NATIONAL ENERGY TECHNOLOGY LABORATORY

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

Timothy J. Skone, P.E.
Office of Strategic Energy Analysis and Planning

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U.S. DEPARTMENT OF ENERGY

Overview

1. Who is NETL?
2. What is the role of natural gas in the United States?
3. Who uses natural gas in the U.S.?
4. Where does natural gas come from?
5. What is the life cycle GHG footprint of domestic natural gas extraction and delivery to large end-users?
6. How does natural gas power generation compare to coal-fired power generation on a life cycle GHG basis?
7. What are the opportunities for reducing GHG emissions?

Question #1:

Who is NETL?

National Energy Technology Laboratory

MISSION
Advancing energy options to fuel our economy, strengthen our security, and improve our environment

Oregon

Pennsylvania

West Virginia

Question #2:

What is the role of natural gas in the United States?

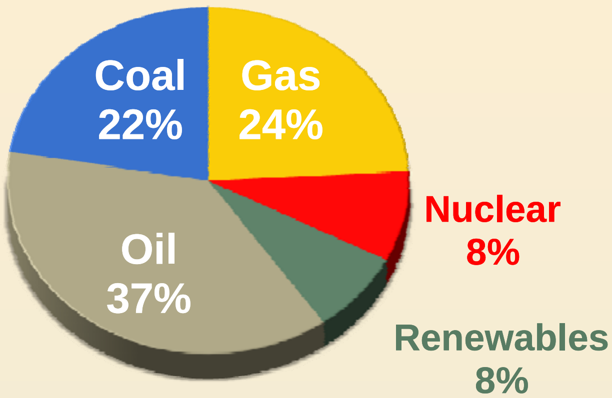
Energy Demand 2008

Energy Demand 2035

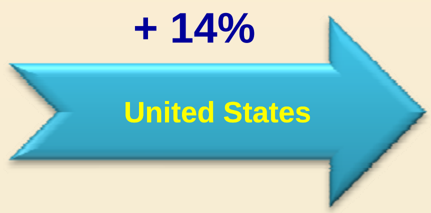
United States

2008

100 QBtu / Year
84% Fossil Energy

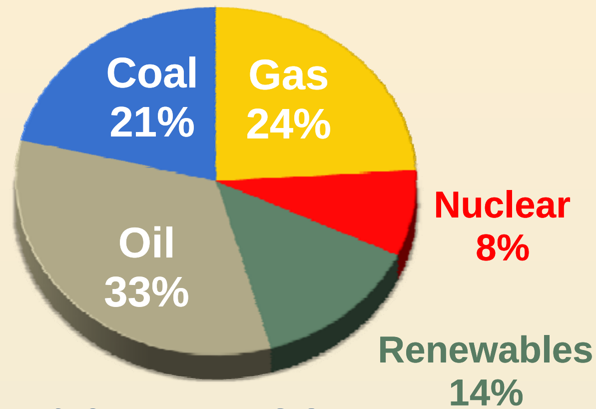


5,838 mmt CO_2



2035

114 QBtu / Year
78% Fossil Energy

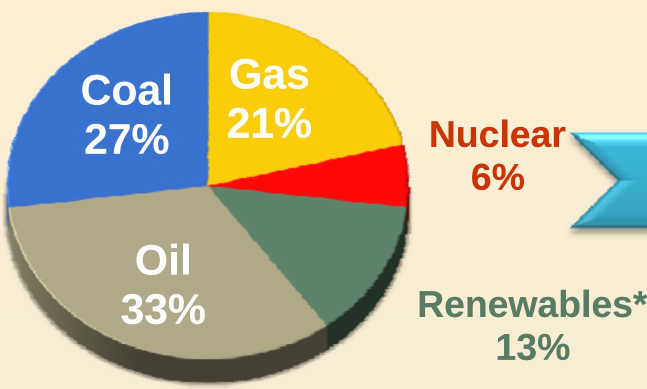


6,311 mmt CO_2

World

2008

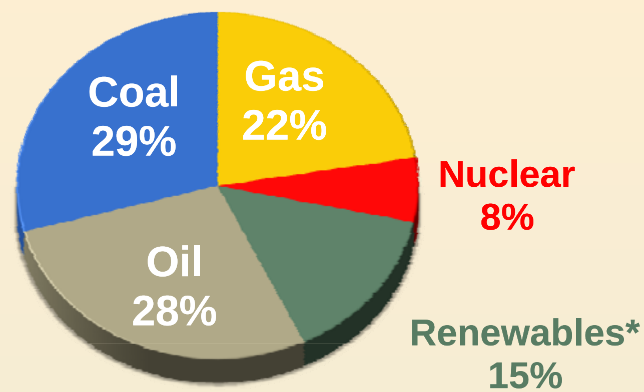
487 QBtu / Year
81% Fossil Energy



29,259 mmt CO_2

2035

716 QBtu / Year
79% Fossil Energy



42,589 mmt CO_2

Sources: U.S. data from EIA, Annual Energy Outlook 2011; World data from IEA, World Energy Outlook 2010, Current Policies Scenario

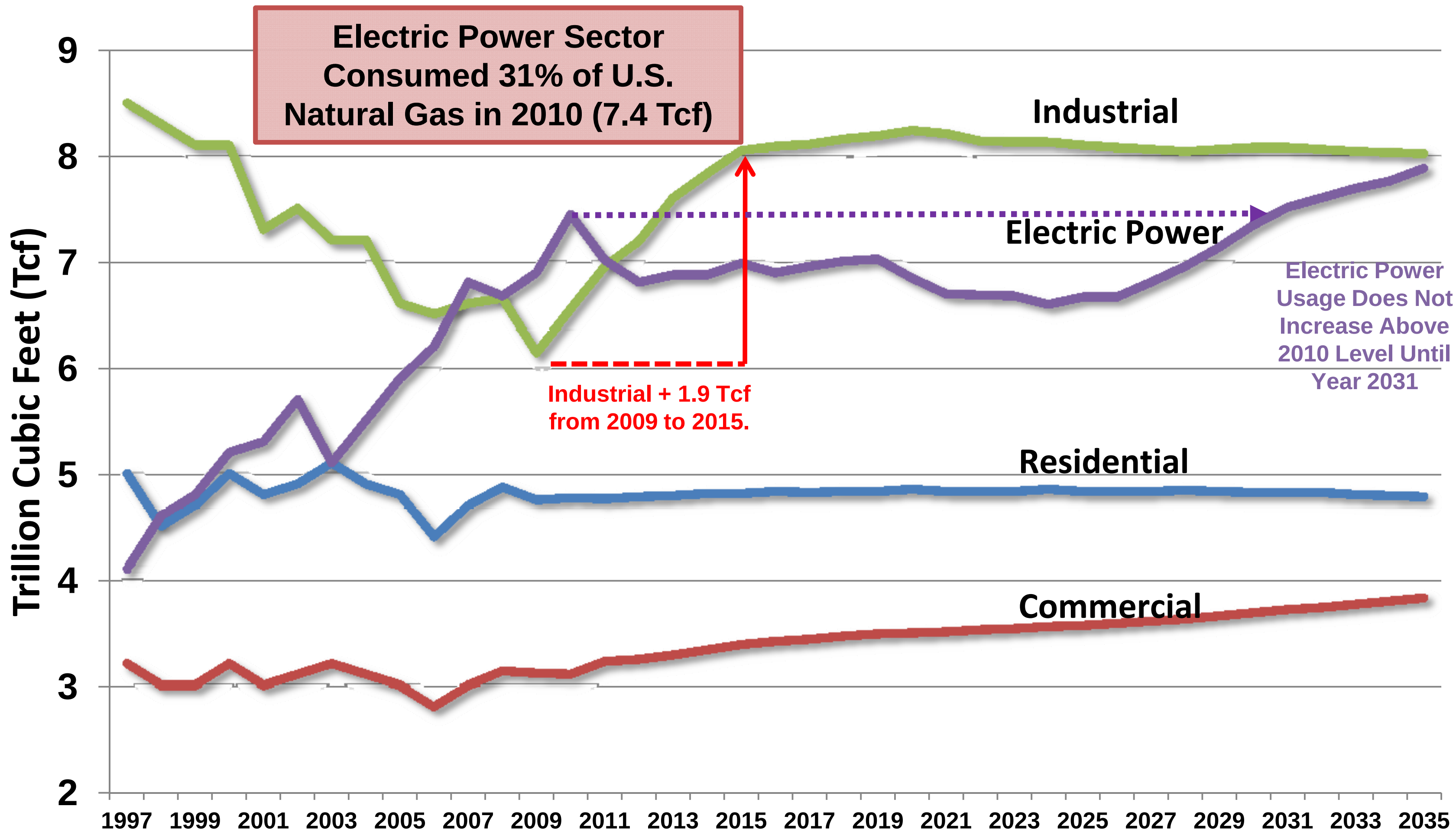
* Primarily traditional biomass, wood, and waste.

Question #3:

Who uses natural gas in the United States?

Domestic Natural Gas Consumption

Sectoral Trends and Projections: 2010 Total Consumption = 23.8 Tcf



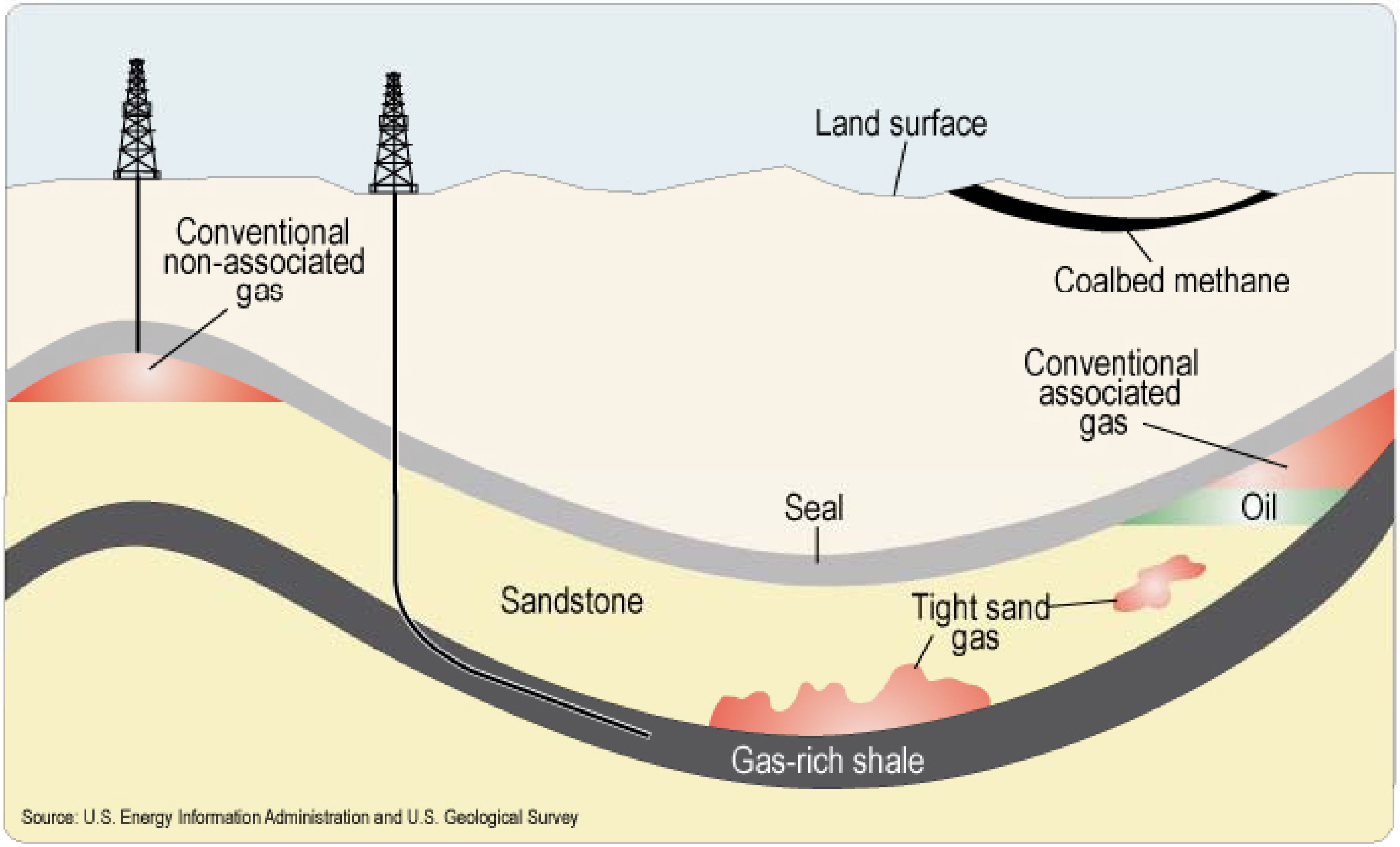
+1.9 Tcf Resurgence in Industrial Use of Natural Gas by 2015 Exceeds the Net Incremental Supply; No Increase in Natural Gas Use for Electric Power Sector Until 2031

Source: EIA Annual Energy Review 2009 and Annual Energy Outlook 2011

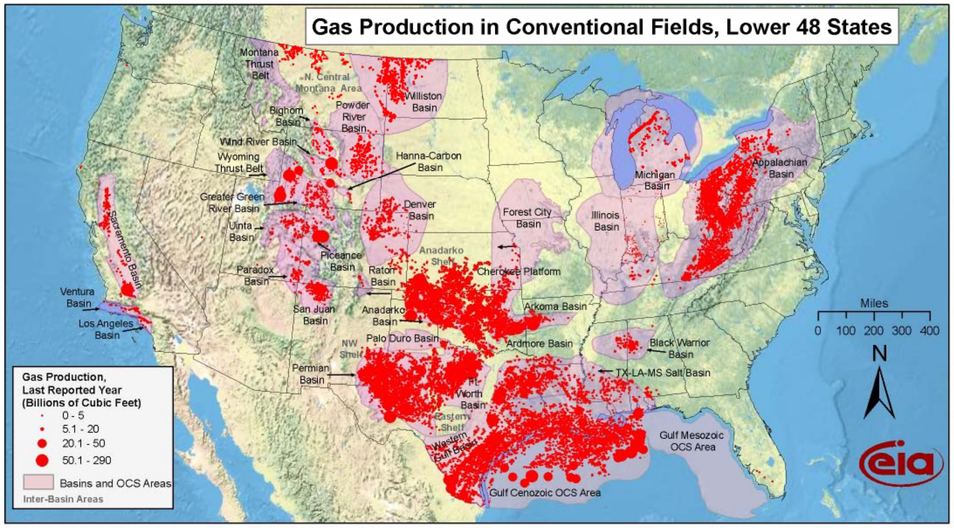
Question #4:

Where does natural gas come from?

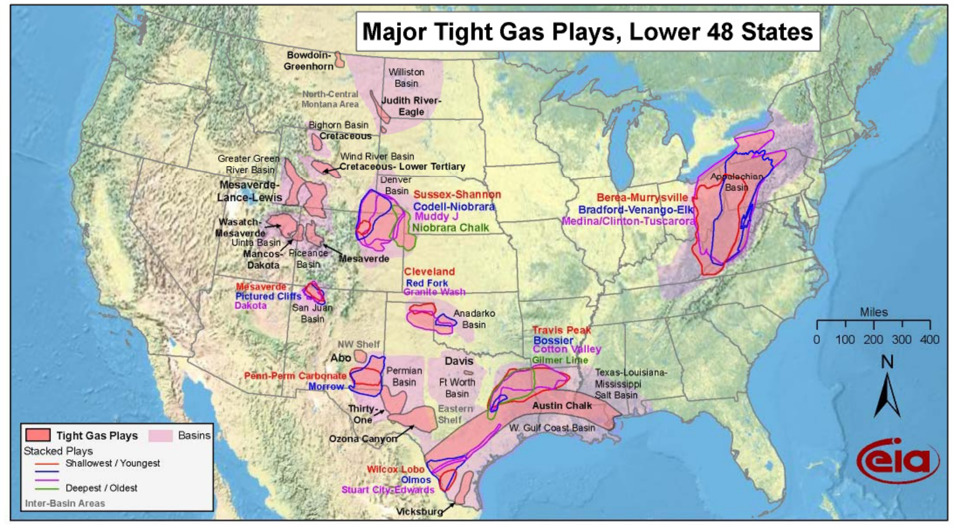
Schematic Geology of Onshore Natural Gas Resources



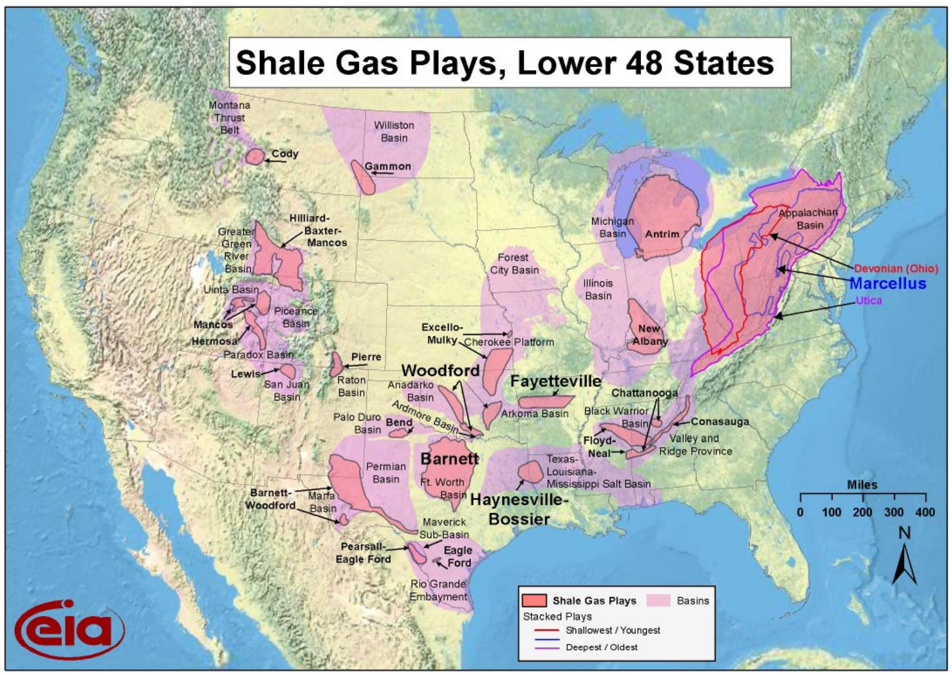
Source: EIA, Today in Energy, February 14, 2011; Modified USGS Figure from Fact Sheet 0113-01; www.eia.doe.gov/todayinenergy/detail.cfm?id=110 Last Accessed May 5, 2011.



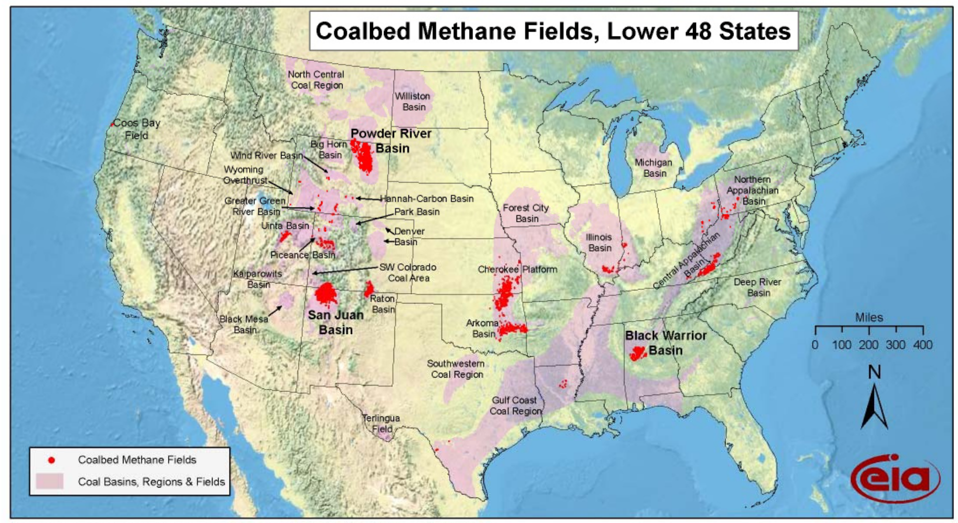
Source: Energy Information Administration based on data from HPDI, IN Geological Survey, USGS
Updated: April 8, 2009



Source: Energy Information Administration based on data from various published studies
Updated: June 6, 2010



Source: Energy Information Administration based on data from various published studies.
Updated: March 10, 2010



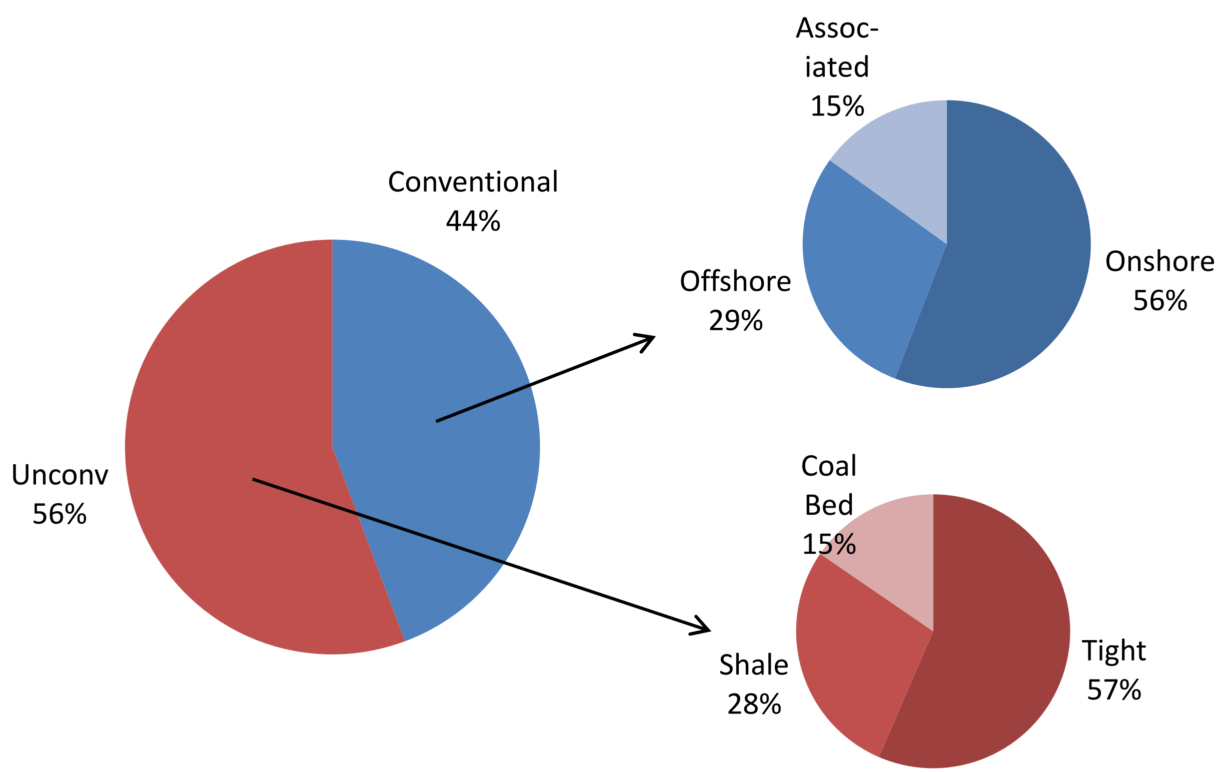
Source: Energy Information Administration based on data from USGS and various published studies
Updated: April 8, 2009

EIA Natural Gas Maps

Source: EIA, Natural Gas Maps, http://www.eia.doe.gov/pub/oil_gas/natural_gas/analysis_publications/maps/maps.htm Last Accessed May 5, 2011.

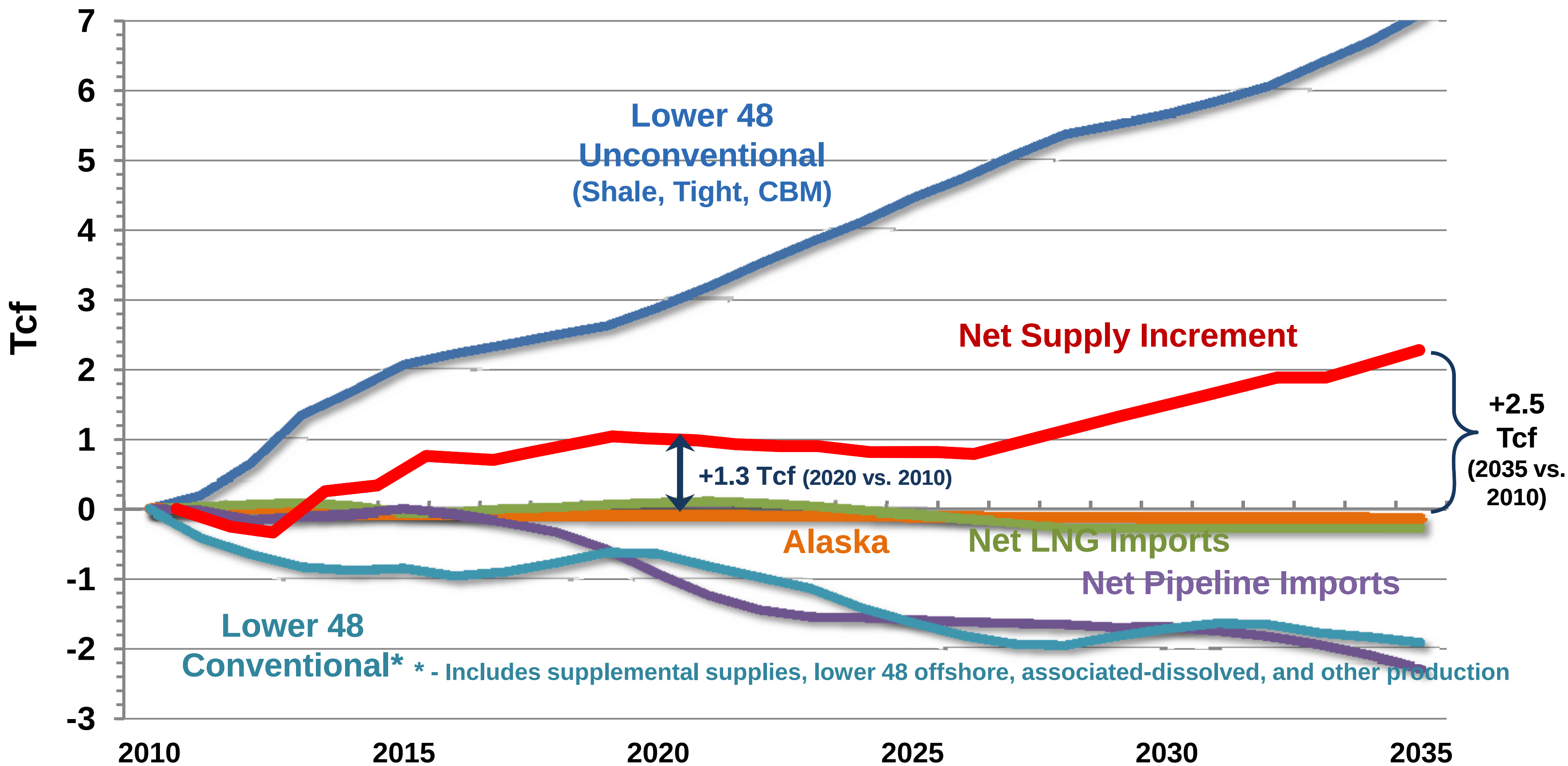
U.S. Domestic Natural Gas Extraction

2009 domestic production was 21.0 Tcf; over half was unconventional natural gas production



Sources of Incremental Natural Gas Supply

(Indexed to 2010)



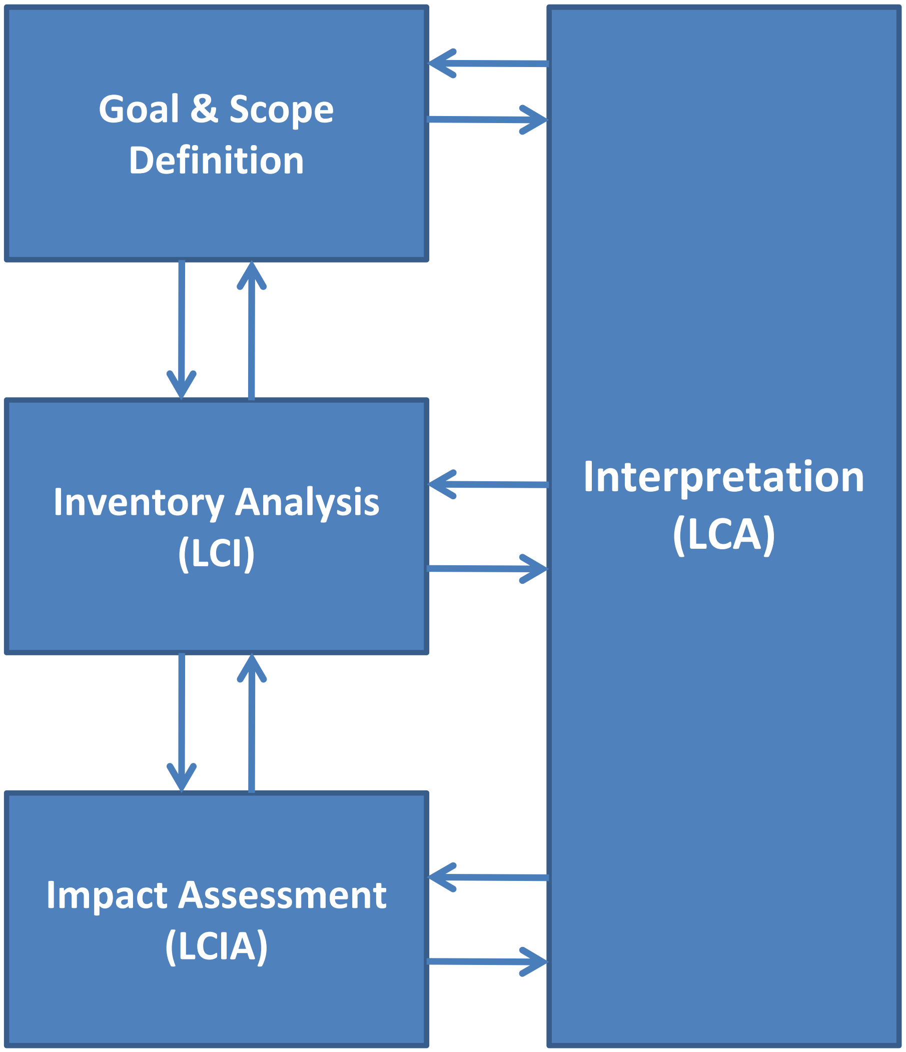
Unconventional Production Growth Offset by Declines in Conventional Production and Net Pipeline Imports; 1.3 Tcf Increment by 2020 Does Not Support Significant Coal Generation Displacement

Source: EIA, Annual Energy Outlook 2011

Question #5:

What is the life cycle GHG footprint of domestic natural gas extraction and delivery to large end-users?

Overview: Life Cycle Assessment Approach



The Type of LCA Conducted Depends on Answers to these Questions:

1. What Do You Want to Know?

2. How Will You Use the Results?

International Organization for Standardization (ISO) for LCA

- ISO 14040:2006 Environmental Management – Life Cycle Assessment – Principles and Framework
- ISO 14044 Environmental Management – Life Cycle Assessment – Requirements and Guidelines
- ISO/TR 14047:2003 Environmental Management – Life Cycle Impact Assessment – Examples of Applications of ISO 14042
- ISO/TS 14048:2002 Environmental Management – Life Cycle Assessment – Data Documentation Format

Source: ISO 14040:2006, Figure 1 – Stages of an LCA (reproduced)

Overview: Life Cycle Assessment Approach

The Type of LCA Conducted Depends on Answers to these Questions :

1. **What Do You Want to Know?**
   - The GHG footprint of natural gas, lower 48 domestic average, extraction, processing, and delivery to a large end-user (e.g., power plant)
   - The comparison of natural gas used in a baseload power generation plant to baseload coal-fired power generation on a lbs CO_2e/MWh basis

2. **How Will You Use the Results?**
   - Inform research and development activities to reduce the GHG footprint of both energy feedstock extraction and power production in existing and future operations

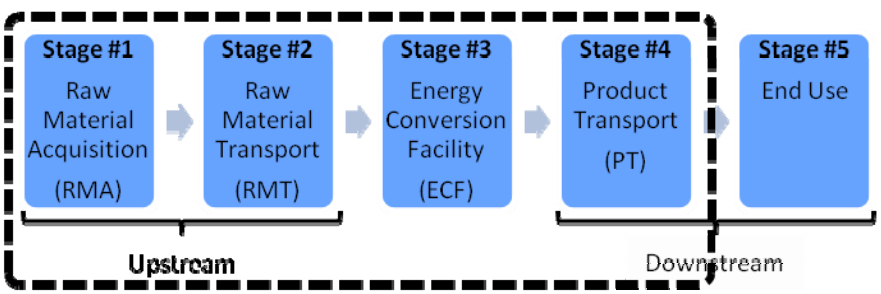
Life Cycle Greenhouse Gas Inventory Boundaries and Functional Units

LCA: Compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product or service throughout its life cycle, from raw material acquisition to the final disposal

Cradle-to-grave

- 1 MWh of electricity delivered to the end customer
- Compared 12 different fuel/baseload plant combinations

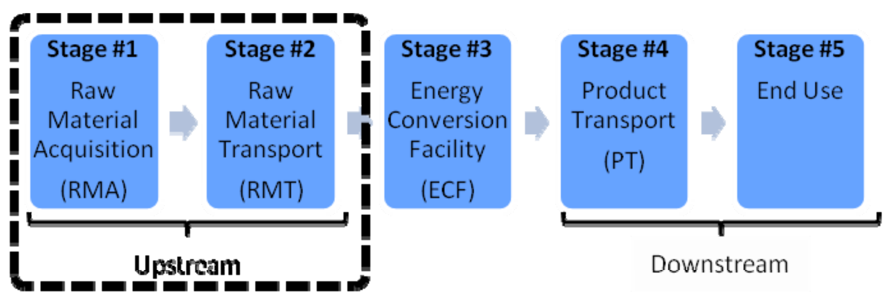
  (6 natural gas, 6 coal)



Cradle-to-gate

- 1 MMBtu of domestic fuel delivered to large end user
- Compared 13 fuel sources/mixes

  (10 natural gas, 3 coal)



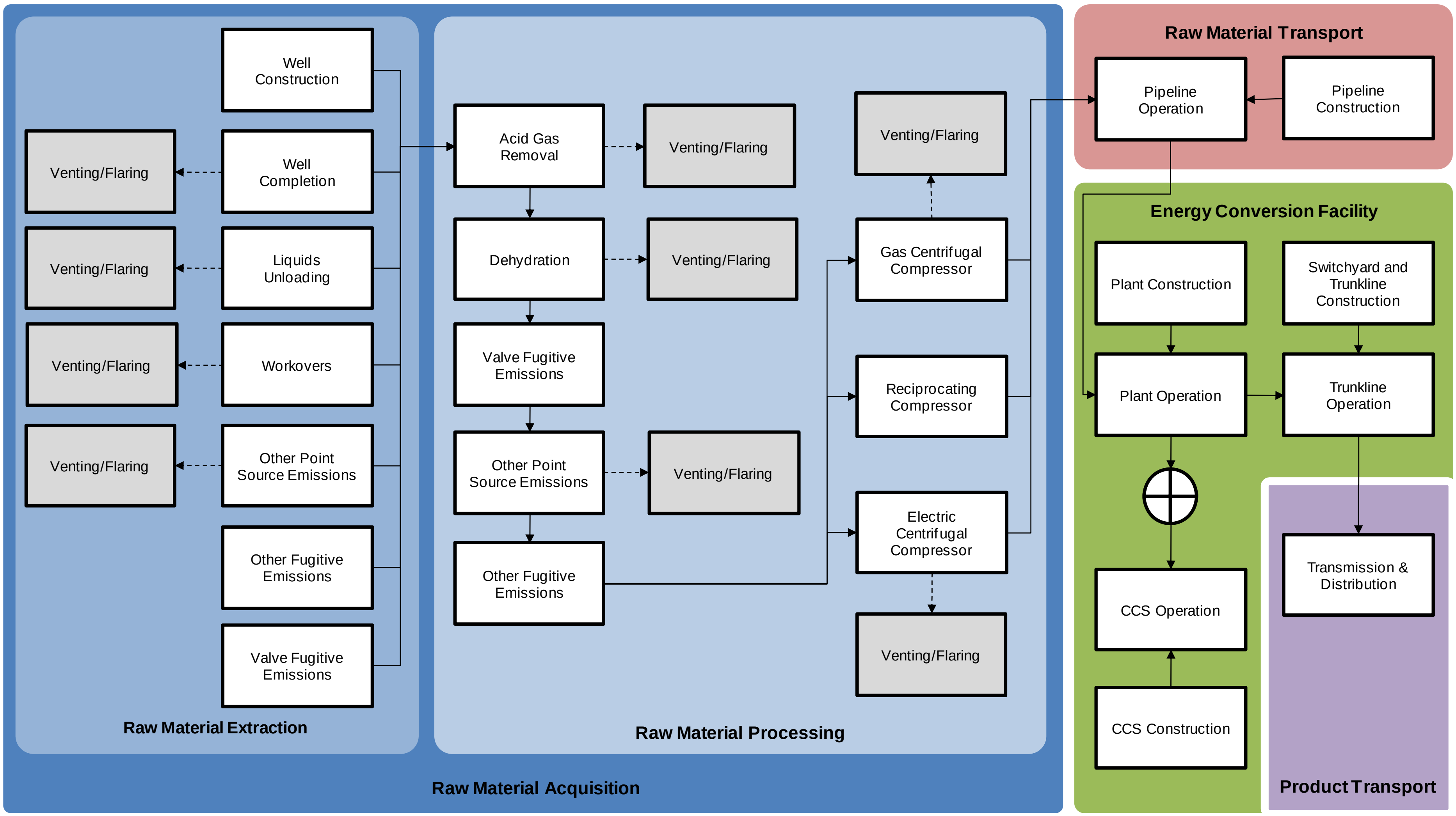
NETL Life Cycle Study Metrics

- **Greenhouse Gases**
  - CO_2, CH_4, N_2O, SF_6
- **Criteria Air Pollutants**
  - NO_X, SO_X, CO, PM10, Pb
- **Air Emissions Species of Interest**
  - Hg, NH_3, radionuclides
- **Solid Waste**
- **Raw Materials**
  - Energy Return on Investment
- **Water Use**
  - Withdrawn water, consumption, water returned to source
  - Water Quality
- **Land Use**
  - Acres transformed, greenhouse gases

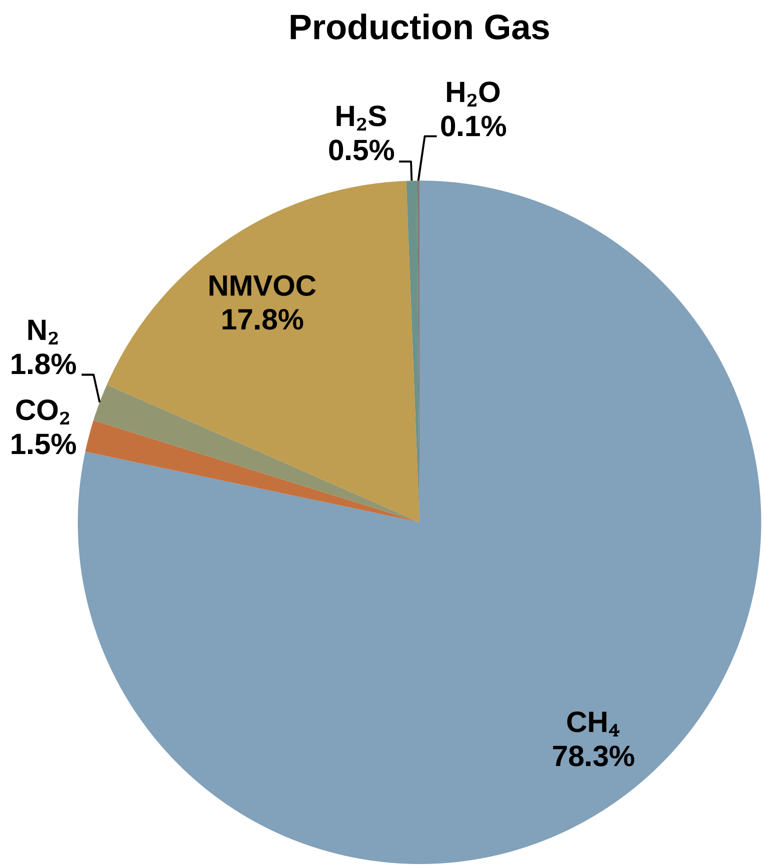
Converted to Carbon Dioxide equivalents using 2007 IPCC Global Warming Potential (GWP)

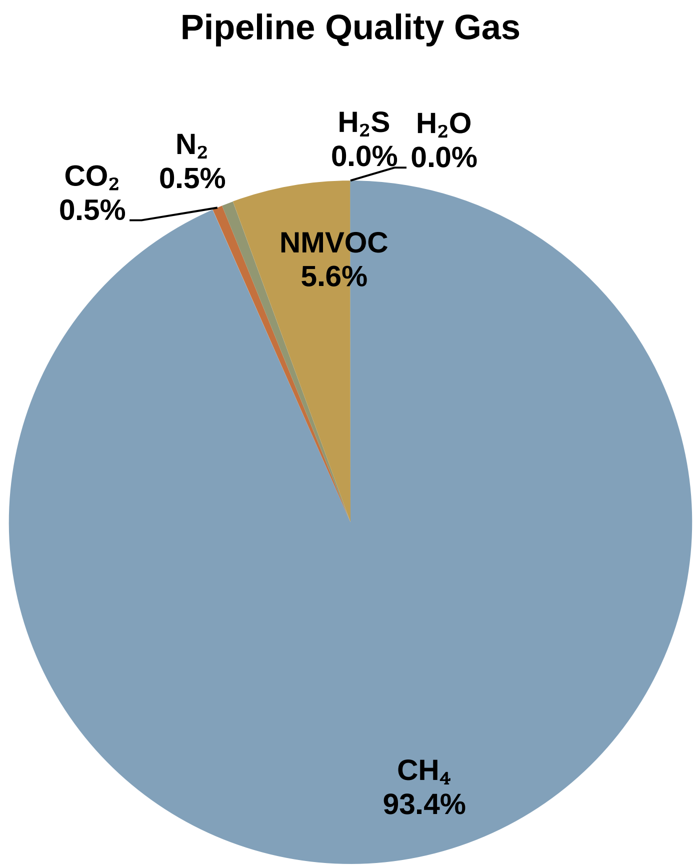
GHG	20-year	100-year (Default)	500-year
CO_2	1	1	1
CH_4	72	25	7.6
N_2O	289	298	153
SF_6	16,300	22,800	32,600

NETL Life Cycle Model for Natural Gas



Natural Gas Composition by Mass





Carbon content (75%) and energy content (1,027 btu/cf) of pipeline quality gas is very similar to raw production gas (within 99% of both values)

Natural Gas Extraction Modeling Properties

Property	Units	Onshore	Associated	Offshore	Tight Sands	Shale	Coal Bed Methane
Natural Gas Source							
Contribution to 2009 Natural Gas Mix	Percent	24.8%	6.7%	12.9%	31.4%	15.6%	8.6%
Production Rate (30-yr average)	MCF/day	66 (46-86)	121 (85-157)	2,800 (1,960-3,641)	110 (77-143)	274 (192-356)	105 (73-136)
Natural Gas Extraction Well							
Flaring Rate at Extraction Well Location	Percent	51% (41-61%)			15% (12-18%)		
Well Completion, Production Gas (prior to flaring)	MCF/completion	47			4,657	11,643	63
Well Workover, Production Gas (prior to flaring)	MCF/workover	3.1			4,657	11,643	63
Well Workover, Number per Well Lifetime	Workovers/well	1.1			3.5	3.5	3.5
Liquids Unloading, Production Gas (prior to flaring)	MCF/episode	23.5	n/a	23.5	n/a	n/a	n/a
Liquids Unloading, Number per Well Lifetime	Episodes/well	930	n/a	930	n/a	n/a	n/a
Pneumatic Device Emissions, Fugitive	lb CH_4/MCF	0.11		0.0001	0.11		
Other Sources of Emissions, Point Source (prior to flaring)	lb CH_4/MCF	0.003		0.002	0.003		
Other Sources of Emissions, Fugitive	lb CH_4/MCF	0.043		0.010	0.043		

Natural Gas Processing Plant Modeling Properties

Property	Units	Onshore	Associated	Offshore	Tight Sands	Shale	Coal Bed Methane
Acid Gas Removal (AGR) and CO_2 Removal Unit							
Flaring Rate for AGR and CO_2 Removal Unit	Percent	100%					
Methane Absorbed into Amine Solution	lb CH_4/MCF	0.04					
Carbon Dioxide Absorbed into Amine Solution	lb CO_2/MCF	0.56					
Hydrogen Sulfide Absorbed into Amine Solution	lb H_2S/MCF	0.21					
NMVOC Absorbed into Amine Solution	lb NMVOC/MCF	6.59					
Glycol Dehydrator Unit							
Flaring Rate for Dehydrator Unit	Percent	100%					
Water Removed by Dehydrator Unit	lb H_2O/MCF	0.045					
Methane Emission Rate for Glycol Pump & Flash Separator	lb CH_4/MCF	0.0003					
Pneumatic Devices & Other Sources of Emissions							
Flaring Rate for Other Sources of Emissions	Percent	100%					
Pneumatic Device Emissions, Fugitive	lb CH_4/MCF	0.0003					
Other Sources of Emissions, Point Source (prior to flaring)	lb CH_4/MCF	0.02					
Other Sources of Emissions, Fugitive	lb CH_4/MCF	0.03					

Natural Gas Processing Plant Modeling Properties

Property	Units	Onshore	Associated	Offshore	Tight Sands	Shale	Coal Bed Methane
Natural Gas Compression at Gas Plant							
Compressor, Gas-powered Combustion, Reciprocating	Percent	100%	100%		100%	75%	100%
Compressor, Gas-powered Turbine, Centrifugal	Percent			100%			
Compressor, Electrical, Centrifugal	Percent					25%	

Natural Gas Transmission Modeling Properties

Property	Units	Onshore	Associated	Offshore	Tight Sands	Shale	Coal Bed Methane
Natural Gas Emissions on Transmission Infrastructure							
Pipeline Transport Distance (national average)	Miles	604 (483 – 725)					
Transmission Pipeline Infrastructure, Fugitive	lb CH_4/MCF-Mile	0.0003					
Transmission Pipeline Infrastructure, Fugitive (per 604 miles)	lb CH_4/MCF	0.18					
Natural Gas Compression on Transmission Infrastructure							
Distance Between Compressor Stations	Miles	75					
Compression, Gas-powered Reciprocating	Percent	78%					
Compression, Gas-powered Centrifugal	Percent	19%					
Compression, Electrical Centrifugal	Percent	3%					

Uncertainty Analysis Modeling Parameters

Parameter	Units	Scenario	Onshore	Associated	Offshore	Tight Sands	Shale	Coal Bed Methane
Production Rate	MCF/day	Low	46(-30%)	85 (-30%)	1,960 (-30%)	77 (-30%)	192 (-30%)	73 (-30%)
		Nominal	**66**	**121**	**2,800**	**110**	**274**	**105**
		High	86 (+30%)	157 (+30%)	3,641 (+30%)	143 (+30%)	356 (+30%)	136 (+30%)
Flaring Rate at Well	%	Low	41% (-20%)			12% (-20%)		
		Nominal	**51%**			**15%**		
		High	61% (+20%)			18% (+20%)		
Pipeline Distance	miles	Low	483 (-20%)					
		Nominal	**604**					
		High	725 (+20%)					

Error bars reported are based on setting each of the three parameters above to the values that generate the lowest and highest result.

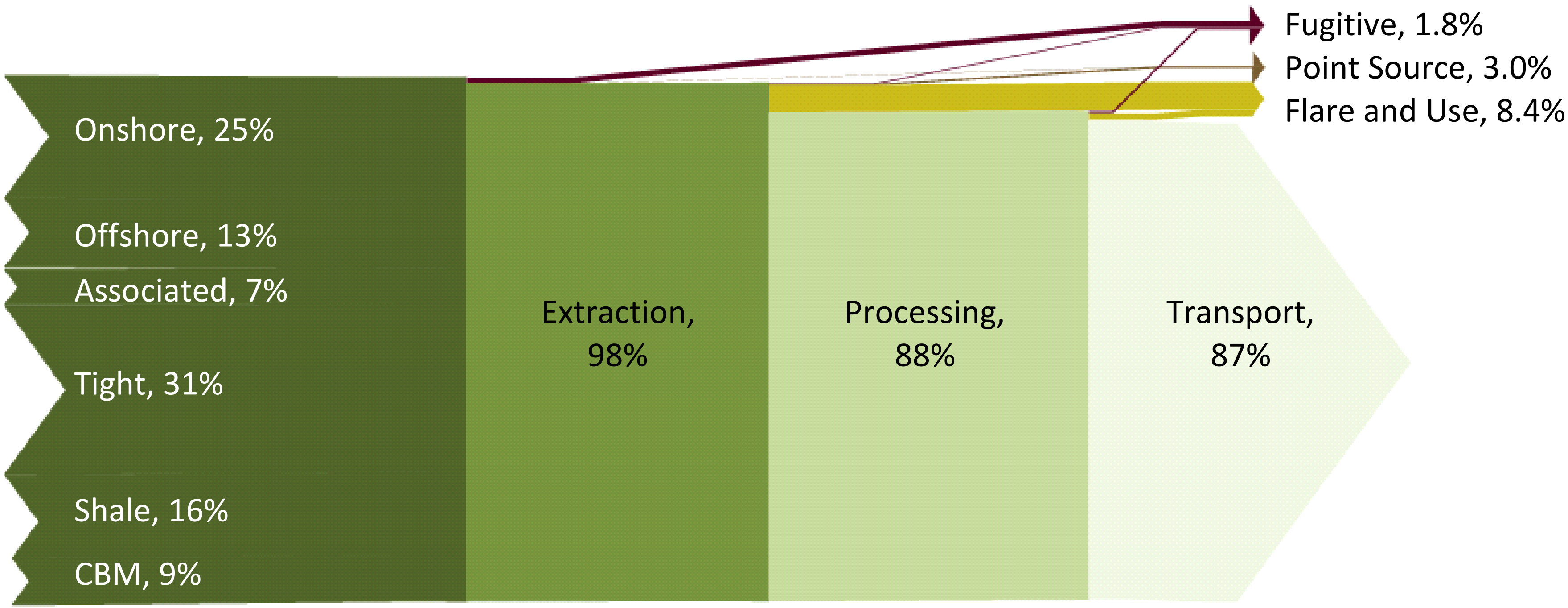
Note: "Production Rate" and "Flaring Rate at Well" have an inverse relationship on the effect of the study result. For example to generate the lower bound on the uncertainty range both "Production Rate" and "Flaring Rate Well" were set to "High" and "Pipeline Distance" was set to "Low".

NETL vs. EPA 2011 GHG Inventory Modeling Assumptions

Property	Units	NETL						EPA	
		Onshore	Associated	Offshore	Tight Sands	Shale	CBM	Conv.	Unconv.
Contribution to 2009 Mix	Percent	25%	7%	13%	31%	16%	9%	n/a	n/a
Production Rate (30-yr average)	Mcf/day	66	121	2,800	110	274	105	n/a	n/a
Active Wells (2007)	Count	n/a	n/a	n/a	n/a	n/a	n/a	431,035	41,790
Flaring Rate at Well	Percent	51%	51%	51%	15%	15%	51%	51%	51%
Completion Emissions	Mcf CH_4/episode	36.7	36.7	36.7	3,670	9,175	49.6	36.7	9,175
Workover Emissions	Mcf CH_4/episode	2.5	2.5	2.5	3,670	9,175	49.6	2.5	9,175
Workover Frequency	Episodes/year	0.04	0.04	0.04	0.12	0.12	0.12	0.04	0.12
Liquids Unloading Emissions	Mcf CH_4/episode	18.5	n/a	18.5	n/a	n/a	n/a	18.5	n/a
Liquids Unloading Frequency	Episodes/year	31	n/a	31	n/a	n/a	n/a	31	31

Accounting for Natural Gas from Extraction thru Delivery to a Large End-User

(Percent Mass Basis)

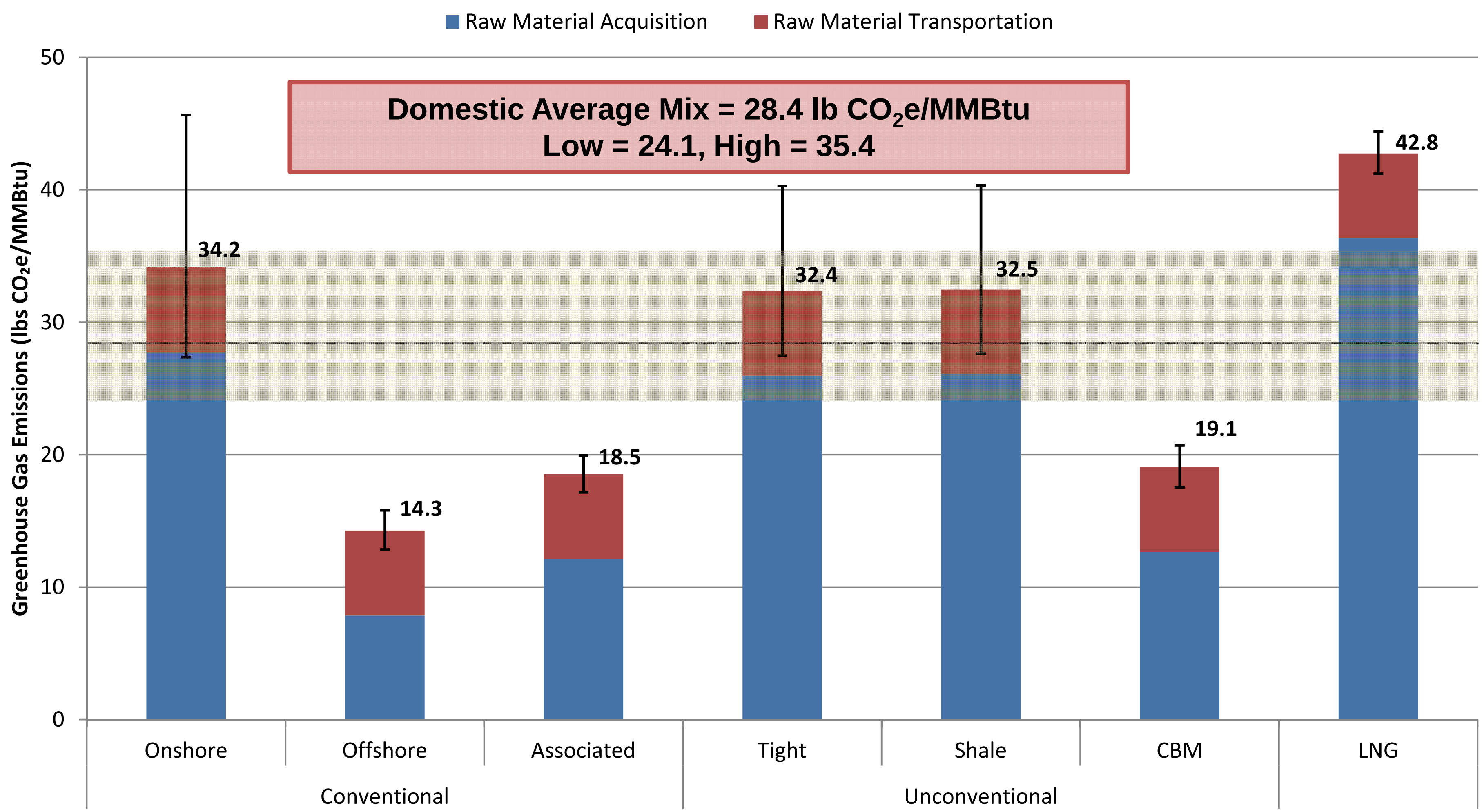


Natural Gas Resource Table	Raw Material Acquisition		Raw Material Transport	Cradle-to-Gate Total:
	Extraction	Processing		
Extracted from Ground	100.0%			100.0%
Fugitive Losses	1.2%	0.1%	0.5%	1.8%
Point Source Losses (Vented or Flared)	0.8%	2.2%	0.0%	3.0%
Fuel Use	0.0%	7.6%	0.8%	8.4%
Delivered to End User				86.9%

13% of Natural Gas Extracted from the Earth is Consumed for Fuel Use, Flared, or Emitted to the Atmosphere (point source or fugitive)

Of this, 70% is Used to Power Equipment

Life Cycle GHG Results for Average Natural Gas Extraction and Delivery to a Large End-User



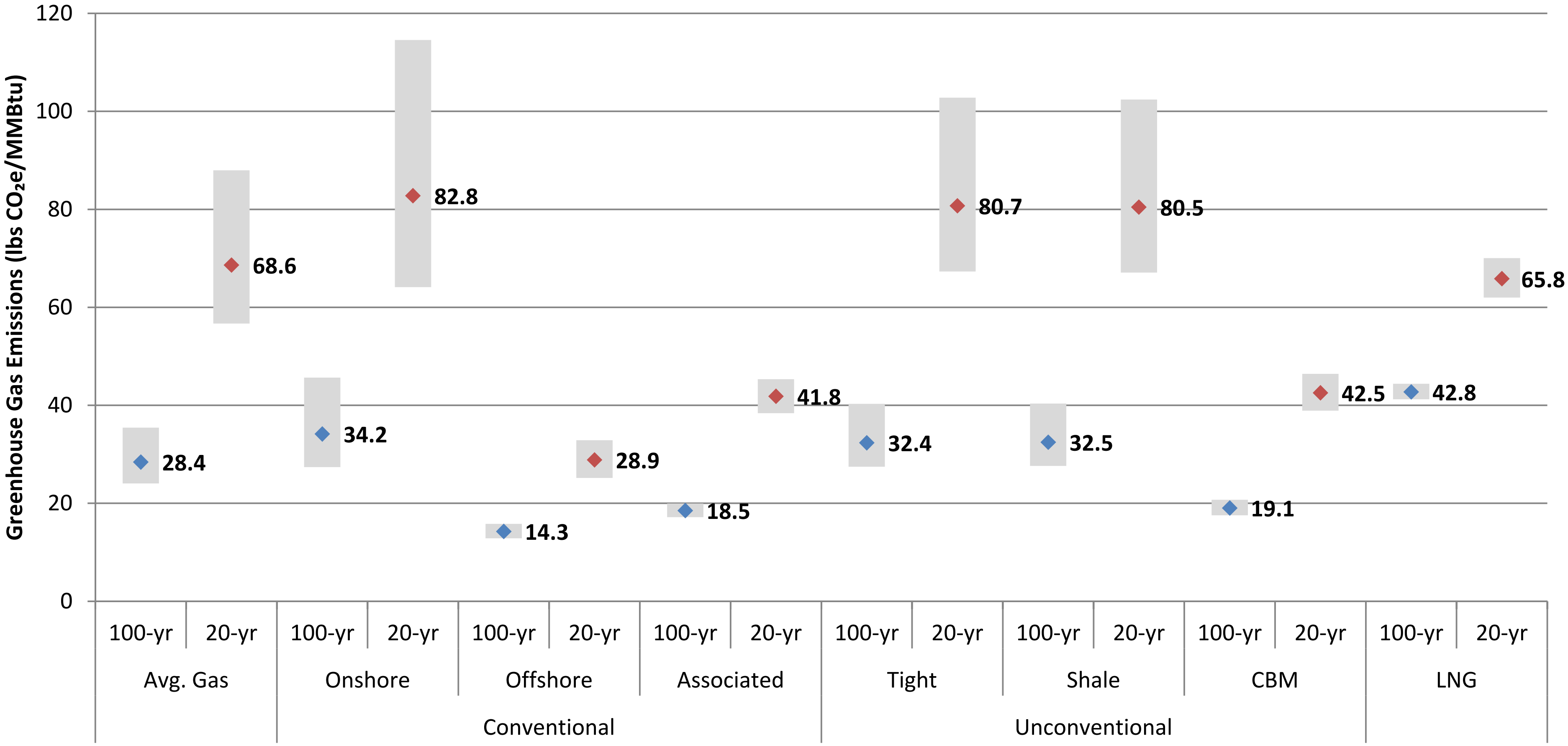
Carbon dioxide equivalents calculated using 2007 IPCC 100-year GWP

Life Cycle GHG Results for Average Natural Gas Extraction and Delivery to a Large End-User

Comparison of 2007 IPCC GWP Time Horizons:

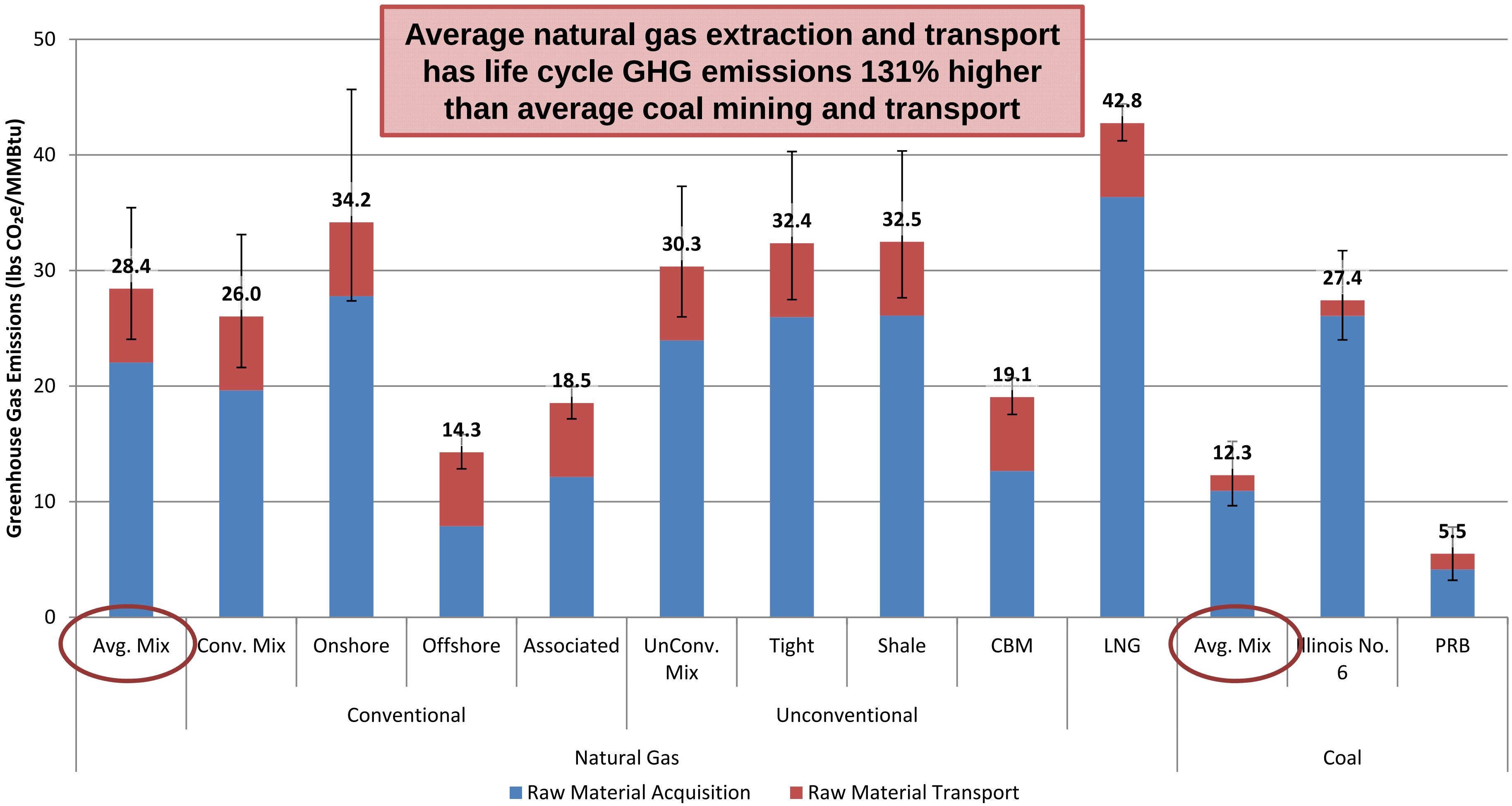
100-year Time Horizon: $CO_2 = 1, CH_4 = 25, N_2O = 298$

20-year Time Horizon: $CO_2 = 1, CH_4 = 72, N_2O = 289$



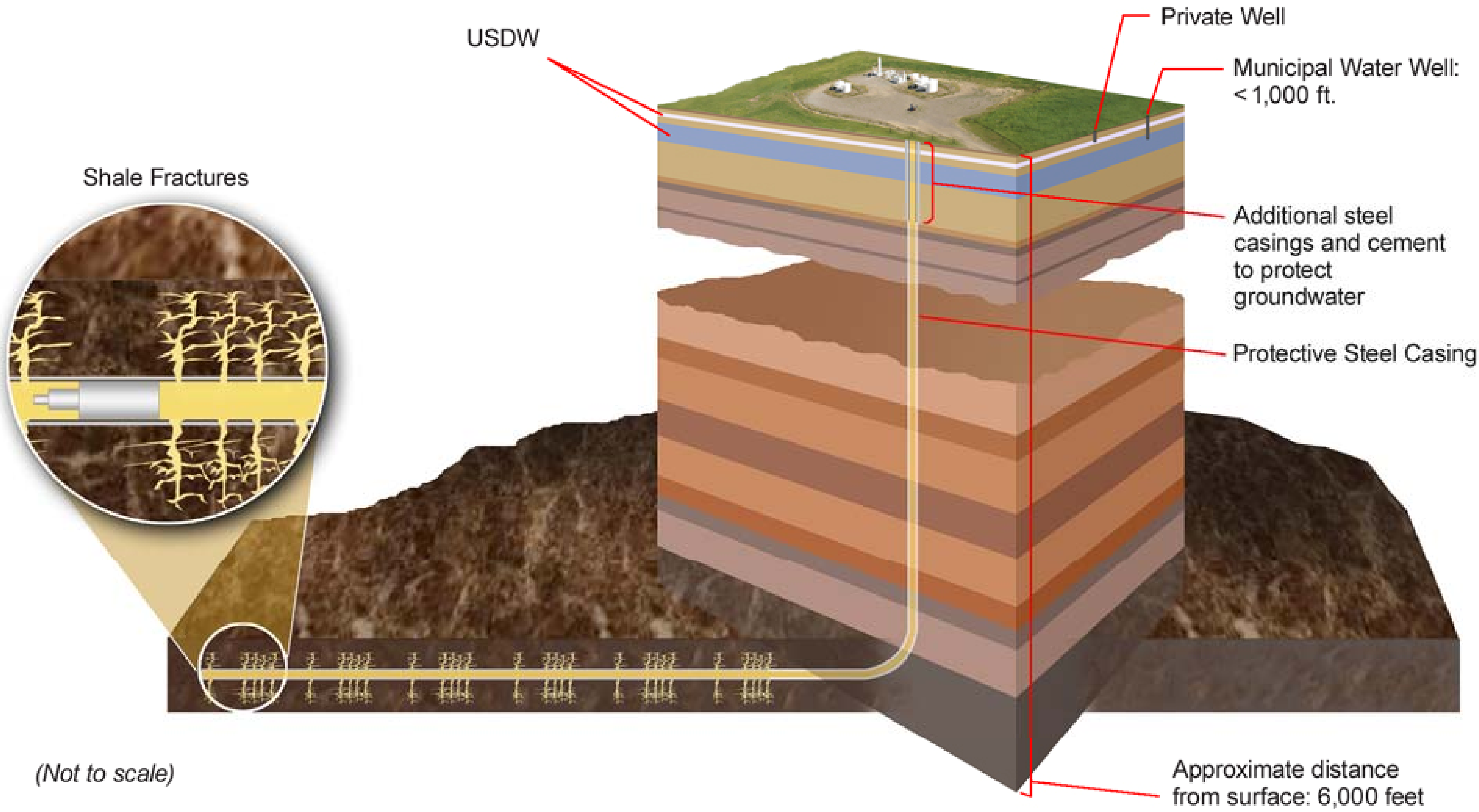
Life Cycle GHG Results for "Average" Natural Gas Extraction and Delivery to a Large End-User

Comparison of Natural Gas and Coal Energy Feedstock GHG Profiles



Carbon dioxide equivalents calculated using 2007 IPCC 100-year GWP

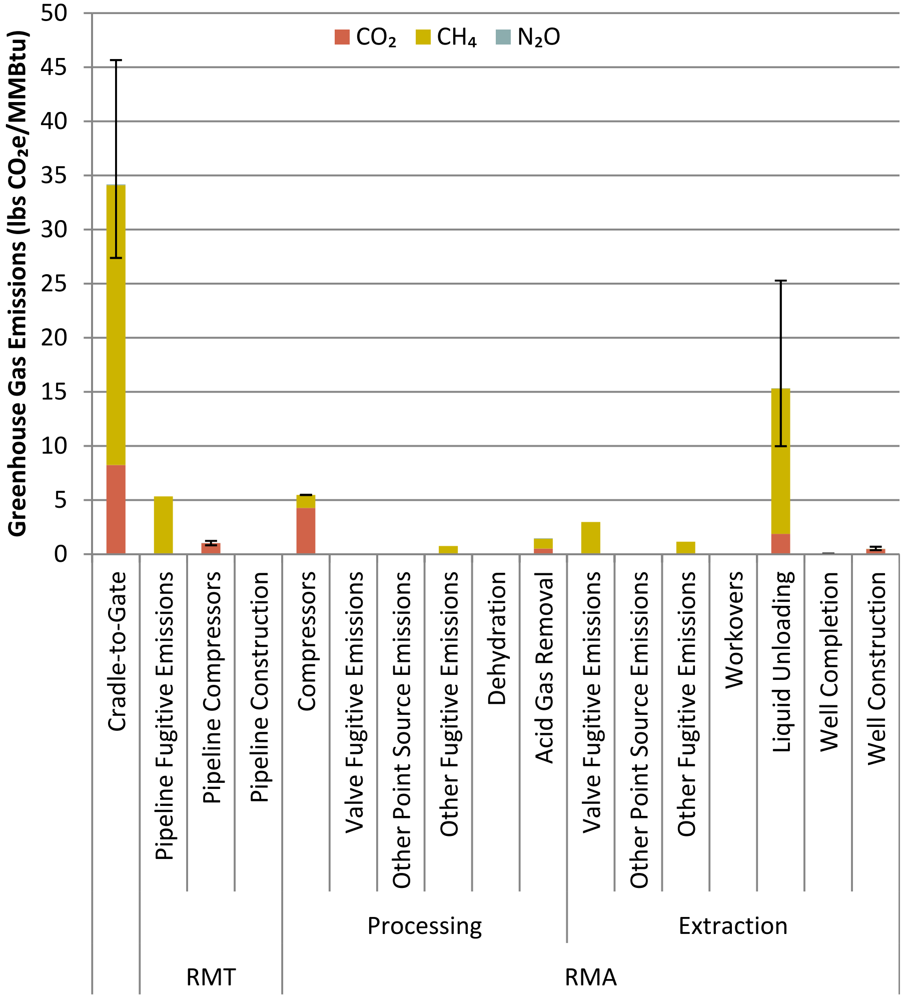
A Deeper Look at Unconventional Natural Gas Extraction via Horizontal Well, Hydraulic Fracturing (*the Barnett Shale Model*)



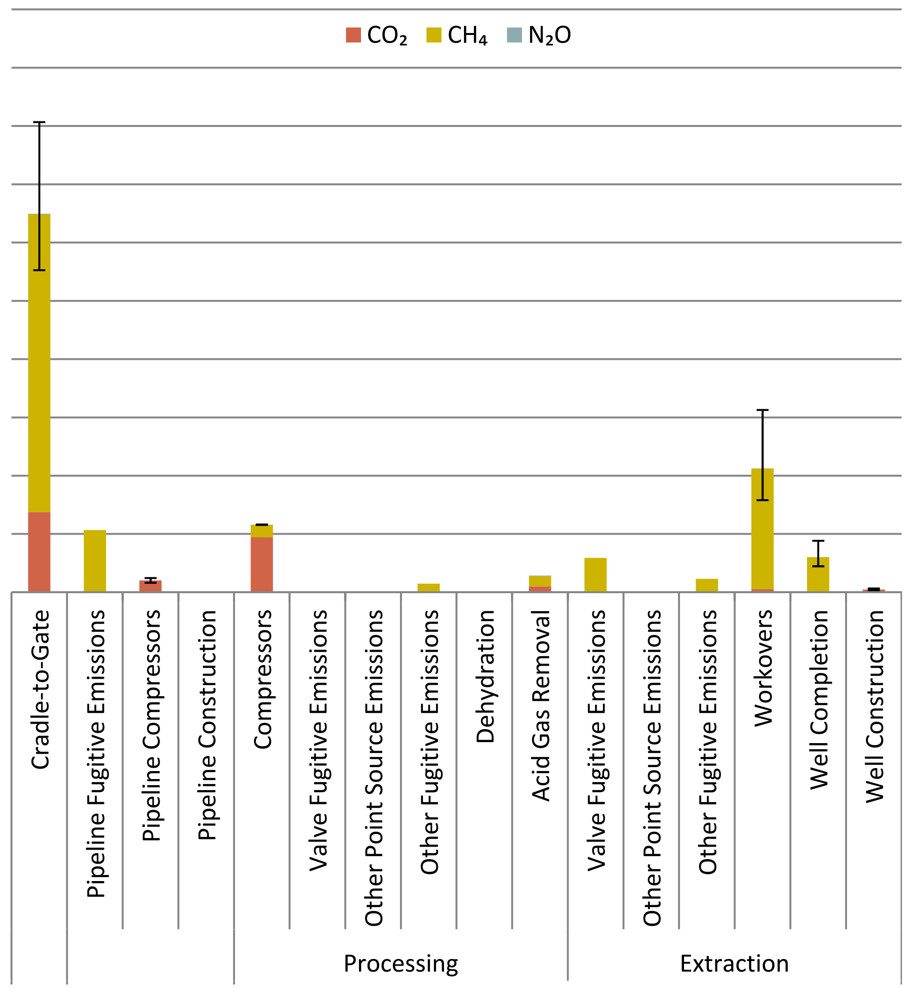
Source: NETL, *Shale Gas: Applying Technology to Solve America's Energy Challenge*, January 2011

Onshore vs. Shale GHG Emission Profiles

Onshore Gas
(34.2 lbs CO_2e/MMBtu)



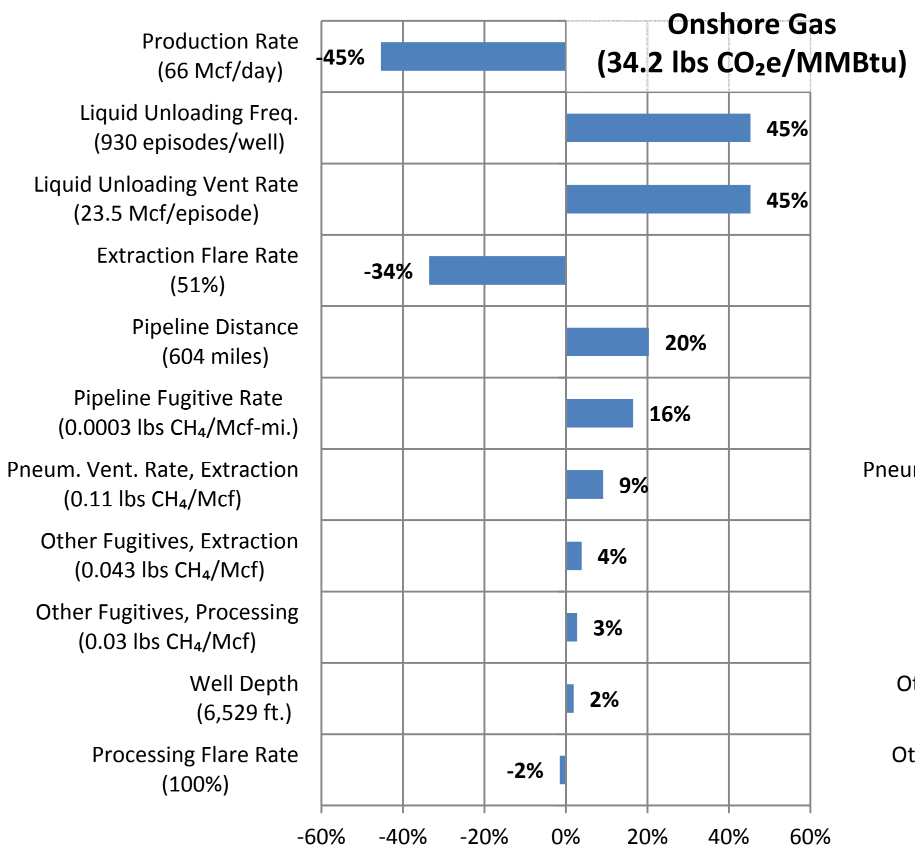
Shale Gas
(32.5 lbs CO_2e/MMBtu)

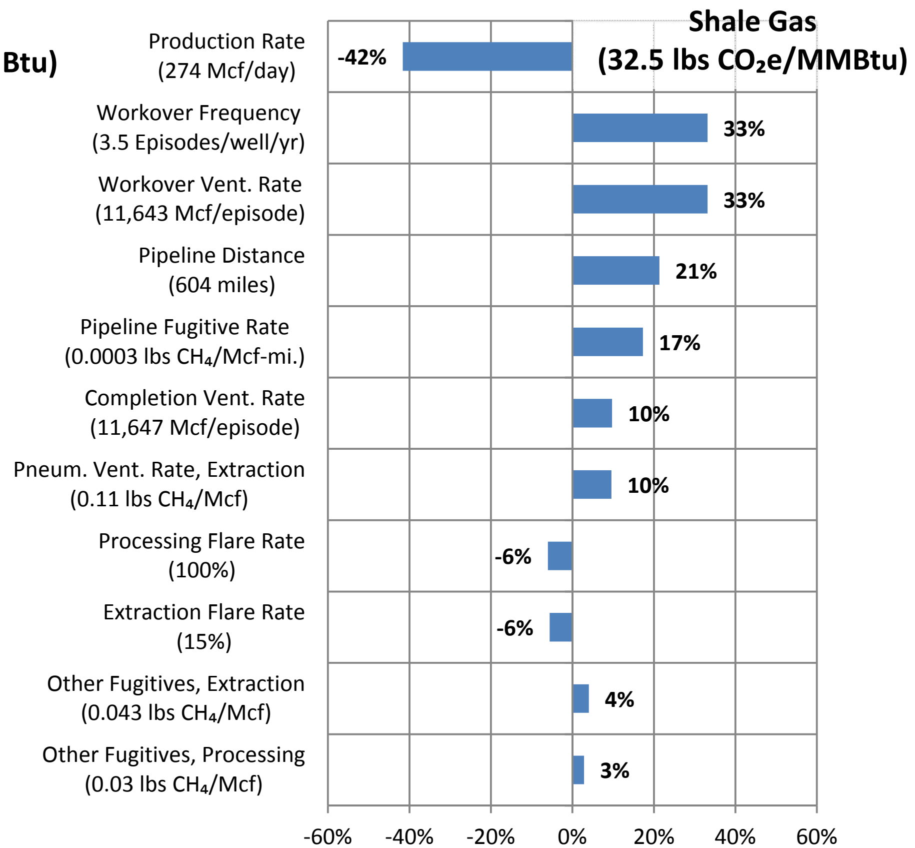


Carbon dioxide equivalents calculated using 2007 IPCC 100-year GWP

Onshore vs. Shale GHG Emission Profiles

Sensitivity of Model Result to Changes in Parameter Values





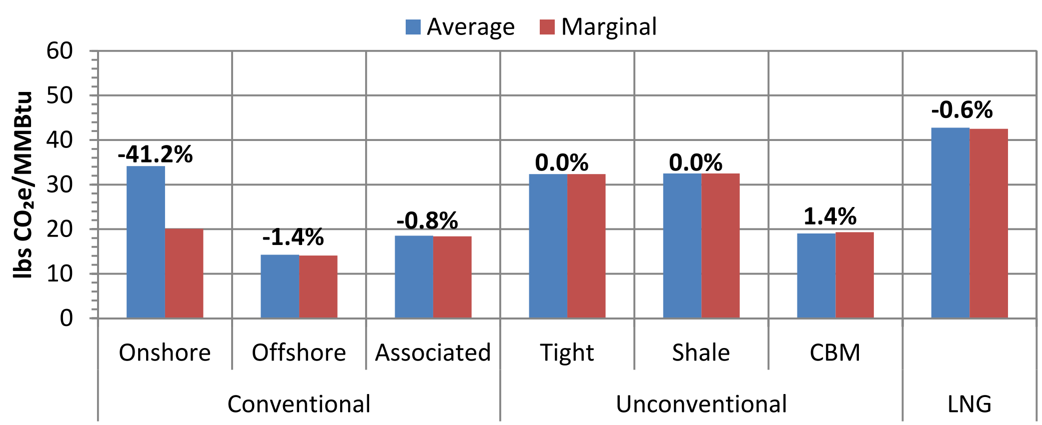
Percentages above are relative to a unit change in parameter value; all parameters are changed by the same amount, allowing comparison of the magnitude of change to the result across all parameters.

Example: A 10% increase in Onshore Production Rate from 66 Mcf/day to 73 Mcf/day would result in a 4.5% (10% of 45%) *decrease* in cradle-to-gate emissions, from 34.2 to 32.6 lbs CO_2e/MMBtu.

Carbon dioxide equivalents calculated using 2007 IPCC 100-year GWP

Average vs. Marginal Natural Gas Production Rates and Results

Source		Well Count	Dry Production (Tcf)	Production Rate (Mcf/day)						Average	Marginal	Percent Change
				Average			Marginal					
				Nominal	L (-30%)	H (+30%)	Nominal	L (-30%)	H (+30%)			
Conventional	Onshore	216,129	5.2	66	46	86	593	297	1,186	34.2	20.1	-41.2%
	Offshore	2,641	2.7	2,801	1,961	3,641	6,179	3,090	12,358	14.3	14.1	-1.4%
	Associated	31,712	1.4	121	85	157	399	200	798	18.5	18.4	-0.8%
Unconventional	Tight	162,656	6.6	111	78	144	110	77	143	32.4	32.4	0.0%
	Shale	32,797	3.3	274	192	356	274	192	356	32.5	32.5	0.0%
	CBM	47,165	1.8	105	73	136	105	73	136	19.1	19.3	1.4%
LNG				2,801	1,961	3,641	6,179	3,090	12,358	42.8	42.5	-0.6%



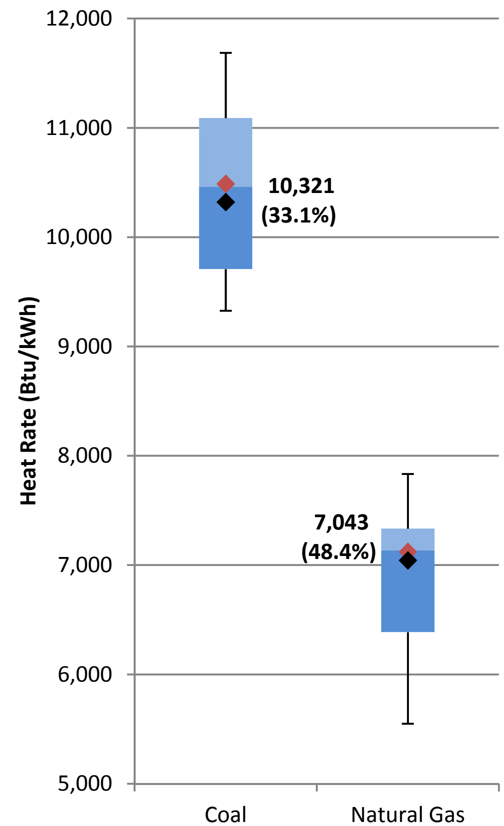
Carbon dioxide equivalents calculated using 2007 IPCC 100-year GWP

Question #6:

How does natural gas power generation compare to coal-fired power generation on a life cycle GHG basis?

Power Technology and Coal Modeling Properties

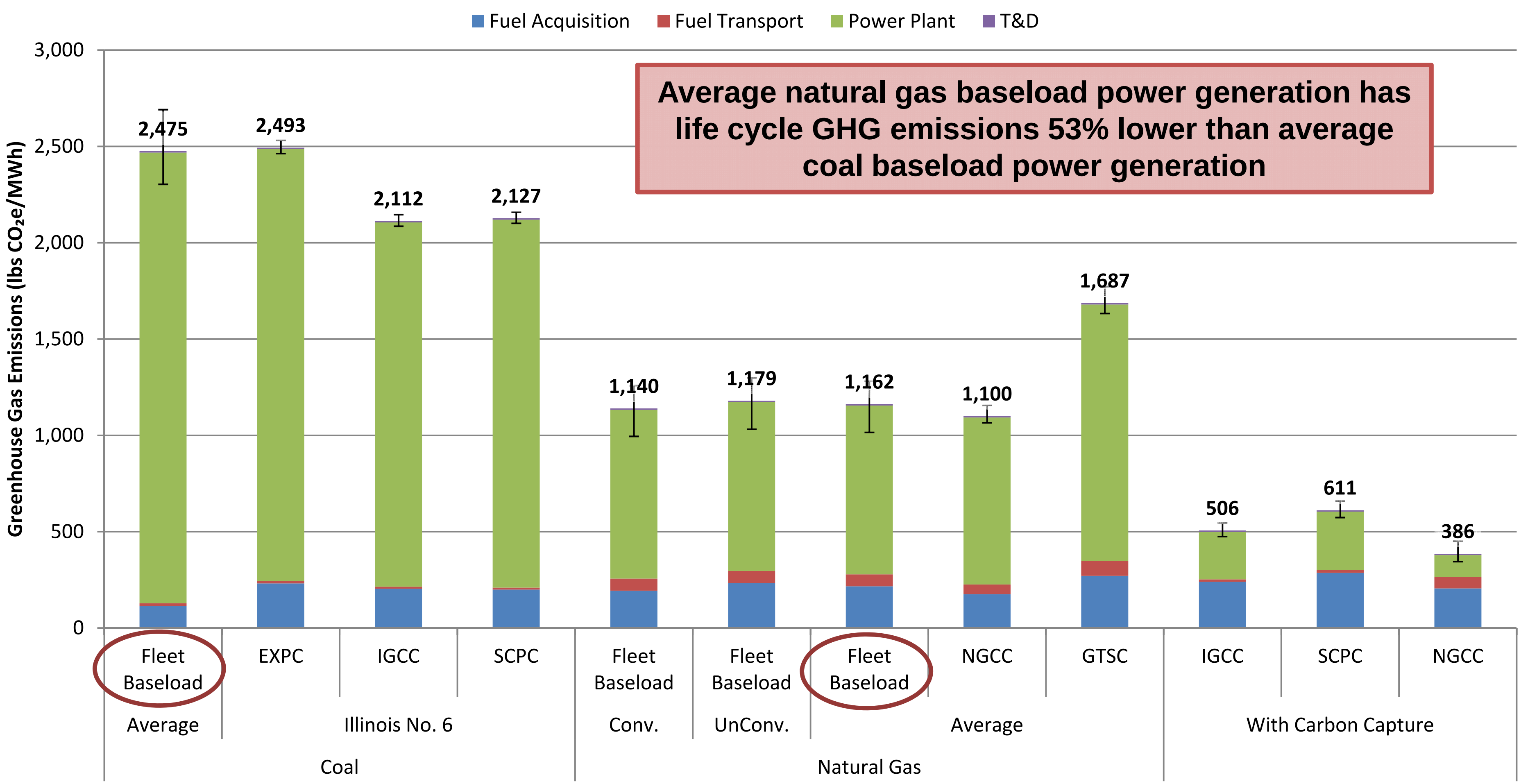
Plant Type		Abbreviation	Fuel Type	Capacity (MW)	Capacity Factor	Efficiency
Coal-fired	2009 Average	Avg. Coal	Domestic Average	> 200	> 60%	33.1%
	Existing Pulverized Coal	EXPC	Illinois No. 6	434	85%	35.0%
	Integrated Gasification Combined Cycle	IGCC	Illinois No. 6	622	80%	39.0%
	Super Critical Pulverized Coal	SCPC	Illinois No. 6	550	85%	39.3%
Natural Gas-fired	2009 Average	Avg. NG	Domestic Average	> 200	> 60%	48.4%
	Natural Gas Combined Cycle	NGCC	Domestic Average	555	85%	50.2%
	Gas Turbine Simple Cycle	GTSC	Domestic Average	360	85%	30.1%
90% Carbon Capture	Integrated Gasification Combined Cycle	IGCC/CCS	Illinois No. 6	543	80%	32.6%
	Super Critical Pulverized Coal	SCPC/CCS	Illinois No. 6	550	85%	28.4%
	Natural Gas Combined Cycle	NGCC/CCS	Domestic Average	474	85%	42.8%



Coal Type	U.S. Supply Share (% by energy)	Energy Content (Btu/lb)	Carbon Content (% by mass)	Methane Emissions (cf CH_4/ton)
Sub-bituminous	69%	8,564	50.1%	8 – 98 (51)
Bituminous	31%	11,666	63.8%	360 – 500 (422)
Average		9,526	54.3%	

Comparison of Power Generation Technology Life Cycle GHG Footprints

Raw Material Acquisition thru Delivery to End Customer (lb CO_2e/MWh)



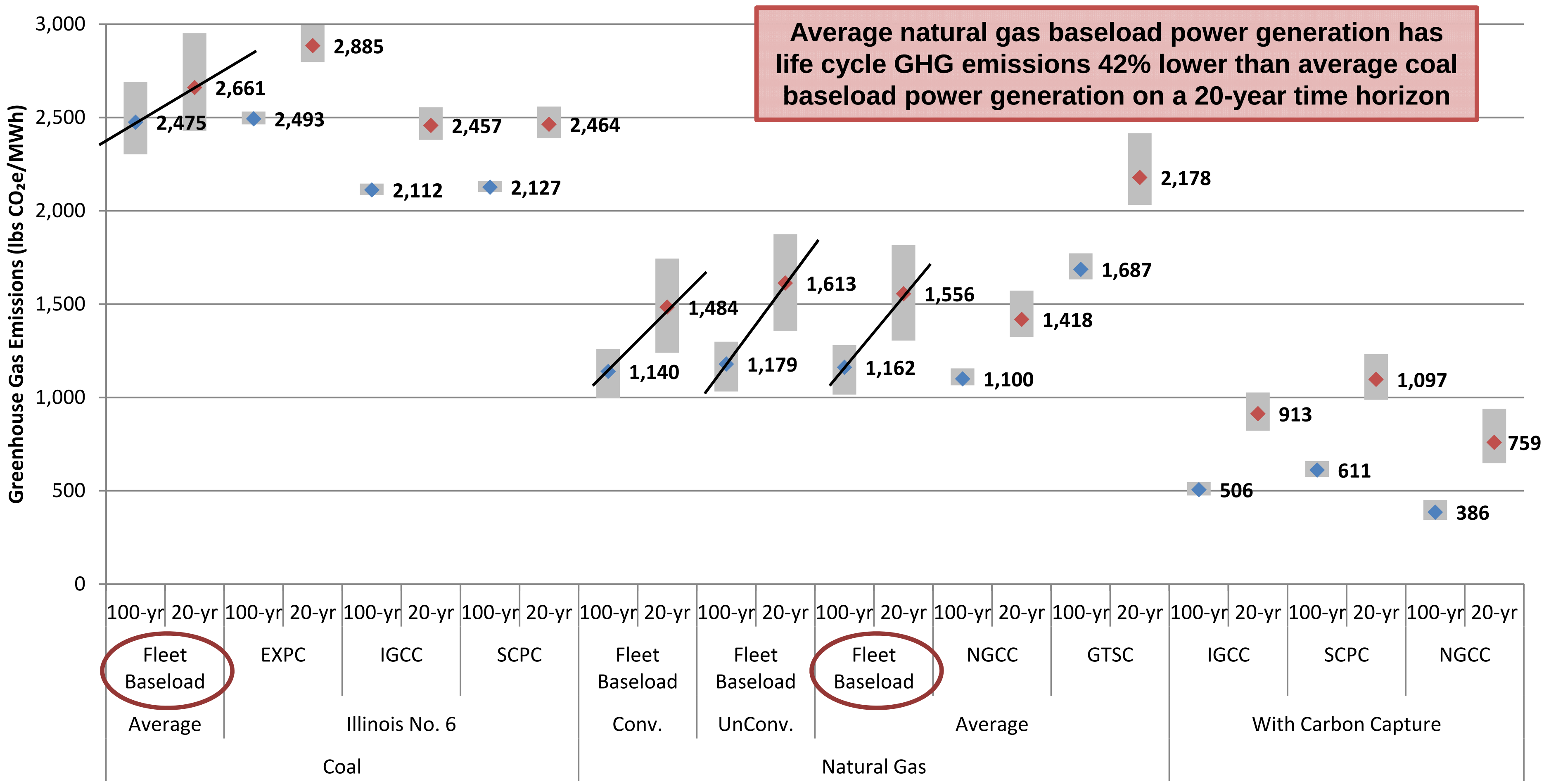
Carbon dioxide equivalents calculated using 2007 IPCC 100-year GWP

Comparison of Power Generation Technology Life Cycle GHG Footprints (lbs CO_2e/MWh)

Comparison of 2007 IPCC GWP Time Horizons:

100-year Time Horizon: CO_2 = 1, CH_4 = 25, N_2O = 298

20-year Time Horizon: CO_2 = 1, CH_4 = 72, N_2O = 289



Note: EXPC, IGCC, SCPC, and NGCC (combustion) results, with and without CCS, are based on scenario specific modeling parameters; not industry average data.

Study Data Limitations

- **Data Uncertainty**
  - Episodic emission factors
  - Formation-specific production rates
  - Flaring rates (extraction and processing)
  - Natural gas pipeline transport distance

- **Data Availability**
  - Formation-specific gas compositions (including CH_4, H_2S, NMVOC, and water)
  - Effectiveness of green completions and workovers
  - Fugitive emissions from around wellheads (between the well casing and the ground)
  - GHG emissions from the production of fracing fluid
  - Direct and indirect GHG emissions from land use from access roads and well pads
  - Gas exploration
  - Treatment of fracing fluid
  - Split between venting and fugitive emissions from pipeline transport

Question #7:

What are the opportunities for reducing GHG emissions?

Technology Opportunities

- **Opportunities for Reducing the GHG Footprint of Natural Gas Extraction and Delivery**
  - Reduce emissions from unconventional gas well completions and workovers
    - Better data is needed to properly characterize this opportunity based on basin type, drilling method, and production rate
  - Improve compressor fuel efficiency
  - Reduce pipeline fugitive emissions thru technology and best management practices (collaborative initiatives)

- **Opportunities for Reducing the GHG Footprint of Natural Gas and Coal-fired Power Generation**
  - Capture the CO_2 at the power plant and sequester it in a saline aquifer or oil bearing reservoir (CO_2-EOR)
  - Improve existing power plant efficiency
  - Invest in advanced power research, development, and demonstration

All Opportunities Need to Be Evaluated on a Sustainable Energy Basis: Environmental Performance, Economic Performance, and Social Performance (e.g., energy reliability and security)

Data Sources

API. (2009). ***Compendium of Greenhouse Gas Emissions for the Oil and Natural Gas Industry. American Petroleum Institute. Retrieved May 18, 2010, from http://www.api.org/ehs/climate/new/upload/2009_GHG_COMPENDIUM.pdf***

Arnold. (1999). ***Surface Production Operations: Design of gas-handling systems and facilities. Houston, Texas: Gulf Professional Publishing.***

Bucyrus International Inc. (2008). ***Walking Draglines: The Range. . Retrieved June 8, 2009, from http://www.bucyrus.com/pdf/surface/Draglines Trifold 0105.pdf***

Burklin, C. E., & Heaney, M. (2006). ***Natural Gas Compressor Engine Survey for Gas Production and Processing Facilities. Houston, Texas.***

Bylin, C., Schaffer, Z., Goel, V., Robinson, D., Campos, A. d. N., & Borensztein, F. (2010). ***Designing the Ideal Offshore Platform Methane Mitigation Strategy. Paper presented at the SPE International Conferences on Health, Safety, and Environment in Oil and Gas Exploration and Production, Rio de Janeiro, Brazil.***

Clyde Bergemann. (2005). PRB Coal Properties. Retrieved June 8, 2009, from http://www.cba-ssd.com/Applications/knowledgeBase/PRBcoal/PRBcoalProperty.htm

Dennis, S. M. (2005). Improved Estimates of Ton-Miles. ***Journal of Transportation and Statistics, 8(1).***

DOE. (1996). ***Buying an Energy-Efficient Electric Motor. (DOE/GO-10096-314). U.S. Department of Energy. Retrieved May 18, 2010, from http://www1.eere.energy.gov/industry/bestpractices/pdfs/mc-0382.pdf***

Data Sources

DOE. (2002). ***Mining Industry of the Future - Energy and Environmental Profile of the U.S. Mining Industry, Chapter 2: Coal.: U.S. Department of Energy. Retrieved June 4, 2009, from http://www.netl.doe.gov/KeyIssues/mining/coal.pdf***

EIA. (2007). ***Natural Gas Compressor Stations on the Interstate Pipeline Network: Developments Since 1996. Washington, DC: Energy Information Administration Retrieved May 18, 2010, from http://www.eia.gov/FTPROOT/features/ngcompressor.pdf***

EIA. (2009). ***Annual Coal Report, 2009. (DOE/EIA-0584(2009)). Washington, DC: Energy Information Administration Office of Oil, Gas, and Coal Supply Statistics. Retrieved June 8, 2009, from http://www.eia.doe.gov/cneaf/coal/page/acr/acr.pdf***

EIA. (2010a). Energy Information Administration: Federal Gulf Distribution of Wells by Production Rate. Retrieved July 19, 2011, from http://www.eia.gov/pub/oil_gas/petrosystem/fg_table.html

EIA. (2010b). Energy Information Administration: United States Distribution of Wells by Production. Retrieved July 19, 2011, from http://www.eia.gov/pub/oil_gas/petrosystem/us_table.html

EIA. (2011a). ***Annual Energy Outlook 2011. Washington, DC: U.S. Department of Energy, Energy Information Administration.***

EIA. (2011b). Energy Information Adminstration: Natural Gas Gross Withdrawals and Production. Retrieved April 5, 2011, from http://www.eia.doe.gov/dnav/ng/ng_prod_sum_a_EPG0_VRN_mmcf_a.htm

Data Sources

EIA. (2011c). Crude Oil and Natural Gas Exploratory and Development Wells. from Energy Information Administration: http://www.eia.gov/dnav/ng/ng_enr_wellend_s1_a.htm

El Paso Pipeline Group (2011). [Compressor Profile of El Paso Pipeline Group].

EPA. (1995). ***Compilation of Air Pollutant Emission Factors, Volume I: Stationary Point and Area Sources. (AP-42). U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. Retrieved May 18, 2010, from http://www.epa.gov/ttnchie1/ap42***

EPA. (2004a). ***Evaluation of Impacts to Underground Sources of Drinking Water by Hydraulic Fracturing of Coalbed Methane Reservoirs, Attachment 5: The Powder River Basin. (EPA 816-R-04-003). U.S. Environmental Protection Agency. Retrieved June 4, 2009, from http://www.epa.gov/OGWDW/uic/pdfs/cbmstudy_attach_uic_attach05_powder.pdf***

EPA. (2004b). ***Final Regulatory Analysis: Control of Emissions from Nonroad Diesel Engines. (EPA420-R-04-007). U.S. Environmental Protection Agency Office of Transportation and Air Quality. Retrieved August 23, 2011, from http://www.epa.gov/nonroaddiesel/2004fr/420r04007a.pdf***

EPA. (2006). ***Replacing Glycol Dehydrators with Desiccant Dehydrators. U.S. Environmental Protection Agency. Retrieved June 1, 2010, from http://www.epa.gov/gasstar/documents/ll_desde.pdf***

EPA. (2008). ***Identifying Opportunities for Methane Recovery at U.S. Coal Mines: Profiles of Selected Gassy Underground Coal Mines 2002-2006. (EPA 430-K-04-003). U.S. Environmental Protection Agency, Coalbed Methane Outreach Program. Retrieved August 23, 2011, from http://www.epa.gov/cmop/docs/profiles_2008_final.pdf***

Data Sources

EPA. (2010). Emissions & Generation Resource Integrated Database (eGRID).. Retrieved June 7, 2011, from United States Environmental Protection Agency http://www.epa.gov/cleanenergy/energy-resources/egrid/

EPA. (2011a). ***Greenhouse Gas Emissions Reporting from the Petroleum and Natural Gas Industry Background Technical Support Document. Washington, D.C.: U.S. Environmental Protection Agency, Climate Change Division. Retrieved August 23, 2011, from http://www.epa.gov/climatechange/emissions/downloads10/Subpart-W_TSD.pdf***

EPA. (2011b). ***Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2009. (EPA 430-R-11-005). Washington, D.C.: Environmental Protection Agency,. Retrieved August 23, 2011, from http://epa.gov/climatechange/emissions/usinventoryreport.html***

EPA. (2011c). ***Natural Gas STAR Recommended Technologies and Practices - Gathering and Processing Sector. U.S. Environmental Protection Agency. Retrieved March 2, 2011, from http://www.epa.gov/gasstar/documents/gathering_and_processing_fs.pdf***

FERC. (2010). Federal Energy Regulatory Commission: Form 2/2A - Major and Non-major Natural Gas Pipeline Annual Report: Data (Current and Historical). Retrieved August 23, 2011, from http://www.ferc.gov/docs-filing/forms/form-2/data.asp

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D. W., et al. (2007). ***Changes in Atmospheric Constituents and in Radiative Forcing. Cambridge, United Kingdom and New York, NY, USA: Intergovernmental Panel on Climate Change.***

Data Sources

Foss, M. M. (2004). *Interstate Natural Gas - Quality Specifications & Interchangeability. Sugar Land, Texas: University of Texas Bureau of Economic Geology Center for Energy Economics. Retrieved August 23, 2011, from http://www.beg.utexas.edu/energyecon/lng/documents/CEE_Interstate_Natural_Gas_Quality_Specifications_and_Interchangeability.pdf*

Gaul, D. (2011). Industry Economist, Office of Oil and Gas, Energy Information Administration. In J. Littlefield (Ed.). Washington, DC.

GE Oil and Gas. (2005). *Reciprocating Compressors. Florence, Italy: . Retrieved August 23, 2011, from http://www.ge-energy.com/content/multimedia/_files/downloads/Reciprocating Compressors.pdf*

General Electric. (2008). The Evolution Series Locomotives. Retrieved August 14 2008, from http://www.getransportation.com/na/en/docs/806527_20020 - B Evo[1][1].Series.lores.pdf

Hayden, J., & Pursell, D. (2005). *The Barnett Shale: Visitors Guid to the Hottest Gas Play in the U.S.: Pickering Energy Partners. Retrieved June 14, 2010, from http://www.tudorpickering.com/pdfs/TheBarnettShaleReport.pdf*

Hedman, B. (2008). *Waste Energy Recovery Opportunities for Interstate Natural Gas Pipelines. Interstate Natural Gas Association of America. Retrieved July 25, 2011, from http://www.ingaa.org/File.aspx?id=6210*

Houston Advanced Research Center. (2006). *Natural Gas Compressor Engine Survey for Gas Production and Processing Facilities, H68 Final Report. . Retrieved May 18, 2010, from http://www.utexas.edu/research/ceer/GHG/files/ConfCallSupp/H068FinalReport.pdf*

Data Sources

Jaramillo, P., Griffin, W. M., & Matthews, H. S. (2007). Comparative Life-Cycle Air Emissions of Coal, Domestic Natural Gas, LNG, and SNG for Electricity Generation. *Environmental Science & Technology, 41(17), 6290-6296.*

Lyle, D. (2011, November 10). Shales Revive Oilpatch, Gas Patch. *2011 North American Unconventional Yearbook, 2010.*

Mining Technology. (2007). Cordero Rojo Coal Mine, WY, USA. Retrieved June 5, 2009, from http://www.mining-technology.com/projects/cordero/

National Mining Association. (2009). *2008 Coal Producer Survey. . Retrieved August 23, 2011, from http://www.nma.org/pdf/members/coal_producer_survey2008.pdf*

NaturalGas.org. (2004). Well Completion. Retrieved July 1, 2010, from http://naturalgas.org/naturalgas/well_completion.asp#liftingwell

NETL. (2007). *Power Plant Water Usage and Loss Study. Pittsburgh, PA: National Energy Technology Laboratory, from http://www.netl.doe.gov/technologies/coalpower/gasification/pubs/pdf/WaterReport_Revised May2007.pdf*

NETL. (2010a). *Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity Report. (DOE/NETL-2010/1397). Pittsburgh, PA: National Energy Technology Laboratory*

NETL. (2010b). *Life Cycle Analysis: Existing Pulverized Coal (EXPC) Power Plant. Pittsburgh, PA: National Energy Technology Laboratory*

Data Sources

NETL. (2010b). ***Life Cycle Analysis: Existing Pulverized Coal (EXPC) Power Plant. Pittsburgh, PA: National Energy Technology Laboratory***

NETL. (2010c). ***Life Cycle Analysis: Integrated Gasification Combined Cycle (IGCC). Pittsburgh, PA: Department of Energy, National Energy Technology Laboratory***

NETL. (2010d). ***Life Cycle Analysis: Natural Gas Combined Cycle (NGCC) Power Plant. Pittsburgh, PA: Department of Energy, National Energy Technology Laboratory***

NETL. (2010e). ***Life Cycle Analysis: Supercritical Pulverized Coal (SCPC) Power Plant. Pittsburgh, PA: National Energy Technology Laboratory***

NGSA. (2010). Unconventional Natural Gas Resources. ***NaturalGas.org, from http://www.naturalgas.org/overview/unconvent_ng_resource.asp***

Peabody. (2006). ***Final Technical Report Powder River Coal Company Plant Wide Assessment. Gillette, WY: Peabody Energy Company. Retrieved August 23, 2011, from http://www.osti.gov/bridge/servlets/purl/881764-FjjYjV/881764.pdf***

Polasek, J. (2006). ***Selecting Amines for Sweetening Units. . Retrieved August 23, 2011, from http://www.bre.com/portals/0/technicalarticles/Selecting Amines for Sweetening Units.pdf***

SME. (1990). ***Surface Mining, 2nd Edition. Society for Mining Metallurgy and Exploration Inc.. Retrieved June 9, 2009, from http://books.smenet.org/Surf_Min_2ndEd/sm-toc.cfm?CFID=820561&CFTOKEN=64890436***

Spath, P. L., & Mann, M. K. (2000). ***Life Cycle Assessment of a Natural Gas Combined Cycle Power Generation System: National Renewable Energy Laboratory.***

Data Sources

Steel Pipes & Tubes. **(2009). Steel Pipe Weight Calculator. Retrieved May 1, 2009, from** **http://www.steel-pipes-tubes.com/steel-pipe-weight-calculator.html**

The Engineering Toolbox. (2011). Fuel Gases - Heating Values. Retrieved May 18, 2011, from **http://www.engineeringtoolbox.com/heating-values-fuel-gases-d_823.html**

U.S. Census Bureau. (2004). ***Bituminous Coal Underground Mining: 2002. (EC02-211-212112(RV)). U.S. Department of Commerce. Retrieved August 23, 2011, from http://www.census.gov/prod/ec02/ec0221i212112.pdf***

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- Life Cycle Analysis: Natural Gas Combined Cycle (NGCC) Power Plant
- Life Cycle Analysis: Supercritical Pulverized Coal (SCPC) Power Plant
- Life Cycle Analysis: Power Studies Compilation Report
- Life Cycle GHG Inventory of Natural Gas Extraction, Delivery and Electricity Production

Analysis complete, report in draft form:

- Life Cycle Assessment of Wind Power with GTSC Backup
- Life Cycle Assessment of Nuclear Power

Other related Life Cycle Analysis publications available on NETL web-site:

- Life Cycle Analysis: Power Studies Compilation Report (Pres., LCA X Conference)
- An Assessment of Gate-to-Gate Environmental Life Cycle Performance of Water-Alternating-Gas CO_2-Enhanced Oil Recovery in the Permian Basin (Report)
- A Comparative Assessment of CO_2 Sequestration through Enhanced Oil Recovery and Saline Aquifer Sequestration (Presentation, LCA X Conference)

Contact Information

Office of Fossil Energy

www.fe.doe.gov

NETL

www.netl.doe.gov

Timothy J. Skone, P.E.
Senior Environmental Engineer
OSEAP - Planning Team
(412) 386-4495
timothy.skone@netl.doe.gov

Dr. Joe Marriott
Associate
Booz Allen Hamilton
(412) 386-7557
marriott_joe@bah.com

James Littlefield
Associate
Booz Allen Hamilton
(412) 386-7560
littlefield_james@bah.com