AMERICAN CLEAN SKIES FOUNDATION

750 1st St, NE
Suite 1100
Washington, DC 20002
202.682.6294 Main
202.682.3050 Fax
www.cleanskies.org

The Climate Impact Of Natural Gas and Coal-Fired Electricity: A Review of Fuel Chain Emissions Based on Updated EPA National Inventory Data

By
Gregory C. Staple
and
Joel N. Swisher

April 19, 2011

The Climate Impact Of Natural Gas and Coal-Fired Electricity: A Review of Fuel Chain Emissions Based on Updated EPA National Inventory Data

By
Gregory C. Staple[1]
and
Joel N. Swisher[2]

Abstract:

This paper provides an updated, comparative fuel chain calculation of the greenhouse gas (GHG) emissions of natural gas- and coal-fired electricity. The analysis incorporates revised 2011 US EPA estimates of fugitive methane emissions from the upstream (i.e., production) portion of the fuel chain. Based on this revised EPA data and average generation heat rates, we find that *existing gas-fired generation is still, on average, about 51% less GHG intensive than existing coal-fired generation*. Similarly, a new gas-fired combined-cycle unit produces about 52% less GHG emissions per kWh than a new coal-fired steam unit; about 58% less than the average coal-fired unit; and about 63% less than a typical older coal-fired unit.

---

[1] Gregory C. Staple is the CEO of the American Clean Skies Foundation (ACSF). From 2000-2009, he was a partner at the Washington, D.C. office of the international energy law firm Vinson & Elkins LLP.

[2] Joel N. Swisher PhD, is a consultant to ACSF and the Director of Technical Services for Camco International, a major carbon offset developer. Prior to joining Camco, Dr. Swisher was managing director of research and consulting at Rocky Mountain Institute (RMI), where he is now Senior Fellow. Dr. Swisher is also a consulting professor of Civil and Environmental Engineering at Stanford University.

Introduction

Valid comparisons of the greenhouse gas (GHG) emissions associated with the fuels used for electric generation require comparing emissions from the full fuel chain; that is, from production to combustion, including fuel processing and transportation. This paper focuses on new data for the fuel chain emissions associated with natural gas-fired electricity and compares these emissions with the fuel cycle emissions for coal-fired generation.[3]

The fuel chain for natural gas includes several sources of GHG emissions. These emissions include CO2, N2O, and methane (CH4), which should be calculated taking into account the different atmospheric lifetimes and radiative forcing power of the gases.[4] Methane emissions from natural gas production and transport to market are the most important of the upstream emissions, due to the quantity of emissions and the fact that methane is a more powerful greenhouse gas than CO2. Coal mining also releases methane and that must be accounted for in a consistent way as well.

Recently, the US Environmental Protection Agency (EPA) revised its estimates of methane emissions from natural gas production, significantly raising estimates, particularly regarding emissions from field production (i.e., drilling sites). Specifically, in the most recent national GHG inventory,[5] and in a related EPA report on GHG

[3] ACSF has previously supported the Department of Energy's proposal to incorporate full-fuel-cycle (FFC) measures into energy efficiency standards for gas and electric appliances. These standards would also provide a new basis for evaluating the comparative GHG impacts of different appliances. The DOE's Notice of Proposed Rulemaking, and Final Rule can be found at: http://www.eere.energy.gov/buildings/appliance_standards/certification_enforcement.html. ACSF's comments are available at: http://www.cleanskies.org/pdf/ACSF_Comments_on_Full_Fuel_Cycle_filing_10_29_10.pdf.

[4] We compare the effect of different GHGs using the 100-year global warming potential ratios from the most recent Intergovernmental Panel on Climate Change (IPCC) report, *IPCC Fourth Assessment Report: Climate Change* (2007), http://www.ipcc.ch/publications_and_data/publications_and_data_reports.shtml. The global warming potential (GWP) is the ratio of the total radiant forcing of a GHG, based on its atmospheric lifetime and radiative forcing power, compared to that of CO2, over a specified time horizon. The 100-year horizon is used most commonly, and the 100-year GWP values from the Second IPCC assessment (in 1995) are codified in the Kyoto Protocol to the UN Framework Convention on Climate Change and used in national inventory accounting, including that of the US EPA cited here.

[5] U.S. EPA, *Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2009* (2011), EPA-430-R-11-005, http://www.epa.gov/climatechange/emissions/usinventoryreport.html.

reporting in the oil and gas industries,[6] the EPA applied a modified methodology for estimating some sources of fugitive methane emissions from upstream production. The EPA increased estimated emissions from "gas well cleanups" by more than 20 times; it also added emissions due to "unconventional gas well completions and workovers involving hydraulic fracturing," which is used to extract natural gas from shale gas deposits.

As a result, the 2009 inventory (and the revised 2008 inventory) show natural gas upstream emissions as about 23% of combustion emissions, which is about double the ratio (approximately 12%) shown in the original 2008 inventory.[7]

The EPA's new reports have led to considerable controversy about the impact of upstream emissions on the comparative GHG intensity of natural gas-based applications. One report, by Pro Publica, suggested that the EPA's modified methodology in estimating upstream emissions "dramatically chang[es]" the overall GHG intensity of gas-fired power generation.[8] However, this interpretation confuses the change in the upstream and non-combustion emissions (which the EPA doubled) with the change in fuel chain GHG emissions (which, as discussed below, increase approximately 10%). It also omits upstream GHG emissions from coal mining; these upstream emissions represent about half of the revised, higher upstream emissions from gas production on a per-kWh basis.

---

[6] *Technical Support Document: Greenhouse Gas Emissions Reporting from the Petroleum and Natural Gas Industry,* EPA-HQ-OAR-2009-0923-3610, at http://www.regulations.gov/#!documentDetail;D=EPA-HQ-OAR-2009-0923-3610.

[7] *See* U.S. Environmental Protection Agency (EPA), *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2008* (2010), EPA-430-R-10-006. http://epa.gov/globalwarming/climatechange/emissions/downloads10/US-GHG-Inventory-2010_Upfront.pdf The 2008 upstream emissions would be 10% of combustion emissions based on the 2008 inventory or 20% based on the 2009 inventory. Our estimates are higher, because we use the latest IPCC GWP ratio of 25 for methane, rather than the value of 21 used by the EPA.

[8] *See* Lustgarten, A., *Climate Benefits of Natural Gas May Be Overstated*, Propublica.org, 25 January 2011, at http://www.propublica.org/article/natural-gas-and-coal-pollution-gap-in-doubt. The article asserts that "when all [the] emissions are counted, gas may be as little as 25% cleaner than coal, and perhaps even less."

Another widely publicized paper, by Cornell Professor Robert Howarth and colleagues,[9] draws on the EPA's revised data and other sources to conclude that "3.6% to 7.9% of the methane from shale-gas production escapes to the atmosphere in venting and leaks over the life-time of a well." Using these data, which Howarth et al. admit is "not well documented,"[10] and novel short term (20 year) GWP values for methane that are 46% higher than the most recent values published by the IPCC,[11] the Cornell team concluded that, "the GHG footprint for shale gas is at least 20% greater than and perhaps more than twice as great as that for coal" per unit of energy; [o]ver the 100-year time frame the GHG footprint is comparable to that for coal…."[12]

Howarth et al. stress that the foregoing analysis "does not consider the efficiency of final use" for gas and coal. The paper nevertheless asserts that "even assuming the greater

---

[9] R.W. Howarth, R. Santoro and A. Ingraffa, "Methane and the Greenhouse-Gas Footprint of Natural Gas From Shale Formations." Available at: http://www.eeb.cornell.edu/howarth/Howarth et al 2011.pdf. The paper has been accepted by the journal, *Climatic Change Letters*.

[10] *Id.* p. 4. Notably, 85% of the additional emissions attributable to shale gas wells – put at 1.9% of total output – are estimated from "2 shale gas and 3 tight-sand formations" with that data showing emissions varying from .6% to 3.2% of life time production. *Id.* At Table 1. Howarth et al. do not use any data from 2010 shale gas wells in the Marcellus or other large fields outside Louisiana.

[11] Howarth et. al. assign a GWP value of 105 to methane on a 20-year time horizon and 33 over 100 years (plus or minus 23 percent) based on a single 2009 research paper by a team at NASA's Goddard Institute For Space Studies at Columbia University. *See* D.T. Shindell et. al. "Improved Attribution of Climate Forcing to Emissions. *Science* vol 326: pp. 716-718 (30 October 2009). The Goddard team's revised GWP values for methane are based on a new approach to climate modeling that seeks to account for the potential interaction between methane, ozone precursors and aerosols -- airborne particles such as sulphate molecules. These molecules, produced when sulfur dioxide is oxidized in the atmosphere, have a cooling effect on the climate as they reflect heat but, according to Shindell et al., increased levels of methane lead to chemical reactions that reduce the level of sulphates. Thus, calculations of GWP that include these gas-aerosol linkages substantially increase the value for methane. While we lack the specialized expertise to assess the models from which these results derive, we note that the higher figures estimated by Shindell et. al. stem from a unique modeling exercise (rather than empirical observations) and have yet to be subject to the international peer review that attends revisions of the IPCC's GWP estimates, which are used by the worldwide scientific community for many purposes. Consequently, given the magnitude of the claimed revision in the GWP numbers, and the critical role the GWP values appear to have on the conclusions of Howarth et al. (see note 14 infra), we think it is premature, at best, to accept the Cornell team's work, including its emphasis on 20 year, rather than 100 year, GWP values. At a minimum, Howarth et. al. should present comparative results based on the GWP values currently accepted by the IPCC.

[12] Howarth et. al.. *Id.* P. 3.

efficiency of gas-fired electricity generation the GHG footprint of shale gas approaches or exceeds coal."[13]

This conclusion is suspect for two major reasons, wholly apart from the questionable data used to estimate upstream emissions and the reliance on inflated GWP values.[14]

First, Howarth et al. did not calculate the GHG intensity associated with the combination of gas and coal per kilowatt hour of electricity based on the actual power sector efficiency data used here. Rather, Howarth et. al.'s conclusion was based on theoretical calculation of the amount of CO2 emitted per unit of *fuel energy input*. This theoretical comparison disregards the efficiency advantage of modern gas-fired generation on an *electric energy output* (kilowatt-hour) basis. And the ultimate output – electricity – is all important, of course, when comparing the fuel-cycle emissions for gas and coal because, with limited exception, coal is not combusted for anything other than electricity generation in the U.S.

Second, as Howarth et al. concede, the additional methane emissions associated with shale gas production (that is, flowback leakage from well completion plus "drill out" emissions[15]) "can be reduced by up to 90% through Reduced Emission Completions technologies or (REC)" [16] according to the 2010 EPA technical report cited above. The foregoing document is also supported by recent industry submissions to the EPA regarding the agency's new emissions data. [17]

---

[13] Howarth et al. *Id.*, p 9.

[14] The use of GWP values that are 46% higher than the IPCC values for a 20 year time span appears, in and of itself, to account for the 20% greater GHG footprint Howarth et al. attribute to shale gas versus coal over a 20 year time horizon.

[15] "Drill out" emissions refer to leakage emitted when the well plugs set to separate stages or sections in the horizontal fracking process are drilled out to release gas for production.

[16] Howarth et al *Id.*, p.9.

[17] *See*, for example, El Paso Corp. *El Paso Comments on the Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2009* (2011), letter from Fiji George to U.S. EPA, 25 March 2011, on file with ACSF. One major emission reduction method to reduce flowback leakage involves the uniform application of plunger or artificial lifts to optimize the opening and closing of well shut off valves. In some cases, El Paso notes, state regulation requires pre-production flaring of some gas (which reduces its GHG footprint) when other options are unavailable.

In sum, much of the press generated by the Howarth et al. paper (e.g., "Shale gas 'worse than coal' for climate"[18]) is misleading. The simple fact is that Howarth et al. did not carry out a full national fuel chain assessment of natural gas and coal for electricity generation based upon the relevant metric (e.g., GHG emissions per kilowatt hour generated). Rather, the Cornell team primarily focused on the pre-combustion footprint of shale gas and other fuels. In contrast, this paper looks at emissions from both the production and combustion portion of the fuel chain for natural gas-fired and coal-fired electric power. We proceed as follows.

Analysis

First, we tabulated the impact of the EPA's new change in upstream emission accounting on the fuel chain GHG emissions of natural gas and gas-fired electricity. We then compared gas-fired and coal-fired electricity using a consistent methodology that includes these updated inputs.

Our results show that, while the increase in estimated GHG emissions from gas-fired generation is significant, these emissions are still substantially less per kilowatt-hour (kWh) of electricity than from coal-fired generation. Based on the revised EPA data and average generation heat rates, we find that *existing gas-fired generation is still about 52% less GHG intensive than existing coal-fired generation*, on average. Similarly, a new gas-fired combined-cycle unit produces about 53% less GHG emissions per kWh than a new coal-fired steam unit.

As noted earlier, this analysis compares the effects of different GHGs (e.g., carbon dioxide (CO2), nitrous oxide (N2O) and methane (CH4)) based on the conventional 100 year global warming potential (GWP) established by the U.N.'s Intergovernmental Panel on Climate Change (IPCC). The IPCC chose this convention because CO2 and most

[18] See eg, Richard Black, "Shale gas 'worse than coal' for climate", BBC News, posted 12 April 2011, at http://www.bbc.co.uk/news/science-environment-13053040. See also Tom Zeller Jr., "Studies Say Natural Gas Has Its Own Environmental Problems," New York *Times*, April 11, 2011, at:http://www.nytimes.com/2011/04/12/business/energy-environment/12gas.html?_r=1

other GHGs remain in the atmosphere for 200 years or more. Some analysts adopt shorter term (e.g., 20 year) GWP values to evaluate GHG footprint because certain short-lived GHGs such as methane have a much higher average GWP over that time horizon (e.g., methane has an average atmospheric life of 12 years). However, fuel comparisons based on 20 year GWPs may be counterproductive in weighing the options for stabilizing global GHG emissions over the longer term (e.g., 2030-2100), because they underweighthe consequences of committing to greater emissions from CO2 and other GHGs that, unlike methane, will impact the climate for hundreds of years.

Combustion Emissions: Efficiency and Fuel Carbon

Basic statistics related to the energy used for gas- and coal-fired electricity generation are shown in Table 1.[19] This table uses 2008 data because that was the last year that GHG emissions from natural gas systems were calculated using EPA's older method, enabling a simple comparison with the new estimates.

Table 1. 2008 Electric Generation and CO2 Emission Statistics for Coal and Natural Gas

Fuel	Coal	Natural Gas
Total Combustion CO2 Emissions (million metric tons)	2072	1,224
Electric Generation CO2 Emissions (million metric tons)	1958	362
Net Generation Energy (Quads, or 10^{15} Btu)	20.55	6.80
Fuel Carbon Content (kg-CO2/MMBtu)	95.3	53.2
Average Heat Rate, or Generation Fuel Efficiency (Btu/kWh)	10350	7700
Total Electric Generation (billion kWh)	1986	883
Combustion-Only CO2 Emission Intensity (kg-CO2/kWh)	0.986	0.410

Based on the values shown in Table 1 we see that, on average, natural gas contains 44% less carbon per unit of energy than does coal for power generation.[20] Also, gas-fired

[19] These statistics are derived from U.S. Energy Information Administration (EIA) (2010). *Annual Energy Review 2009*, DOE/EIA-0384 (2009), at http://www.eia.doe.gov/aer/pdf/aer.pdf

[20] While the energy and carbon content of pipeline quality natural gas is uniform throughout the US (1000Btu/cuft), regional steam coal resources vary considerably from 4000 to over 15000 Btu/lb. The coal carbon content value in Table 1 is the average of all coal used for power generation in the U.S. This

electricity generally has a lower heat rate, indicating an efficiency advantage and, on average, uses 26% less energy than coal-fired generation to generate each kWh of electricity.[21] Combining these figures, the CO2 emission intensity for gas-fired generation is 58% lower on average than coal-fired generation. The direct CO2 emissions per kWh are therefore more than twice as high on average for coal-fired power (0.99 kg-CO2/kWh) than for power from gas-fired generation (0.41 kg-CO2/kWh).

Calculating Fuel Chain Emissions

In addition to direct CO2 emissions from fossil fuel combustion, the GHG impact of using a fuel includes emissions of methane and other GHGs upstream in the fuel supply chain, as well as non-CO2 GHGs from combustion. To estimate the fuel chain emissions for power generation, we add emissions of non-combustion CO2 and methane (CH4), expressed as CO2-equivalents (CO2e).[22] Also, we include the CO2-equivalent values of N2O and methane emissions that result, in addition to CO2, from combustion of the fuels. This is not a complete fuel-cycle analysis for these fuels, but it is a consistent accounting of the main GHG sources that are identified in the national inventory.[23]

We add upstream emissions for both coal and natural gas and, in the case of natural gas, compare the old and new EPA estimates, as well as the values used by the US Energy Information Administration (EIA) in the Department of Energy's 2008 GHG Inventory.[24]

---

average is weighted according to the amount of energy generated, by simply dividing total emissions by total fuel energy used for generation in the coal-fired fleet.

[21] Heat rate (efficiency) values for both coal- and gas-fired generation units vary widely. By and large, gas-fired combined-cycle gas turbine (CCGT), which compete directly with coal, are more efficient than coal-fired steam units. Simple-cycle combustion turbines are less efficient and used mostly to meet load peaks.

[22] Tons of CO2e reflect the emissions of all greenhouse gases, accounting for the varying atmospheric lifetimes and radiative forcing power of the gases including CO2, N2O, methane (CH4) and others. CO2e is thus the equivalent number of tons of CO2 alone that would cause the same total radiative forcing, integrated over a 100-year time horizon. Because we use the more recent IPCC Fourth Assessment Report (2007) data [in which the GWP for methane is 25] rather than the Second Assessment Report (1995) data used in EPA's national GHG inventory [in which the GWP for methane was 21] our estimates of the CO2e values for methane are about 20% higher than those reported in the EPA documents cited here. Values for N2O are nearly unchanged between the two sources.

[23] Of the potential fuel chain GHG emissions sources not included here, the most significant is likely to be CO2 emissions from energy use in the production and transport of the fuels (e.g., pipeline compressors, coal trucks).

[24] U.S. Energy Information Administration (EIA). *Emissions of Greenhouse Gas in the United States 2008* (2009), DOE/EIA-0573, at http://www.eia.doe.gov/oiaf/1605/ggrpt/pdf/0573(2008).pdf

We sought to explore the implications of the potential range of results from using these uncertain data, without concluding here that one data set is necessarily more accurate than another. For example, detailed fuel-cycle emission studies have shown lower GHG emissions for natural gas than the EPA inventory results.[25] Moreover, if further research lowers the EPA's recent estimates of methane emissions from gas production, as some industry critics suggest, the resulting fuel chain GHG intensity values will also lie within the range that we explore here.

Our calculations are summarized in Table 2. First, since upstream emissions result from producing coal and gas that is used by consumers other than for electric generation, we need to allocate these emissions according to the total consumption of each fuel. We divide the sum of reported upstream emissions of CO2 (Line 3) in the natural gas fuel chain (from flaring and venting) and methane (Line 4) in both coal and natural gas fuel chains by the total CO2 emissions from combustion of each fuel (Line 1). The resulting ratio in Line 5 is about 4% for coal, and 12-23% for gas, depending on the data source.

Table 2. Estimation of 2008 Fuel Chain GHG Emissions from Coal- and Natural-Gas-Fired Electric Generation, with Comparison of Data Sources

Fuel	**Coal**	**Natural Gas (under Different Inventory Data Sources)**		
GHG Data Source	**EPA**	**EIA**	**EPA**	**EPA**
Inventory Version	**2008-revised**	**2008**	**2008**	**2008-revised**
1. Total Combustion CO2 Emissions (million metric tons)	2072	1,242	1,227	1,224
2. Electric Generation CO2 Emissions (million metric tons)	1958	362	362	362
3. Upstream Fuel Chain CO2 Emissions (million metric tons)	0	0	30	33
4. Upstream CH4 Emissions as CO2e (million metric tons) GWP = 25	80	213	115	252
5. Upstream CO2e Emissions as % of Total Combustion CO2 Emissions	**3.9%**	**17.1%**	**11.9%**	**23.4%**
6. Electric Generation CH4 Emissions as CO2e (million metric tons) GWP = 25	0.5	0.1	0.1	0.1
7. Electric Generation N2O Emissions as CO2e (million metric tons)	9.6	0.2	0.2	0.2
8. CH4/N2O CO2e Emissions as % of Generation CO2 Emissions	**0.5%**	**0.1%**	**0.1%**	**0.1%**

[25] *See* National Energy Technology Laboratory (NETL). *Life Cycle Analysis: Power Studies Compilation Report* (2010), at http://www.netl.doe.gov/energy-analyses/pubs/PowerLCA_Comp_Rep.pdf

9. Total Upstream + non-CO2 Emissions as % of Generation CO2 Emissions	**4.4%**	**17.2%**	**11.9%**	**23.4%**
10. Total Electric Generation CO2e Emissions (million metric tons)	**2044**	**424**	**405**	**446**
11. Fuel-based GHG Intensity (kg-CO2e/MMBtu)	**99.4**	**62.4**	**59.5**	**65.6**
12. Total Electric Generation (billion kWh)	1986	883	883	883
13. Combustion-Only CO2 Emission Intensity (kg-CO2/kWh)	0.986	0.410	0.410	0.410
14. Combustion + Fuel Chain GHG Emission Intensity (kg-CO2e/kWh)	**1.029**	**0.481**	**0.459**	**0.505**

Next, since combustion emissions of methane (Line 6) and N2O (Line 7) are reported specifically for power generation, we divide these emissions by the total CO2 emissions from combustion of both coal and natural gas fuel for power generation (Line 2). The resulting ratio in Line 8 is 0.5% for coal, and 0.1% for gas. These two ratios (Lines 5 and 8) are then added together to get the ratio in Line 9, "Total Upstream + non-CO2 Emissions as % of Generation CO2 Emissions", which is then added to 100% and multiplied by Line 2 to arrive at Line 10, "Total Electric Generation CO2e Emissions" for both coal and natural gas power generation.[26]

After one accounts for the upstream and non-CO2 GHG emissions reported in the 2011 EPA inventory in terms of CO2e, fuel chain emissions from coal-fired generation are increased 4.4%, compared to combustion CO2 emissions only (the ratio in Table 2, Line 9). The GHG emissions due to methane losses from mining add about 4% to the CO2e values for coal,[27] and methane and N2O emissions from stationary combustion add about 0.5% to the CO2e values for coal.

Fuel chain GHG emissions from gas-fired generation are increased by 23.4% using the most recent EPA data, which roughly doubles the upstream and non-combustion GHG

[26] Methane emissions in our analysis are based on a 100 year global warming potential value of 25 and are thus about 20% higher than the values reported in the EPA and EIA source documents, all of which use a GWP for methane of 21. The higher (25) GWP value for methane accords with the values adopted by the most recent IPCC Fourth Assessment; *See* note 2 *supra* Chapter 2, Table 2.14, p.212.

[27] We exclude methane emissions from abandoned coal mines in our estimates of coal fuel chain emissions.

emissions compared to the previous EPA inventory. The GHG emissions due to methane losses from the gas production and transportation system add about 20% to the CO_2e values for natural gas, while CO_2 releases from production add about 3%. Methane and N_2O emissions from stationary combustion add an insignificant amount. Note that data from the EIA inventory yield CO_2e estimates between the two EPA results, and that EIA used upstream methane emission values that are closer to the revised, higher EPA values.

Comparing Fuel Chain GHG Emissions from Natural Gas and Coal

These additional fuel chain GHG emissions raise the CO_2e emission estimates for both coal- and gas-fired generation. The fuel chain GHG intensity of coal as a fuel is 99.4 kg-CO_2e/MMBtu (see Table 2, Line 11), compared to a combustion-only CO_2 intensity of 95.3 kg-CO_2e/MMBtu, which represents the carbon content of the fuel itself. Accounting for the revised, but unconfirmed, EPA upstream methane emissions data, the fuel chain GHG intensity of natural gas as a fuel increases, from 59.5 kg-CO_2e/MMBtu to 65.6 kg-CO_2e/MMBtu (see Table 2, Line 11), based on a combustion-only CO_2 intensity of 53.2 kg-CO_2/MMBtu. These fuel-related emission intensities do not account for differences in the efficiencies with which the fuels are used, for example to generate electricity.

Taking efficiencies (heat rates) for electricity generation into account, the emission-intensity difference between coal and natural gas is amplified. Based on the revised EPA data and average generation heat rates, gas-fired generation is still less than half as GHG intensive in CO_2-equivalent terms, with a fuel chain GHG intensity of 0.51 kg-CO_2e/kWh, compared to coal, with a GHG intensity of 1.03 kg-CO_2e/kWh, a 51% difference (see Table 2, Line 14). Note that the incremental increase in the GHG intensity of gas-fired generation from EPA's data revisions, from 0.46 kg-CO_2e/kWh to 0.51 kg-CO_2e/kWh, represents about 4.5% of the GHG intensity of coal-fired generation.

Emission estimates and GHG intensities shown in Table 2 are based on average generation efficiency values for coal- and gas-fired generation. It is also instructive to consider fuel chain GHG emissions from new, more efficient generation units, and also for older coal-fired plants. These plants are now at risk of retirement, due to the cost of compliance with pending environmental regulations on SO2, NOx, mercury, coal ash waste and cooling (not to mention possible GHG regulation). How much GHG emissions would closing these units save? Table 3 compares each of these cases.

Table 3. Fuel Chain GHG Emissions by Generation Unit Type and Fuel

Generation Plant Type	Fuel-based GHG Intensity (kg-CO2e/MMBtu)	Heat Rate (Btu/kWh)	Electricity-based GHG Intensity (kg-CO2e/kWh)
New Gas-Fired Combined Cycle	65.6	6,500	0.427
Average Existing Gas-Fired Unit	65.6	7,700	0.505
New Coal-Fired Steam Unit	99.4	9,000	0.895
Average Existing Coal-Fired Unit	99.4	10,350	1.029
Older, At-Risk Coal-Fired Unit	99.4	11,750	1.168

The values in Table 3 show that today's average gas-fired generation unit produces about 44% less GHG emissions per kWh than a new coal-fired unit, about 51% less than the average coal-fired unit (as noted above), and about 57% less than a typical older, out-of-compliance coal-fired unit. A new gas-fired combined-cycle unit produces about 52% less GHG emissions per kWh than a new coal-fired unit, about 58% less than the average coal-fired unit, and about 63% less than a typical older, out-of-compliance coal-fired unit.

Conclusions

On average, our paper shows that ,using the most current U.S. national inventory data, and standard international assumptions on the relevant time horizon for estimating the GWP of methane and other GHGs, the large comparative GHG advantage of natural gas-fired power plants continues to outweigh the negative GHG impact from the estimated rates of methane leakage from natural gas production.

The EPA's large upward revision of estimated methane leakage rates from natural gas production is attributable primarily to new fugitive emissions from unconventional production (i.e., largely shale gas), and gas from these wells currently accounts for a small portion (approximately 20%) of total US production. Some natural gas producers have criticized the revised EPA methane emission estimates, contending that they are now unrealistically high.[28] Even researchers who believe that the revised EPA estimates

[28] El Paso Corp. 2011, *op. cit*.

of fugitive emissions from unconventional production are too low acknowledge that the industry can reduce such leakages by up to 90% using available technologies.

Consequently, even if the percentage of shale gas production increases to a third or more of total U.S. output, so long as the industry adopts available best practices, we expect that natural gas-fired electric power will retain its large comparative advantage in fuel chain GHG emissions over coal-fired generation.