Table 3-36, U.S. EPA, “Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2009”.

[21] http://epa.gov/gasstar/accomplishments/index.html

[22] http://www.arb.ca.gov/cc/non-co2-clearinghouse/non-co2-clearinghouse.htm#Methane

Appendix A: Calculation Details

Table A.1: Combustion Emissions Calculations

Fuel Use	2009 Consumption data From EIA (Bcf)	Absolute Emissions (MMTCO2)	Emissions as a function of Production (lb./MMBtu)
Flaring	165.4	9.1	0.7
Lease	913.2	50.0	4.0
Pipeline	598.2	32.8	2.6
Plant	362.0	19.8	1.6
Total Direct Emissions	2,038.8	111.7	9.0
Electricity		1.8	

Notes:

a) Consumption data from EIA. http://www.eia.gov/dnav/ng/ng_cons_sum_dcu_nus_a.htm

b) Conversion to metric tonnes based on higher heating value (HHV) of 1030 Btu/scf, CO_2 emission factor of 117 lb./MMBtu.

c) Conversion to lb./MMBtu based on gross production (26.5 tcf) and HHV or 1030 Btu/scf

Table A.2: Natural Methane Gas Emissions (2009 Million Tonnes)

	Jaramillo et al			NPC using DRAFT 2009 EPA Emissions (MMT CO2e)	
Segment		MMTCO2		Fugitive/Vented	Non Comb
Production	0.38%	44.3		155.1	10.9
Processing	0.16%	18.6		20.8	21.2
Trans & Strge	0.53%	61.8		52.9	0.1
Distribution	0.35%	40.8		34.5	
Total	**1.42%**	**165.5**		**263.3**	**32.2**
Total- Distribution		**124.7**		**228.8**	

Note: All emissions adjusted for GWP of 25 and employ 2009 Natural Gas Production estimates from the EIA and 96% methane content in natural gas

Table A.3a: Recreating Jaramillo et al Emissions: Table 5S: 1997 Fuel Consumption at Coal Mines							
	Fuel Oil (1000 bbl)			Gas	Gasoline	Electricity	Total Emissions (MMTCO2)
Mine Type	Total	Distillate	Residual	(10^9 ft3)	(10^6 gal)	(10^6 KWh)	
Surface	8,280	7,524	756	0.7	30	42,474	
Underground	801	656	145	0.5	4	7,123	
Total	9,081	8,180	901	1	34	49,597	
MMTCO2		3.49	0.45	0.07	0.30	30.86	**35.17**

Table A.3b Carbon Content, and Heat Content of Different Fuels Used to compute emissions(From Jaramillo Support DocumentationTable 6S:).				
	Carbon Content of Fuel	Heat Content of Fuel		
Fuel Type		MMBtu/MMcf)	Fraction	
	lb./MMBtu Fuel	(MMBtu/bbl -	Oxidized	
Distillate	43.98	5.825	0.99	
Residual	47.38	6.287	0.99	
Gas	31.9	1,030	0.995	
Gasoline	42.66	5.253	0.99	

Table A.4: NPC Estimates of Combustion Emissions from Coal Mining Operations using 2007 Economic Census Data									
	MMBtu (Calculated)						MWh		
Parameters	Coal	Distillate	Natural Gas	Gasoline	Residual Oil	Other	Electricity		Total Combustion Emissions (MMTCO2e)
MMBtu	3,607,020	52,597,178	2,487,920	4,846,529	25,739,212	2,039,820	11,444,477	MWh	
kg Co2/MMBtu	94.38	73.96	53.02	70.22	75.1	62.98	636.36	kg/MWh	
Emissions (MMCO2e)	0.3	3.9	0.1	0.3	1.9	0.1	7.3		**14.0**

Source: http://factfinder.census.gov/servlet/IBQTable?_bm=y&-geo_id=&-ds_name=EC0721I3&-_lang=en

Appendix B: Summary of Reported Break-Even Leak Rates (Natural Gas - Coal)

Author(s)	**Time Frame (GWP)**		
	20 year	**100 year**	
Rodhe (1990)		6%	H. Rodhe (1990), Science, **248**, 1217-1219 (see note 1)
Lelieveld et al (1993)	4.9-6.3% (60)	10.5-12.0% (22)	J. Lelieveld, P.J. Crutzen, and C. Bruhl (1993), Chemosphere, **26,** 739-768
Lelieveld et al (2005)	5.6 +/- 0.7% (60)	11.3 +/- 0.7% (22)	J. Lelieveld et al. (2005), Nature, **434**, 841-842
Okken (1990)	13% (N/A)		P.A. Okken (1990), “Methane leakage from natural gas,” Energy Policy, March 1990, 202-204
Mitchell et al (1990)	5.3% (63)	~11.5% (21)	C. Mitchell et al. (1990), Energy Policy, November 1990, 809-818
GRI/EPA (1996)	4% (72)	13% (21)	Gas Research Institute and U.S. EPA, June 1996, "Methane Emissions from the Natural Gas Industry, Volume 2: Technical Report", Appendix B (see Note 2)