

**NATIONAL ENERGY TECHNOLOGY LABORATORY**



## **Life Cycle Greenhouse Gas Analysis of Natural Gas Extraction & Delivery in the United States**

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Presented at: Cornell University Lecture Series



# 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**



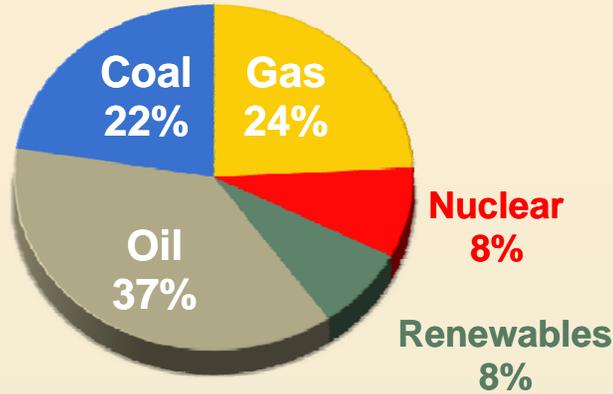
**West Virginia**

**Question #2:**

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

## Energy Demand 2008

100 QBtu / Year  
84% Fossil Energy



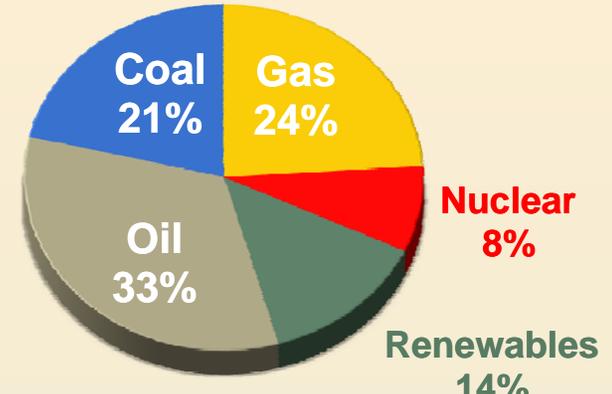
5,838 mmt CO<sub>2</sub>

+ 14%

United States

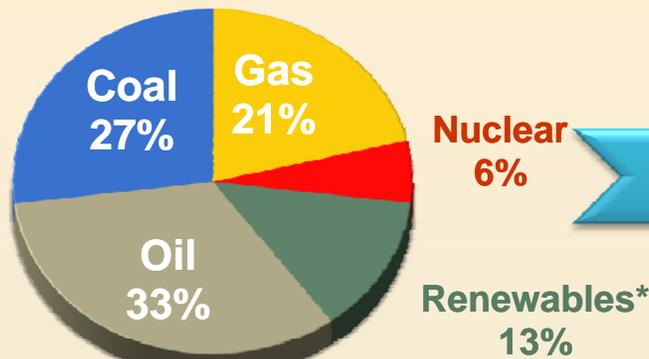
## Energy Demand 2035

114 QBtu / Year  
78% Fossil Energy



6,311 mmt CO<sub>2</sub>

487 QBtu / Year  
81% Fossil Energy

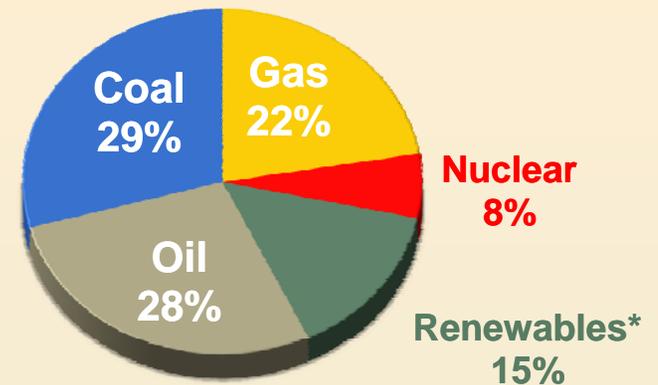


29,259 mmt CO<sub>2</sub>

+ 47%

World

716 QBtu / Year  
79% Fossil Energy



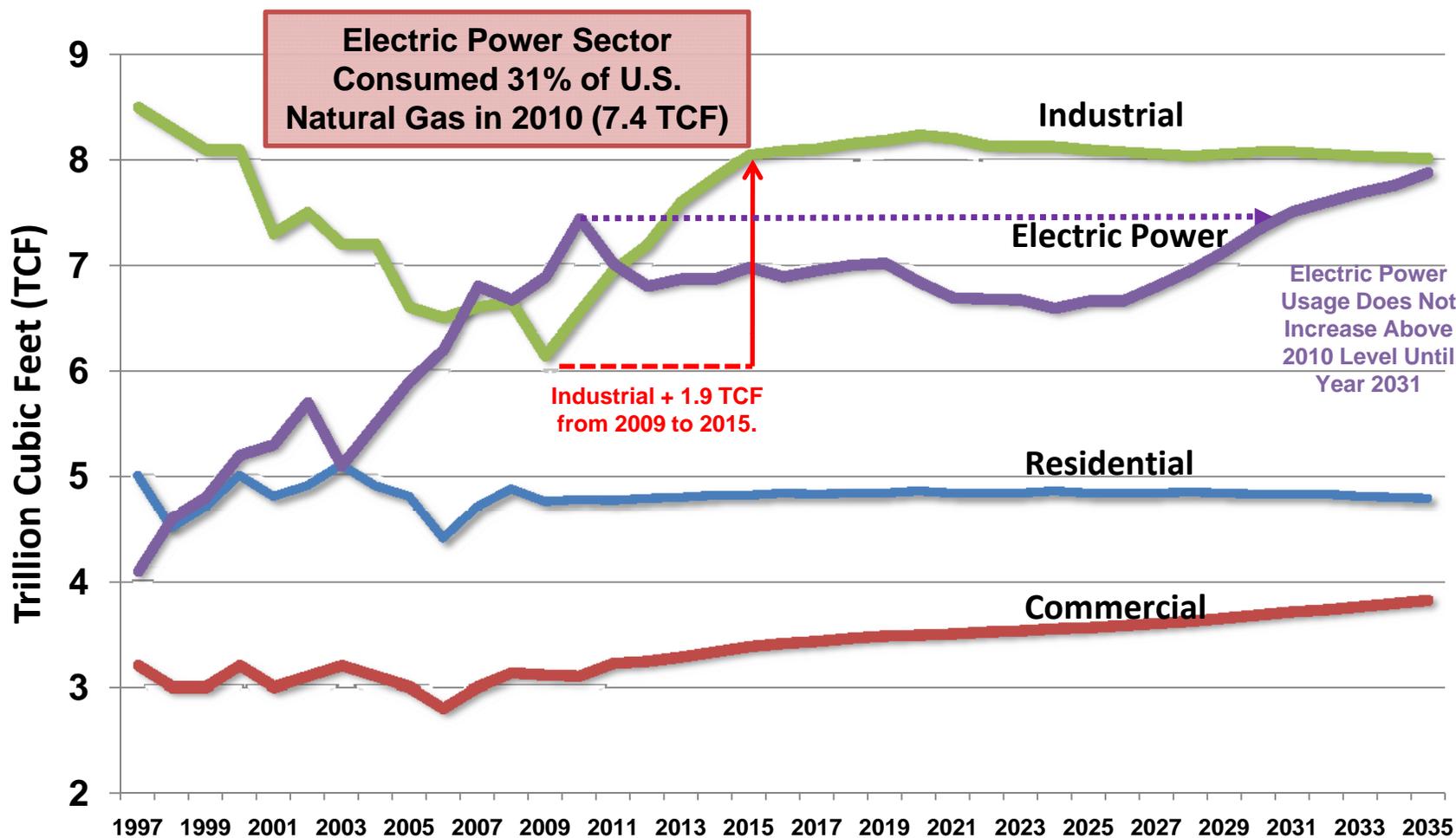
42,589 mmt CO<sub>2</sub>

**Question #3:**

**Who uses natural gas in the United States?**

# Domestic Natural Gas Consumption

Sectoral Trends and Projections: 2010 Total Consumption = 23.8 TCF

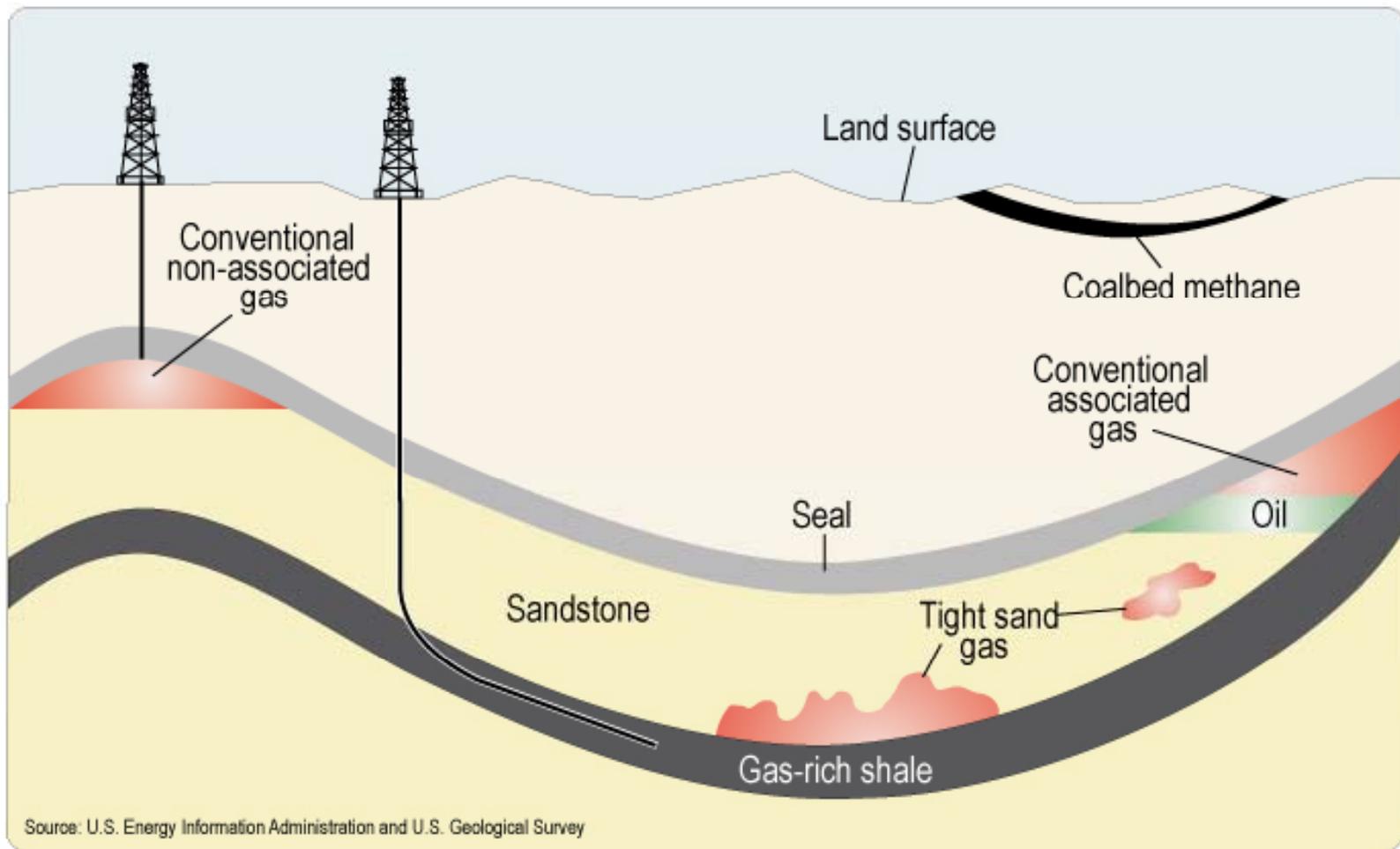


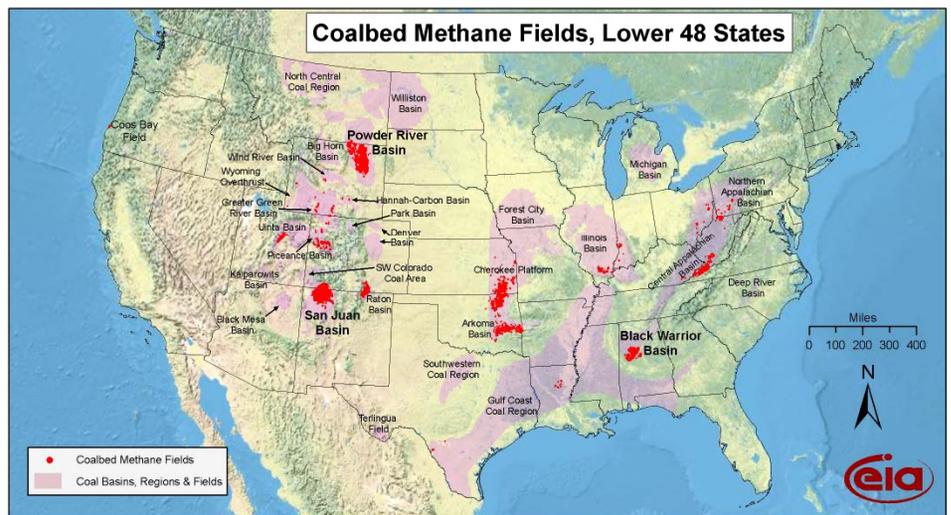
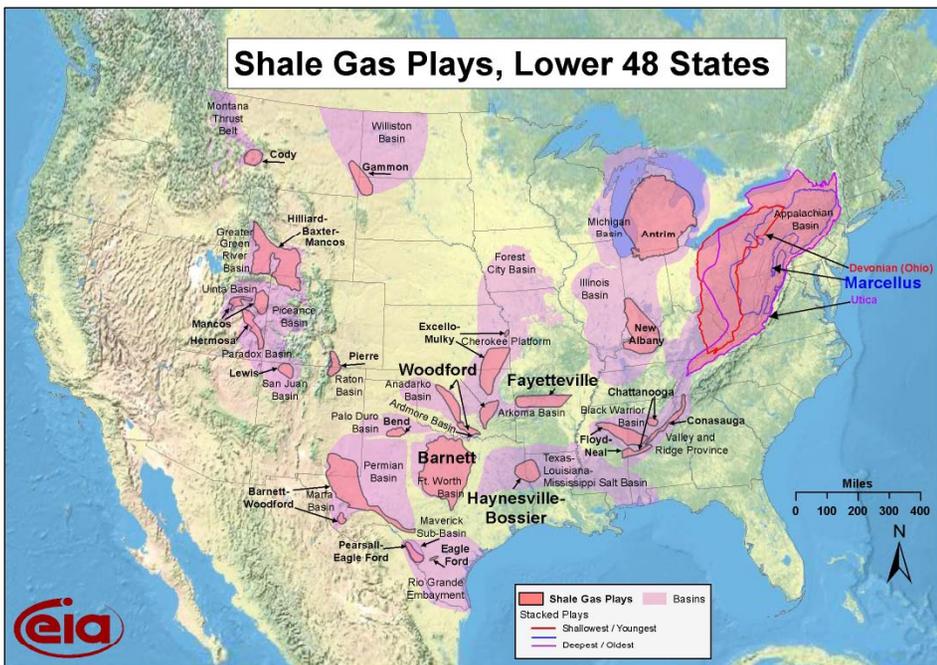
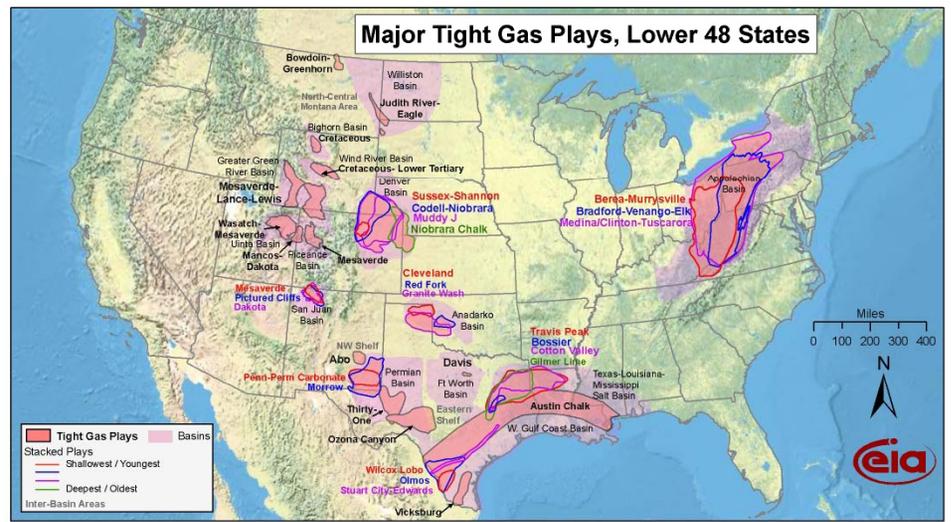
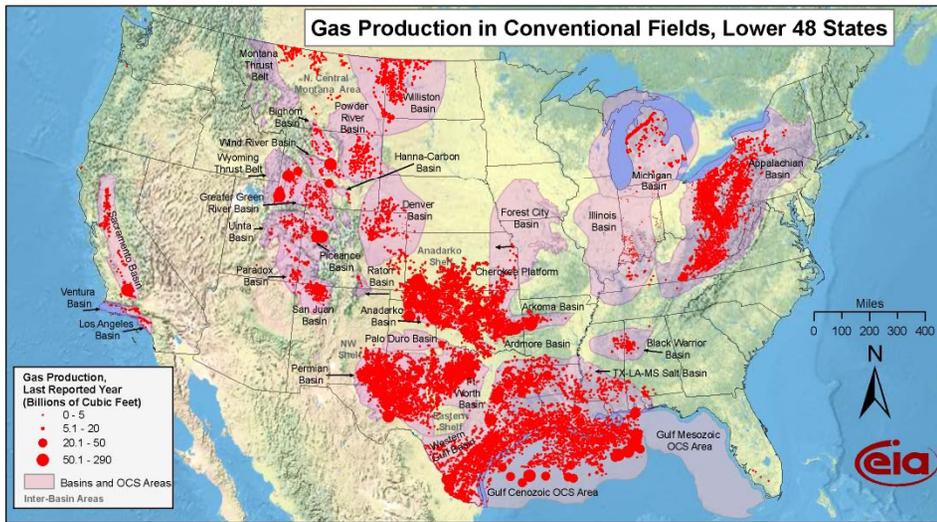
**+1.9 TCF Resurgence in Industrial Use of Natural Gas by 2015 Exceeds the Net Incremental Supply; No Increase in Natural Gas Use for Electric Power Sector Until 2031**

**Question #4:**

**Where does natural gas come from?**

# Schematic Geology of Onshore Natural Gas Resources



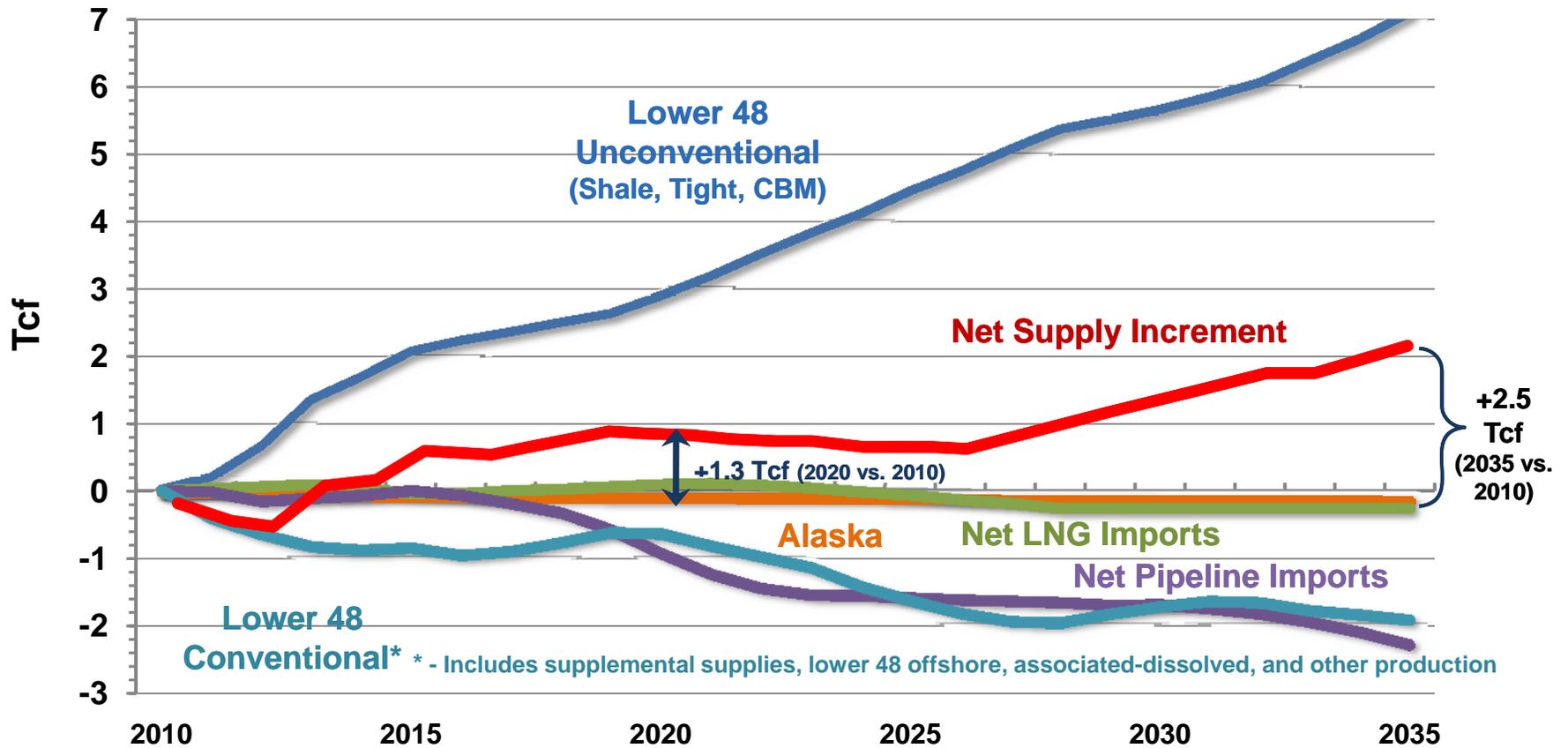


# EIA Natural Gas Maps

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# Sources of Incremental Natural Gas Supply

(Indexed to 2010)

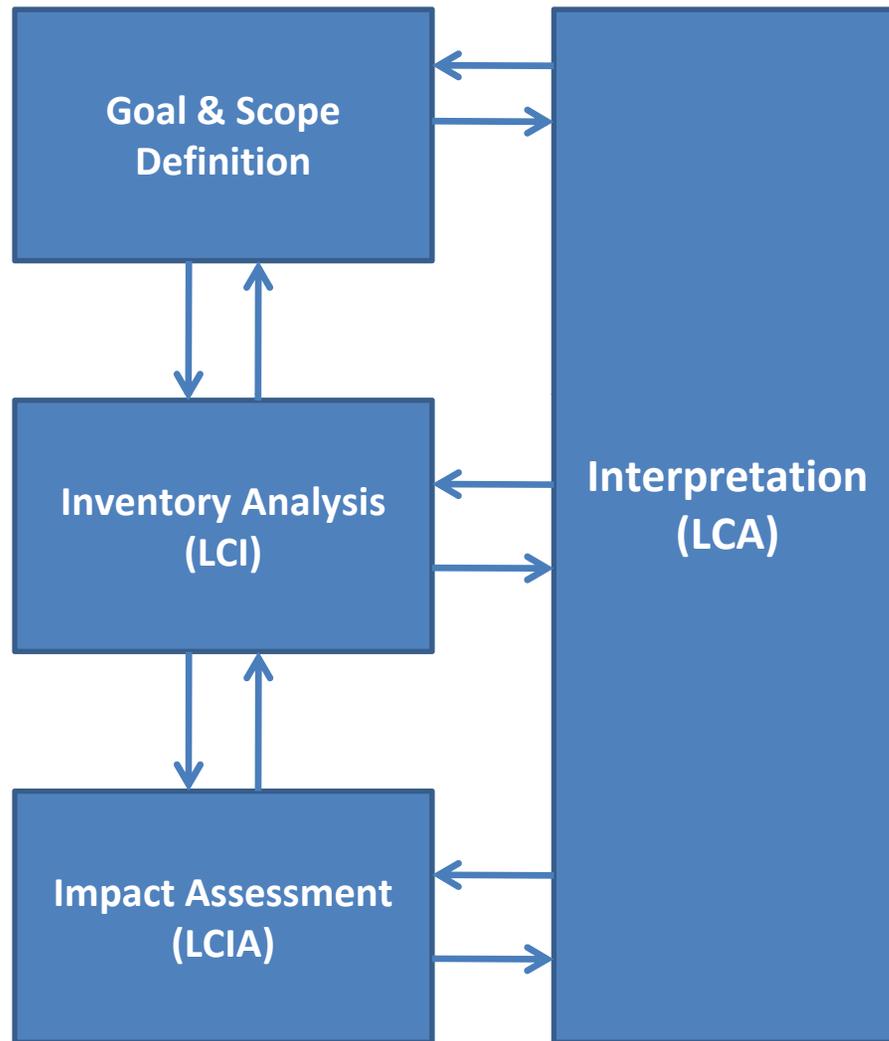


**Unconventional Production Growth Offset by Declines in Conventional Production and Net Pipeline Imports; 1.3 Tcf Increment by 2020 Does Not Support Significant Coal Generation Displacement**

**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?

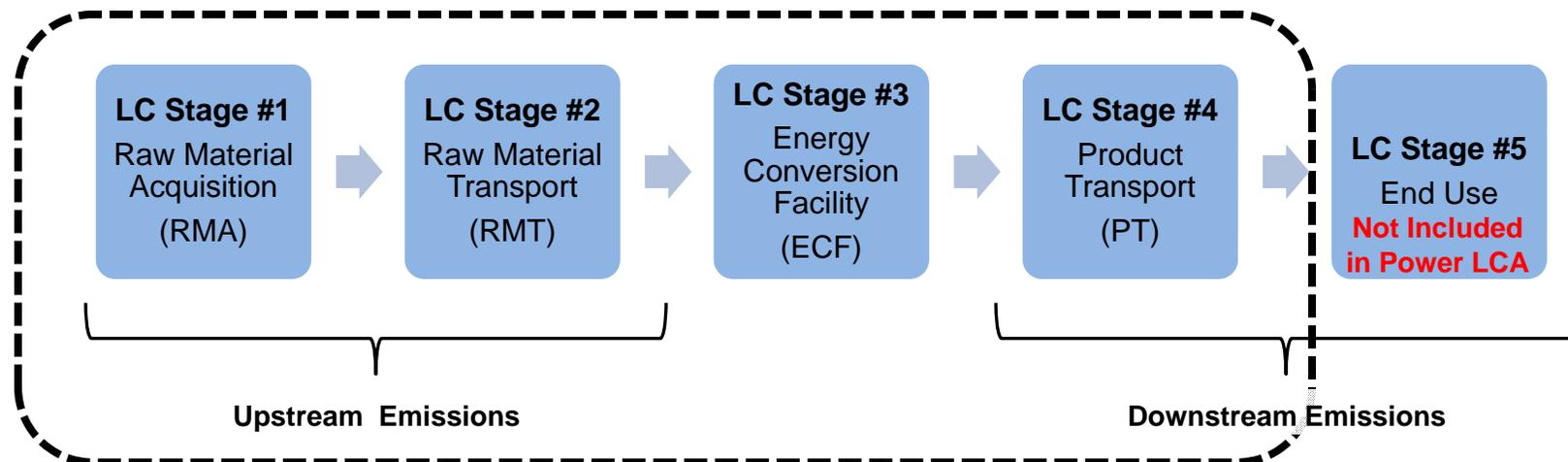
- ❑ The GHG footprint of natural gas, lower 48 domestic average, extraction, processing, and delivery to a large end-user (e.g., power plant)
- ❑ The comparison of natural gas used in a baseload power generation plant to baseload coal-fired power generation on a lbs CO<sub>2</sub>e/MWh basis

### 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

# NETL Life Cycle Analysis Approach

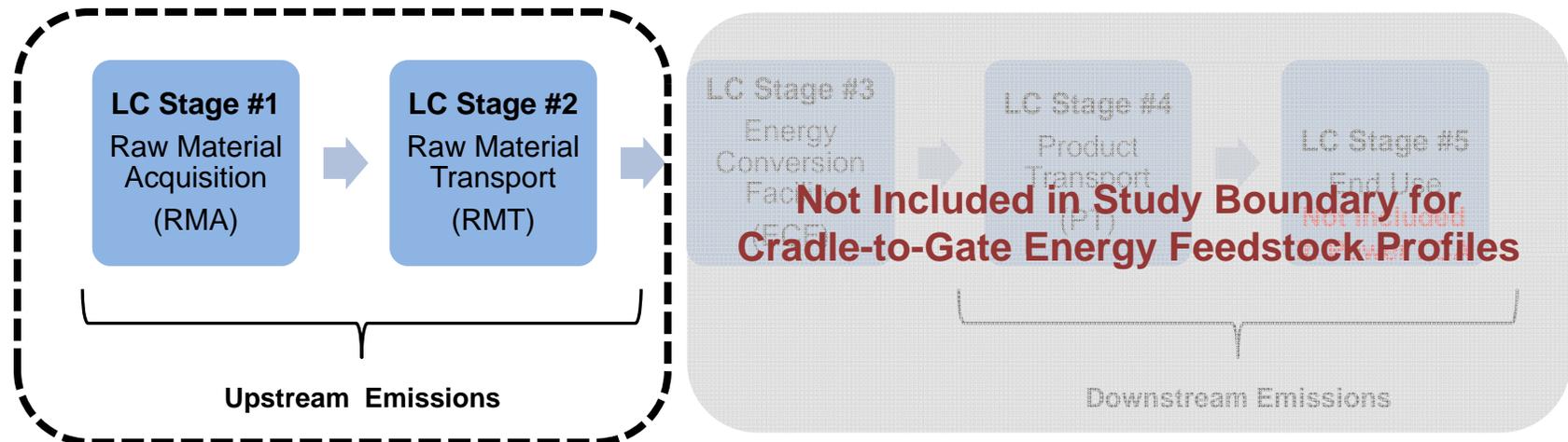
- **Compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product or service throughout its life cycle, from raw material acquisition to the final disposal**



- **The ability to compare different technologies depends on the functional unit (denominator); for power LCA studies:**
  - 1 MWh of electricity delivered to the end user

# NETL Life Cycle Analysis Approach for Natural Gas Extraction and Delivery Study

- The study boundary for “domestic natural gas extraction and delivery to large end-users” is represented by Life Cycle (LC) Stages #1 and #2 only.



- **Functional unit (denominator) for energy feedstock profiles is:**
  - 1 MMBtu of feedstock delivered to end user  
(MMBtu = million British thermal units)

# NETL Life Cycle Study Metrics

- **Greenhouse Gases**

- $\text{CO}_2, \text{CH}_4, \text{N}_2\text{O}, \text{SF}_6$

- **Criteria Air Pollutants**

- $\text{NO}_x, \text{SO}_x, \text{CO}, \text{PM}_{10}, \text{Pb}$

- **Air Emissions Species of Interest**

- Hg,  $\text{NH}_3$ , radionuclides

- **Solid Waste**

- **Raw Materials**

- Energy Return on Investment

- **Water Use**

- Withdrawn water, consumption, water returned to source

- Water Quality

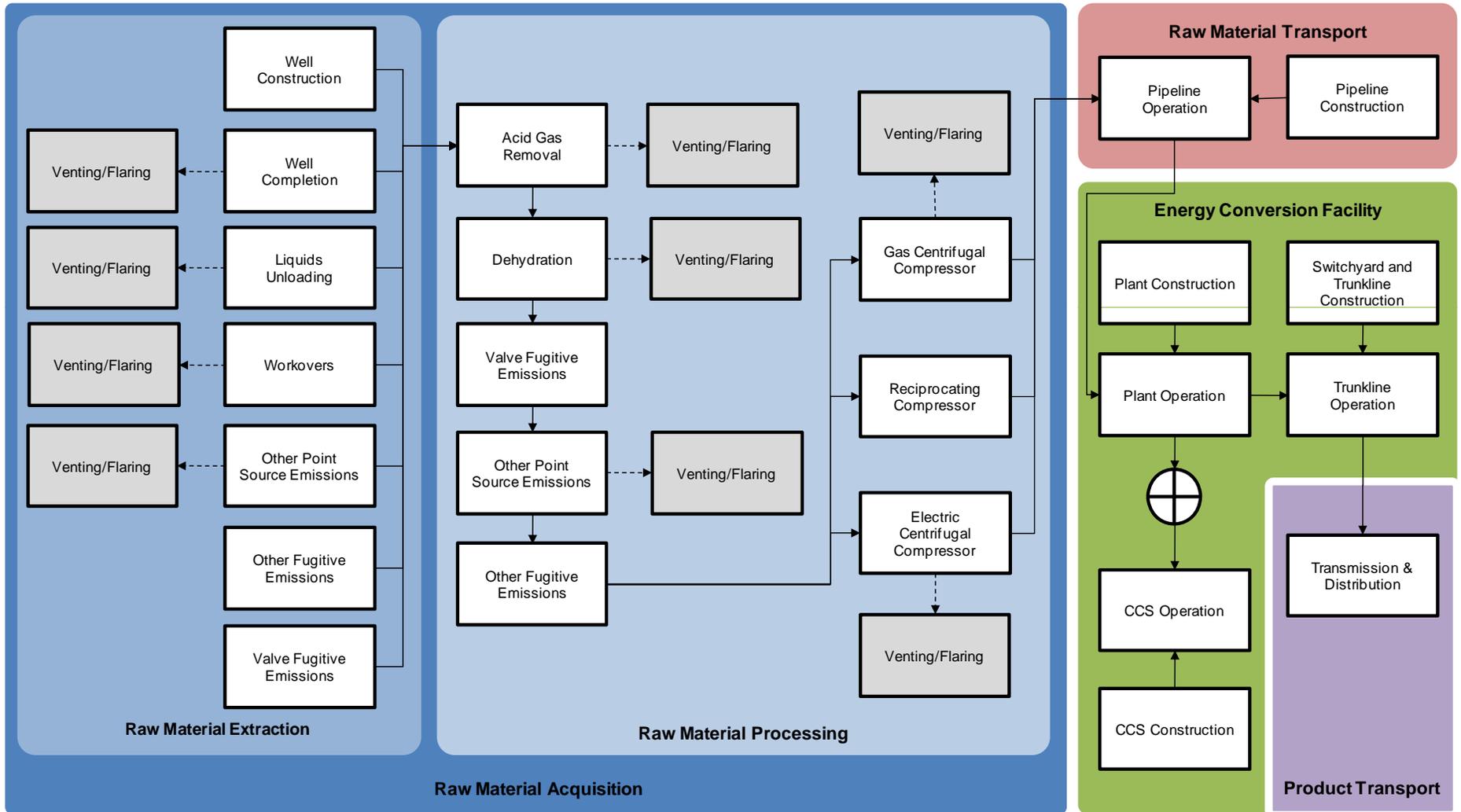
- **Land Use**

- Acres transformed, greenhouse gases

Converted to Global Warming  
Potential using IPCC 2007  
100-year  $\text{CO}_2$  equivalents

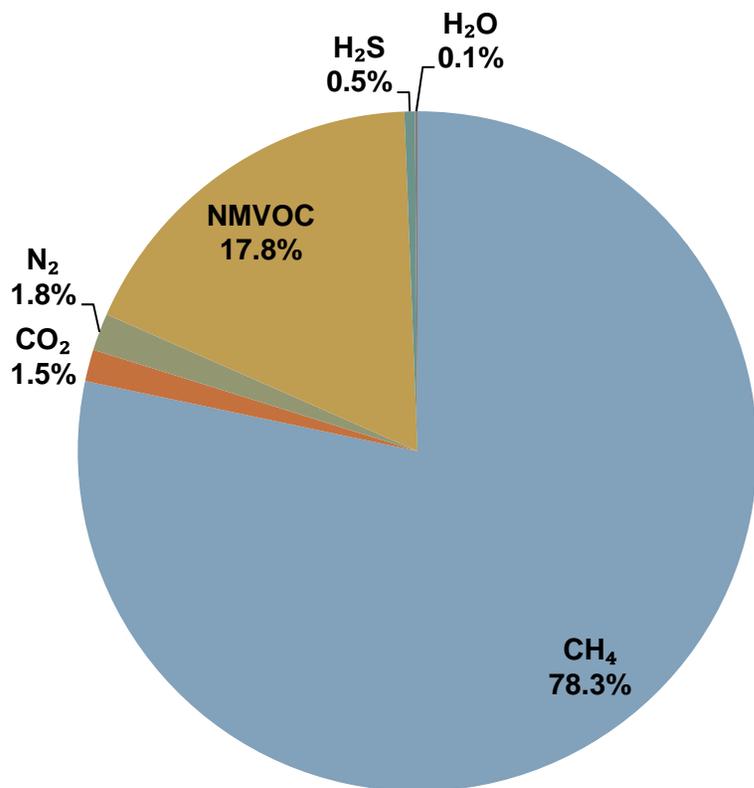
$\text{CO}_2 = 1$   
 $\text{CH}_4 = 25$   
 $\text{N}_2\text{O} = 298$   
 $\text{SF}_6 = 22,800$

# NETL Life Cycle Model for Natural Gas

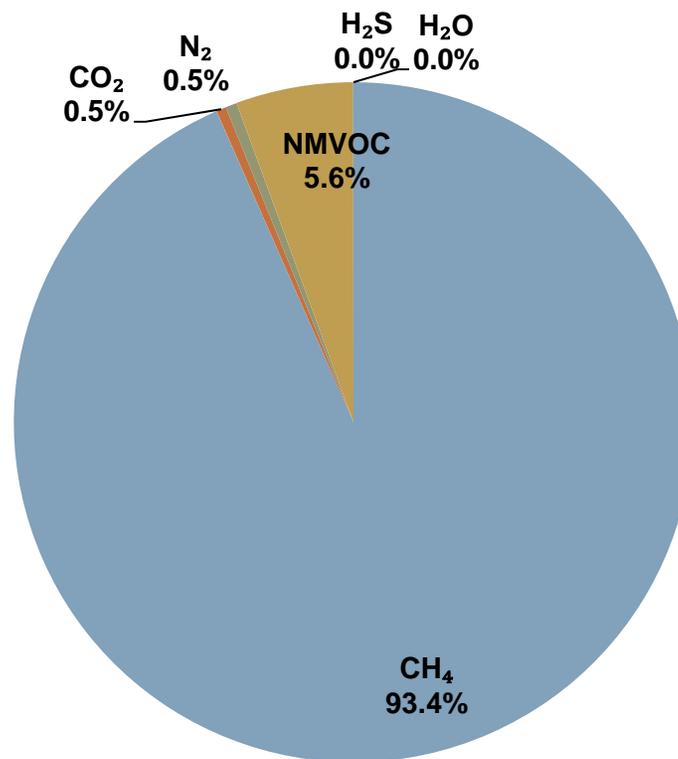


# Natural Gas Composition by Mass

Production Gas



Pipeline Quality Gas



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 Conventional Well	Onshore Associated Well	Offshore Conventional Well	Tight Sands - Vertical Well	Barnett Shale - Horizontal Well	Coal Bed Methane (CBM) Well
<b>Natural Gas Source</b>							
Contribution to 2009 Natural Gas Mix	Percent	23%	7%	13%	32%	16%	9%
Estimated Ultimate Recovery (EUR), Production Gas	BCF/well	8.6	4.4	67.7	1.2	3.0	0.2
Production Rate (30-yr average)	MCF/day	782	399	6,179	110	274	20
<b>Natural Gas Extraction Well</b>							
Flaring Rate at Extraction Well Location	Percent	51%	51%	51%	15%	15%	51%
Well Completion, Production Gas (prior to flaring)	MCF/completion	47	47	47	4,657	11,643	63
Well Workover, Production Gas (prior to flaring)	MCF/workover	3.1	3.1	3.1	4,657	11,643	63
Well Workover, Number per Well Lifetime	Workovers/well	1.1	1.1	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 <sub>4</sub> /MCF	0.11	0.11	0.0001	0.11	0.11	0.11
Other Sources of Emissions, Point Source (prior to flaring)	lb CH <sub>4</sub> /MCF	0.003	0.003	0.002	0.003	0.003	0.003
Other Sources of Emissions, Fugitive	lb CH <sub>4</sub> /MCF	0.043	0.043	0.010	0.043	0.043	0.043

# Natural Gas Processing Plant Modeling Properties

Property	Units	Onshore Conventional Well	Onshore Associated Well	Offshore Conventional Well	Tight Sands - Vertical Well	Barnett Shale - Horizontal Well	Coal Bed Methane (CBM) Well
<b><i>Acid Gas Removal (AGR) and CO<sub>2</sub> Removal Unit</i></b>							
Flaring Rate for AGR and CO <sub>2</sub> Removal Unit	Percent				100%		
Methane Absorbed into Amine Solution	lb CH <sub>4</sub> /MCF				0.04		
Carbon Dioxide Absorbed into Amine Solution	lb CO <sub>2</sub> /MCF				0.56		
Hydrogen Sulfide Absorbed into Amine Solution	lb H <sub>2</sub> S/MCF				0.21		
NM VOC Absorbed into Amine Solution	lb NM VOC/MCF				6.59		
<b><i>Glycol Dehydrator Unit</i></b>							
Flaring Rate for Dehydrator Unit	Percent				100%		
Water Removed by Dehydrator Unit	lb H <sub>2</sub> O/MCF				0.045		
Methane Emission Rate for Glycol Pump & Flash Separator	lb CH <sub>4</sub> /MCF				0.0003		
<b><i>Pneumatic Devices &amp; Other Sources of Emissions</i></b>							
Flaring Rate for Other Sources of Emissions	Percent				100%		
Pneumatic Device Emissions, Fugitive	lb CH <sub>4</sub> /MCF				0.0003		
Other Sources of Emissions, Point Source (prior to flaring)	lb CH <sub>4</sub> /MCF				0.02		
Other Sources of Emissions, Fugitive	lb CH <sub>4</sub> /MCF				0.03		

# Natural Gas Processing Plant Modeling Properties

Property	Units	Onshore Conventional Well	Onshore Associated Well	Offshore Conventional Well	Tight Sands - Vertical Well	Barnett Shale - Horizontal Well	Coal Bed Methane (CBM) Well
<b>Natural Gas Compression at Gas Plant</b>							
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 Conventional Well	Onshore Associated Well	Offshore Conventional Well	Tight Sands - Vertical Well	Barnett Shale - Horizontal Well	Coal Bed Methane (CBM) Well
<b>Natural Gas Emissions on Transmission Infrastructure</b>							
Pipeline Transport Distance (national average)	Miles				604		
Transmission Pipeline Infrastructure, Fugitive	lb CH <sub>4</sub> /MCF-Mile				0.0003		
Transmission Pipeline Infrastructure, Fugitive (per 604 miles)	lb CH <sub>4</sub> /MCF				0.18		
<b>Natural Gas Compression on Transmission Infrastructure</b>							
Distance Between Compressor Stations	Miles				75		
Compression, Gas-powered Reciprocating	Percent				29%		
Compression, Gas-powered Centrifugal	Percent				64%		
Compression, Electrical Centrifugal	Percent				7%		

# Uncertainty Analysis Modeling Parameters

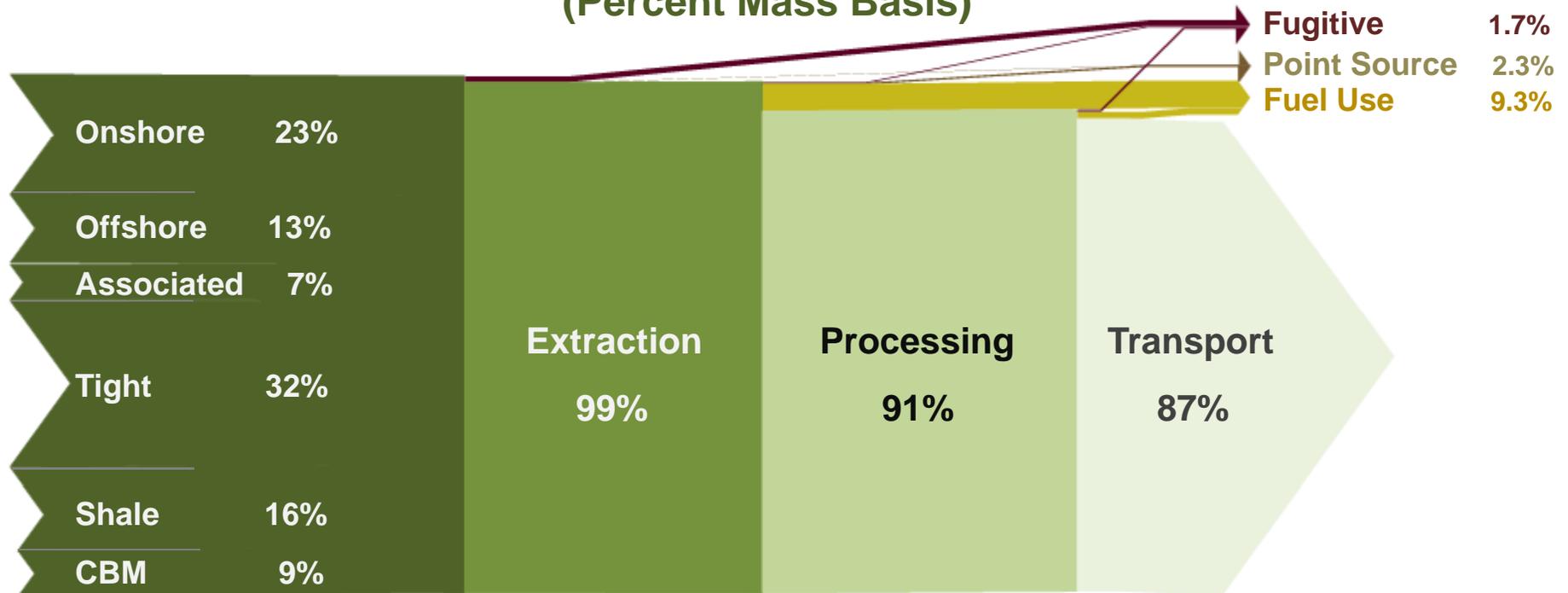
Parameter	Units	Scenario	Onshore Conventional Well	Onshore Associated Well	Offshore Conventional Well	Tight Sands - Vertical Well	Barnett Shale - Horizontal Well	Coal Bed Methane (CBM) Well
Production Rate	MCF/day	Low	403 (-49%)	254 (-36%)	3,140 (-49%)	77 (-30%)	192 (-30%)	14 (-30%)
		<b>Nominal</b>	<b>782</b>	<b>399</b>	<b>6,179</b>	<b>110</b>	<b>274</b>	<b>20</b>
		High	1,545 (+97%)	783 (+96%)	12,284 (+99%)	142 (+30%)	356 (+30%)	26 (+30%)
Flaring Rate at Well	%	Low	41% (-20%)	41% (-20%)	41% (-20%)	12% (-20%)	12% (-20%)	41% (-20%)
		<b>Nominal</b>	<b>51%</b>	<b>51%</b>	<b>51%</b>	<b>15%</b>	<b>15%</b>	<b>51%</b>
		High	61% (+20%)	61% (+20%)	61% (+20%)	18% (+20%)	18% (+20%)	61% (+20%)
Pipeline Distance	miles	Low	483 (-20%)	483 (-20%)	483 (-20%)	483 (-20%)	483 (-20%)	483 (-20%)
		<b>Nominal</b>	<b>604</b>	<b>604</b>	<b>604</b>	<b>604</b>	<b>604</b>	<b>604</b>
		High	725 (+20%)	725 (+20%)	725 (+20%)	725 (+20%)	725 (+20%)	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”.**

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

(Percent Mass Basis)

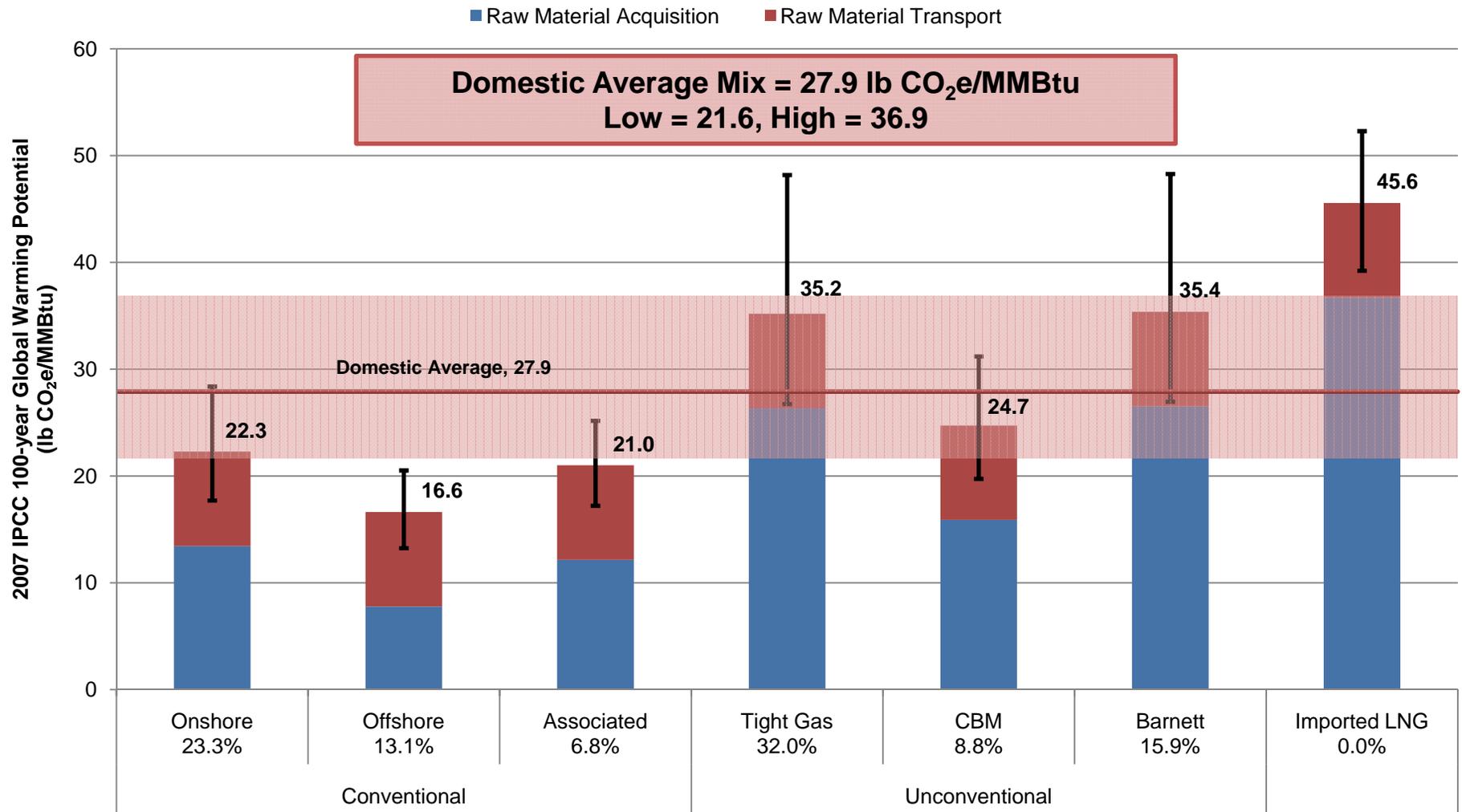


Natural Gas Resource Table	Raw Material Acquisition		Raw Material Transport	Cradle-to-Gate Total:
	Extraction	Processing		
Extracted from Ground	100.0%	n/a	n/a	100.0%
Fugitive Losses	1.2%	0.1%	0.5%	1.7%
Point Source Losses (Vented or Flared)	0.1%	2.3%	0.0%	2.3%
Fuel Use	0.0%	7.7%	1.6%	9.3%
Delivered to End User	n/a	n/a	86.7%	86.7%

**13.3% of Natural Gas Extracted from the Earth is Consumed for Fuel Use, Flared, or Emitted to the Atmosphere (point source or fugitive)**

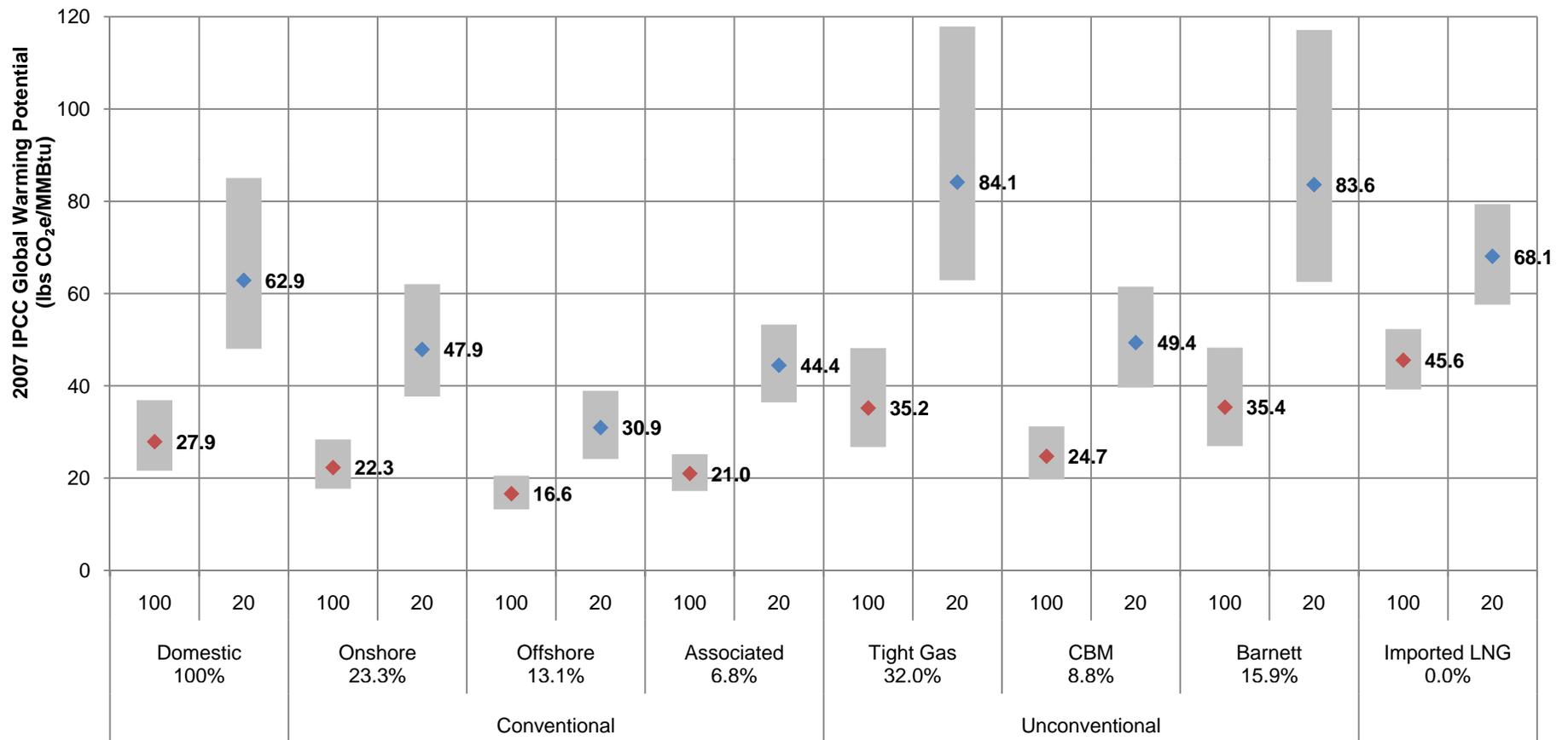
**Of this, 70% is Used to Power Equipment**

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



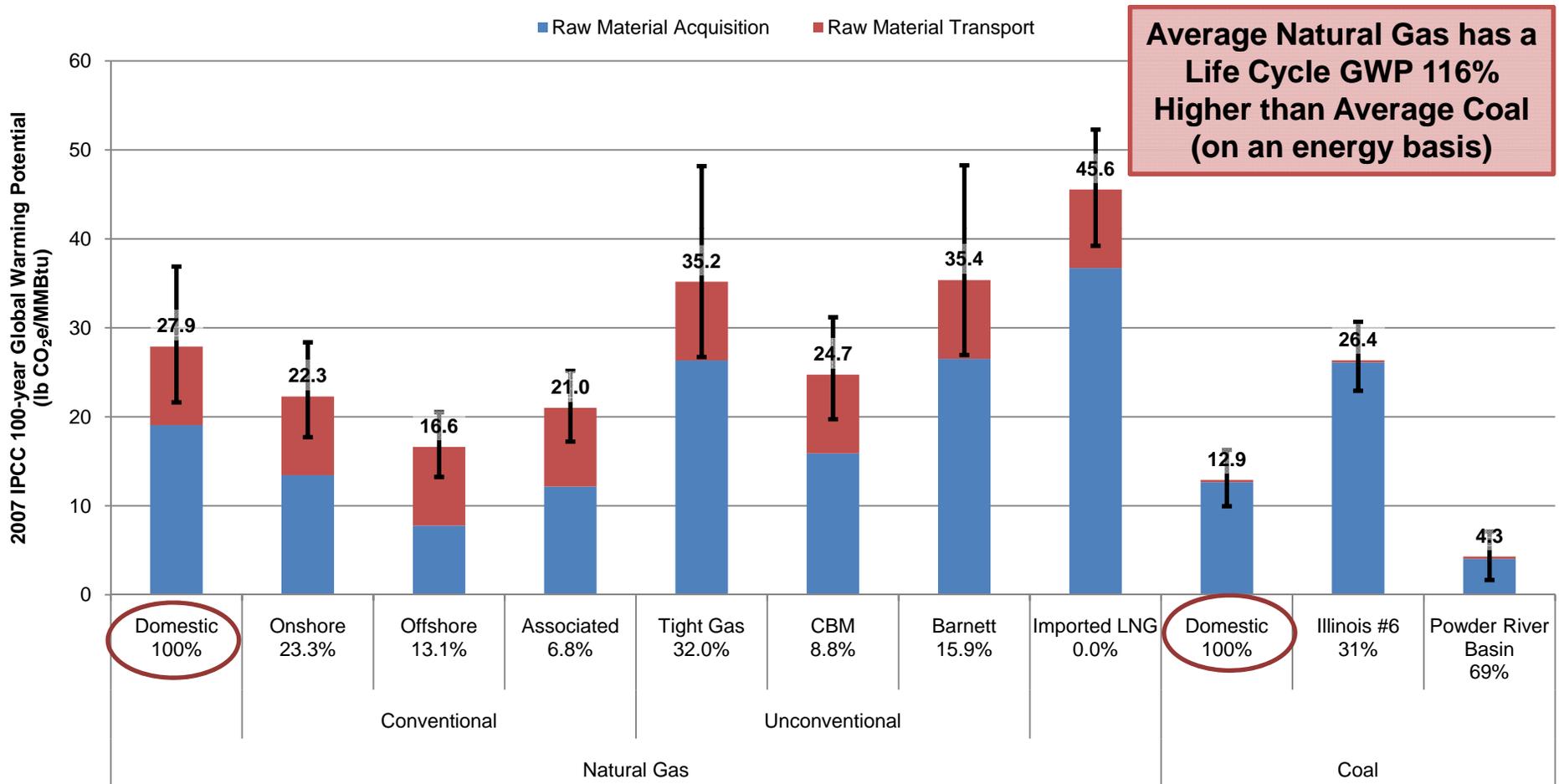
# Life Cycle GHG Results for Average Natural Gas Extraction and Delivery to a Large End-User

**Comparison of 2007 IPCC GWP Time Horizons:**  
**100-year Time Horizon:  $CO_2 = 1, CH_4 = 25, N_2O = 298$**   
**20-year Time Horizon:  $CO_2 = 1, CH_4 = 72, N_2O = 289$**

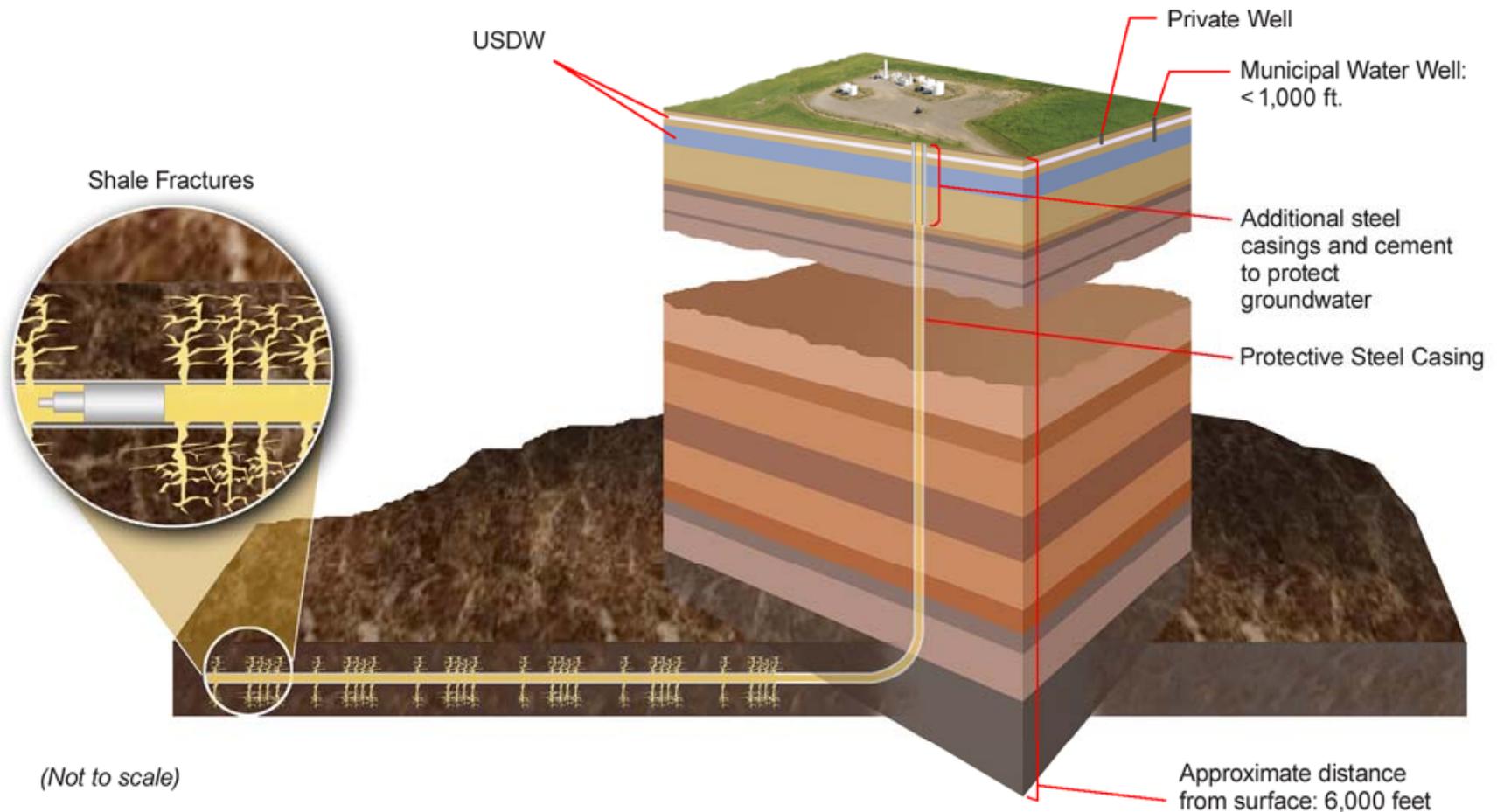


# Life Cycle GHG Results for “Average” Natural Gas Extraction and Delivery to a Large End-User

## Comparison of Natural Gas and Coal Energy Feedstock GHG Profiles



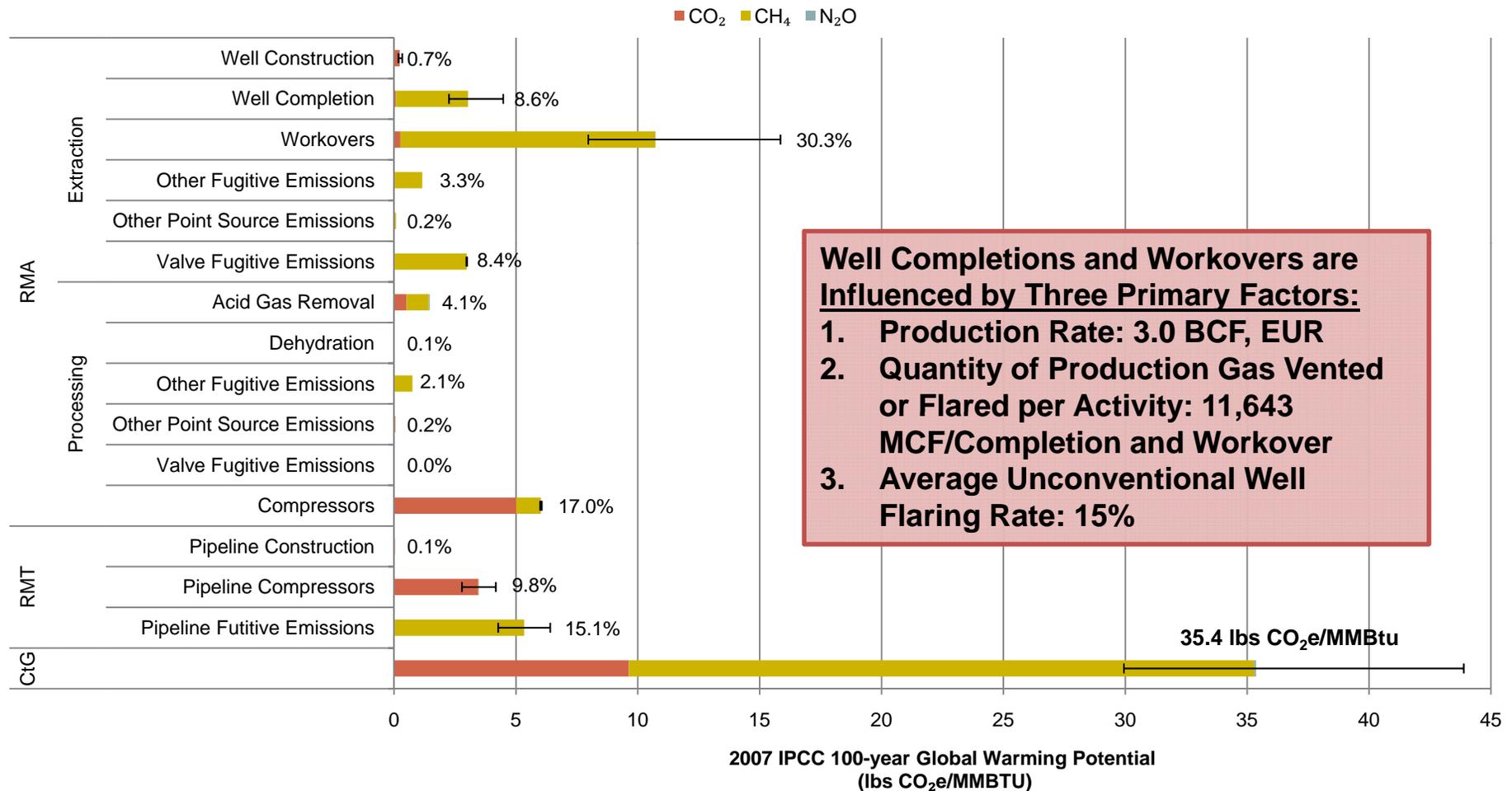
# A Deeper Look at Unconventional Natural Gas Extraction via Horizontal Well, Hydraulic Fracturing (*the Barnett Shale Model*)



(Not to scale)

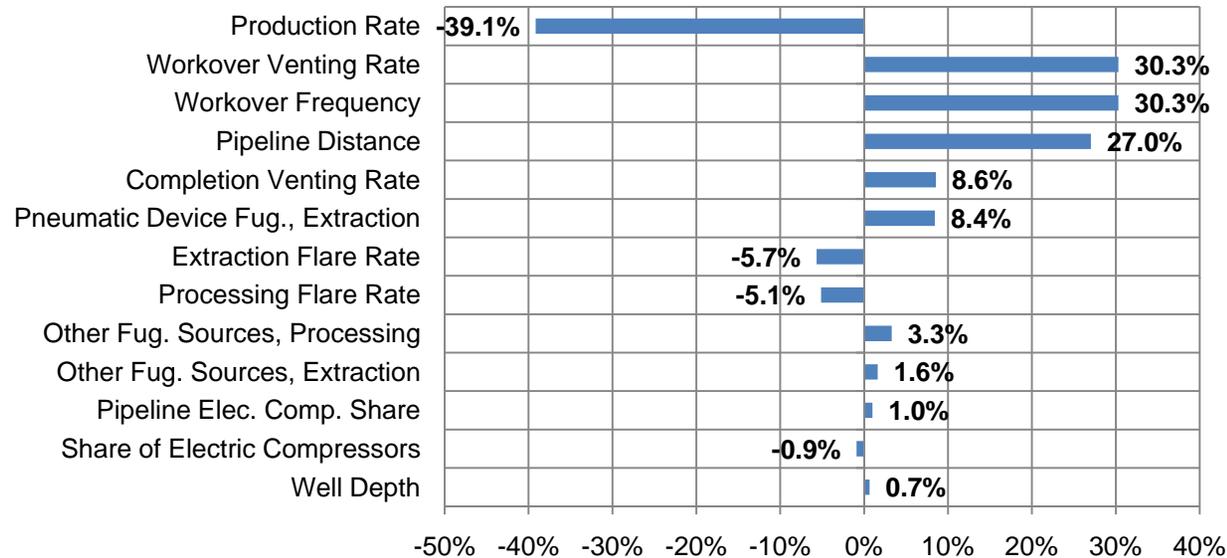
# NETL Upstream Natural Gas Profile: Barnett Shale: Horizontal Well, Hydraulic Fracturing

**GWP Result: IPCC 2007, 100-yr (lb CO<sub>2</sub>e/MMBtu)**



# NETL Upstream Natural Gas Profile: Barnett Shale: Horizontal Well, Hydraulic Fracturing

## *Sensitivity of Model Result to Changes in Parameter Values*



Default Value	Units
11,508	lb/day
489,023	lb/episode
0.118	episodes/yr
604	miles
489,023	lb/episode
0.001210	lb fugitives/lb extracted gas
15.0	%
100	%
0.001119	lb fugitives/lb extracted gas
0.001089	lb fugitives/lb processed gas
7	%
25	%
13,000	feet

"0%" = 35.4 lb CO<sub>2</sub>e/MMBtu Delivered; IPCC 2007, 100-yr Time Horizon

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 5% increase in Production Rate from 11,508 lb/day to 12,083 lb/day would result in a 1.96% (5% of 39.1%) decrease in cradle-to-gate GWP, from 35.4 to 34.7 lbs CO<sub>2</sub>e/MMBtu. A 5% increase in Well Depth to 13,650 feet results in a 0.035% increase to 35.41 – the result is less sensitive to changes in Well Depth than Production Rate.

**Question #6:**

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

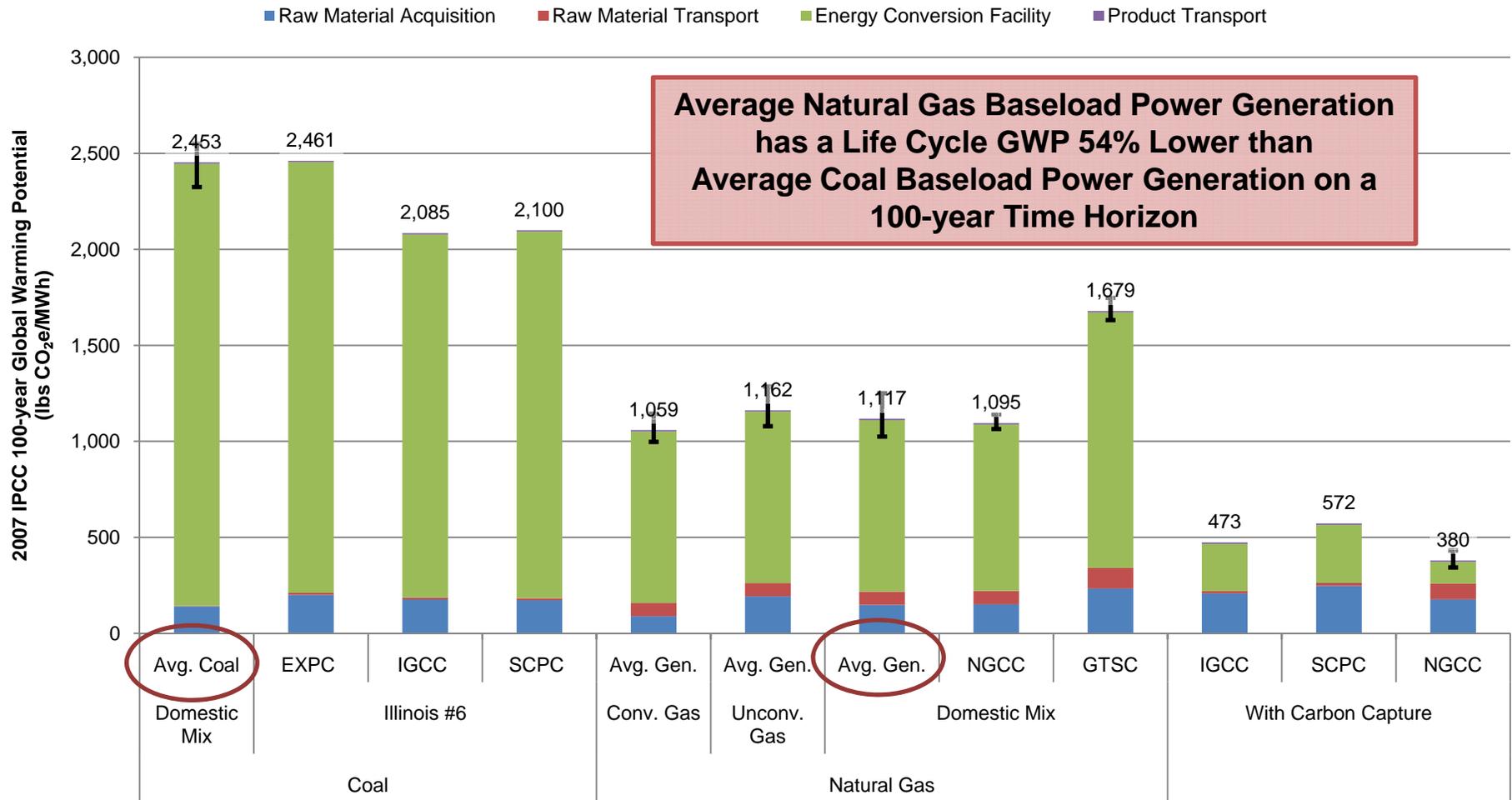
# Power Technology Modeling Properties

Plant Type	Plant Type Abbreviation	Fuel Type	Capacity (MW)	Capacity Factor	Net Plant HHV Efficiency
2009 Average Coal Fired Power Plant <sup>a</sup>	Avg. Coal	Domestic Average	Not Calculated	Not Calculated	33.0%
Existing Pulverized Coal Plant	EXPC	Illinois No. 6	434	85%	35.0%
Integrated Gasification Combined Cycle Plant	IGCC	Illinois No. 6	622	80%	39.0%
Super Critical Pulverized Coal Plant	SCPC	Illinois No. 6	550	85%	36.8%
2009 Average Baseload (>40% CapFac) Natural Gas Plant <sup>a</sup>	Avg. Gen.	Domestic Average	Not Calculated	Not Calculated	47.1%
Natural Gas Combined Cycle Plant	NGCC	Domestic Average	555	85%	50.2%
Gas Turbine Simple Cycle	GTSC	Domestic Average	360	85%	32.6%
Integrated Gasification Combined Cycle Plant with 90% Carbon Capture	IGCC/CCS	Illinois No. 6	543	80%	32.6%
Super Critical Pulverized Coal Plant with 90% Carbon Capture	SCPC/CCS	Illinois No. 6	550	85%	26.2%
Natural Gas Combined Cycle Plant with 90% Carbon Capture	NGCC/CCS	Domestic Average	474	85%	42.8%

<sup>a</sup> Net plant higher heating value (HHV) efficiency reported is based on the weighted mean of the 2007 fleet as reported by U.S. EPA, eGrid (2010).

# Comparison of Power Generation Technology Life Cycle GHG Footprints

*Raw Material Acquisition thru Delivery to End Customer (lb CO<sub>2</sub>e/MWh)*



**Average Natural Gas Baseload Power Generation has a Life Cycle GWP 54% Lower than Average Coal Baseload Power Generation on a 100-year Time Horizon**

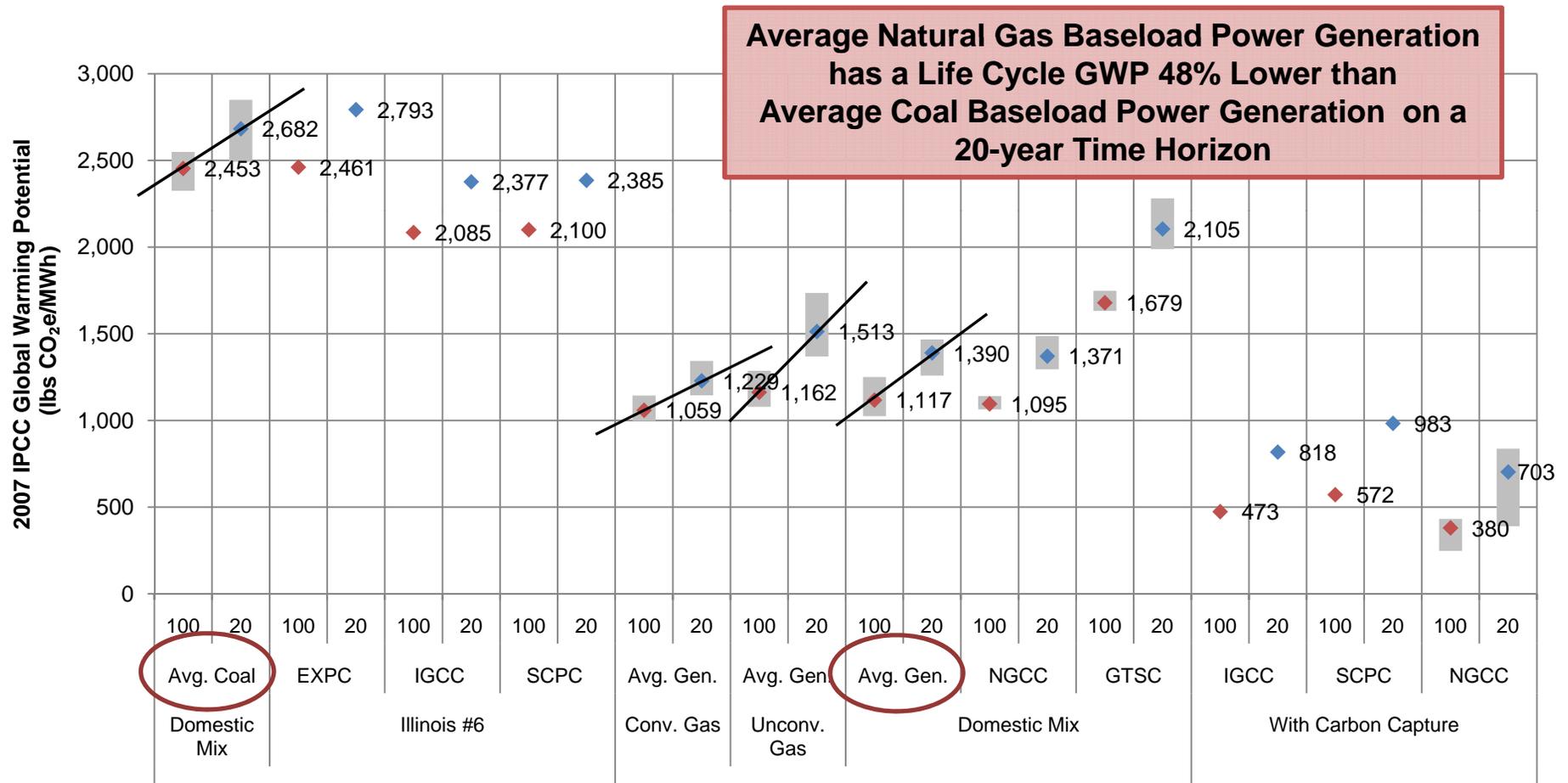
Note: EXPC, IGCC, SCPC, and NGCC (combustion) results, with and without CCS, are based on scenario specific modeling parameters; not industry average data.

# Comparison of Power Generation Technology Life Cycle GHG Footprints (lbs CO<sub>2</sub>e/MWh)

Comparison of 2007 IPCC GWP Time Horizons:

100-year Time Horizon: CO<sub>2</sub> = 1, CH<sub>4</sub> = 25, N<sub>2</sub>O = 298

20-year Time Horizon: CO<sub>2</sub> = 1, CH<sub>4</sub> = 72, N<sub>2</sub>O = 289



# 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<sub>4</sub>, H<sub>2</sub>S, 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 fracturing fluid
- Direct and indirect GHG emissions from land use from access roads and well pads
- Gas exploration
- Treatment of fracturing 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<sub>2</sub> at the power plant and sequester it in a saline aquifer or oil bearing reservoir (CO<sub>2</sub>-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

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