NATIONAL ENERGY TECHNOLOGY LABORATORY

Life Cycle Assessment of Natural Gas Extraction, Delivery and Electricity Production

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U.S. DEPARTMENT OF ENERGY

National Energy Technology Laboratory

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

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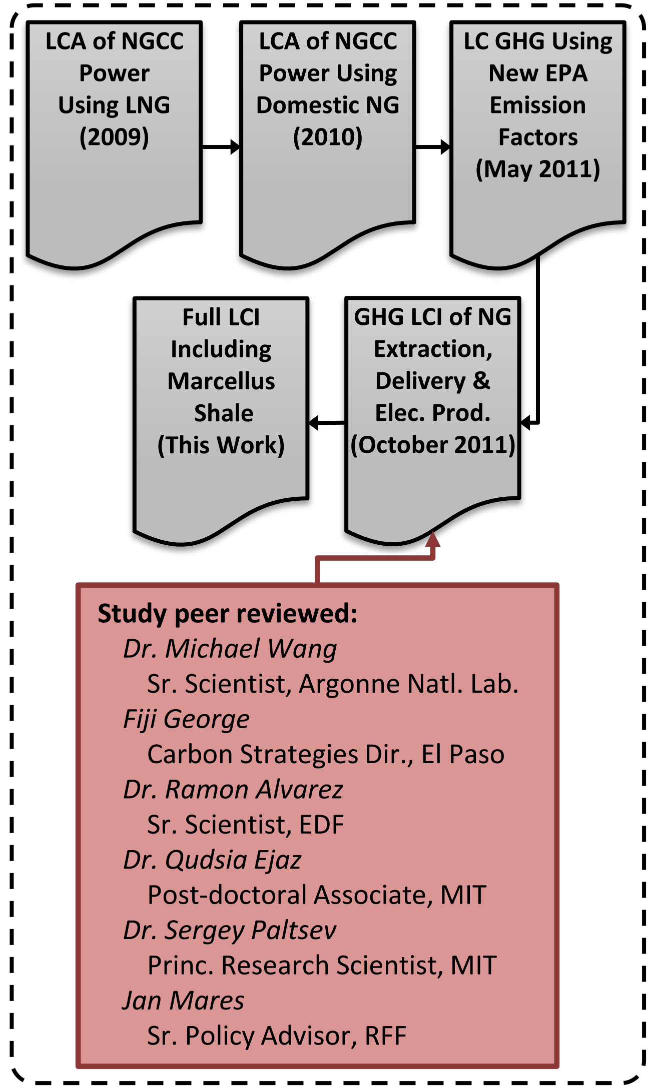
Type of LCA Conducted Depends On:

What you want to know

- **The environmental footprint of U.S. natural gas (including unconventional) extraction, processing, and delivery to a large end-user (e.g., power plant)**
- **The comparison of natural gas-fired baseload power to coal-fired baseload power on the basis of a delivered MWh**

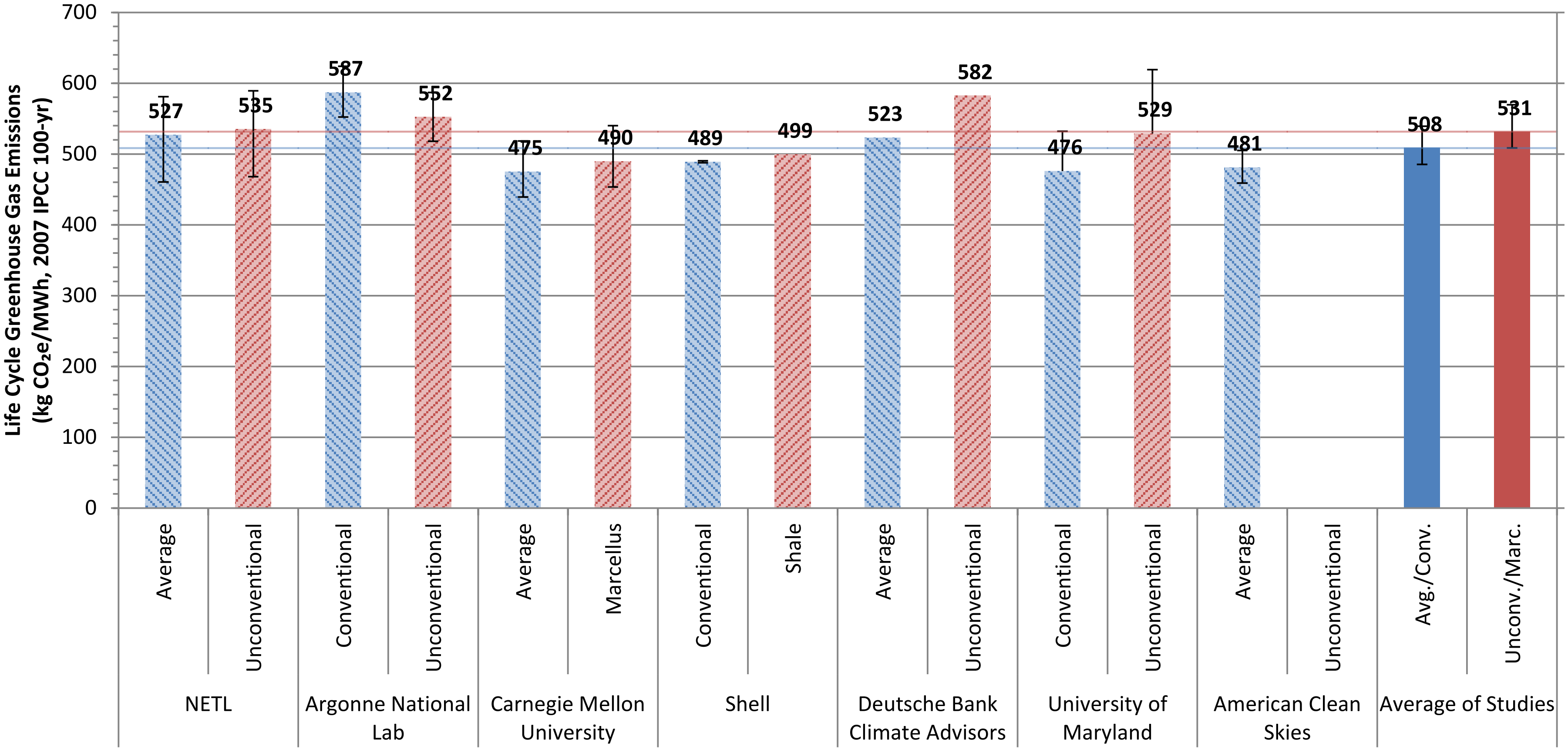
How you will use the results

- **Inform research and development activities to reduce the environmental footprint of both energy feedstock extraction and power production in existing and future operations**



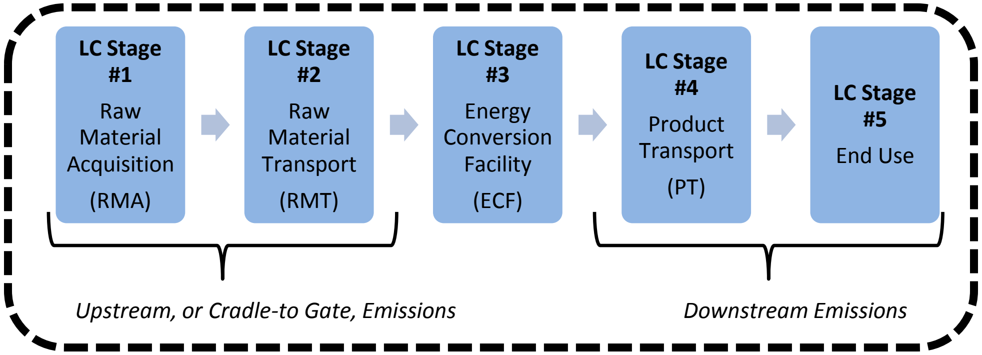
General Agreement Among LC GHG Estimates

- Much of the variability among recent (2011) studies, and some of the uncertainty within studies, comes from assumption about NG power plant heat rate or efficiency, ranging between 39-50%
- Unconventional, shale or Marcellus natural gas (generally) has more LC GHGs than average or conventional gas, but only by about 4% - within the uncertainty bounds of the studies



LCA Overview: Definitions, Boundaries, Metrics, Purpose

- **Compilation and evaluation of inputs, outputs, and potential environmental impacts of a product or service throughout its life cycle, from raw material acquisition to final use and disposal**
- **The ability to compare different technologies depends on functional unit (denominator); e.g., for energy studies:**
  - 1 MWh of electricity delivered to end user
  - 1 MJ of fuel combusted



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

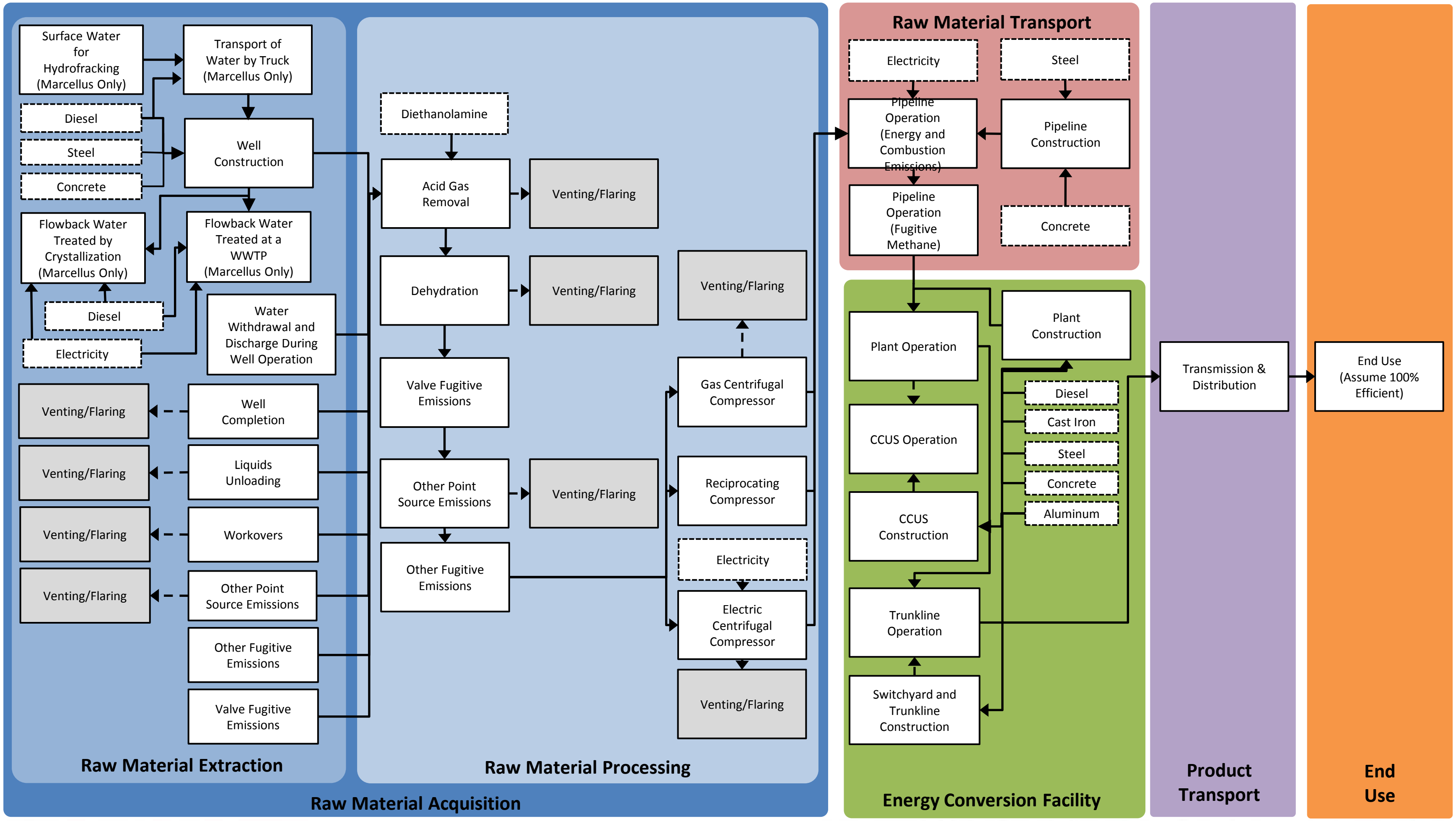
GHG	20-year	100-year (Default)	500-year
CO_2	1	1	1
CH_4	72	25	7.6
N_2O	289	298	153
SF_6	16,300	22,800	32,600

- **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
- **Life Cycle Cost**
  - Cost of Electricity (COE), Total Overnight Cost (TOC)

Boundaries for Natural Gas Life Cycle

Cradle-to-grave
- 1 MWh of electricity delivered to the end customer
- Compared 22 different fuel/baseload plant combinations (16 natural gas, 6 coal)

Cradle-to-gate
- 1 MJ of domestic fuel delivered to large end user
- Compared 22 fuel sources/mixes (19 natural gas, 3 coal)



Natural Gas Extraction Modeling Properties

Property	Units	Conventional			Unconventional			
		Onshore	Associated	Offshore	Tight Gas	Barnett	Marcellus	Coal Bed Methane
Natural Gas Source								
Contribution to 2009 Natural Gas Mix	Percent	44.3%			55.7%			
		24.8%	6.7%	12.9%	31.4%	15.6%	0.0%	8.6%
Production Rate (30-yr average)	MCF/day	66 (46-86)	121 (85-157)	2,801 (1,960-3,641)	111 (78-144)	274 (192-356)	297 (201-450)	105 (73-136)
Estimated Ultimate Recovery (EUR)	BCF	0.5 (0.7-0.9)	1.3 (0.9-1.7)	30.7 (21.5-39.9)	1.2 (0.9-1.6)	3.0 (2.1-3.9)	3.2 (2.2-4.9)	1.1 (0.8-1.5)
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	11,643	63
Well Workover, Production Gas (prior to flaring)	MCF/workover	3.1			4,657	11,643	11,643	63
Well Workover, Number per Well Lifetime	Workovers/well	1.1			3.5	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	n/a
Liquids Unloading, Number per Well Lifetime	Episodes/well	930	n/a	930	n/a	n/a	n/a	n/a
Pneumatic Device Emissions, Fugitive	g CH_4/MCF	49.9		0.05	49.9			
Other Sources of Emissions, Point Source (prior to flaring)	g CH_4/MCF	1.36		0.91	1.36			
Other Sources of Emissions, Fugitive	g CH_4/MCF	19.5		4.54	19.5			

Natural Gas Processing Modeling Properties

Property	Units	Conventional			Unconventional			
		Onshore	Associated	Offshore	Tight Gas	Barnett	Marcellus	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	g CH_4/MCF	18.14						
Carbon Dioxide Absorbed into Amine Solution	g CO_2/MCF	254.0						
Hydrogen Sulfide Absorbed into Amine Solution	g H_2S/MCF	95.25						
NMVOC Absorbed into Amine Solution	g NMVOC/MCF	2,989						
Glycol Dehydrator Unit								
Flaring Rate for Dehydrator Unit	Percent	100%						
Water Removed by Dehydrator Unit	g H_2O/MCF	20.41						
Methane Emission Rate for Glycol Pump & Flash Separator	g CH_4/MCF	0.136						
Pneumatic Devices & Other Sources of Emissions								
Flaring Rate for Other Sources of Emissions	Percent	100%						
Pneumatic Device Emissions, Fugitive	g CH_4/MCF	0.136						
Other Sources of Emissions, Point Source (prior to flaring)	g CH_4/MCF	9.072						
Other Sources of Emissions, Fugitive	g CH_4/MCF	13.61						

Natural Gas Processing Modeling Properties

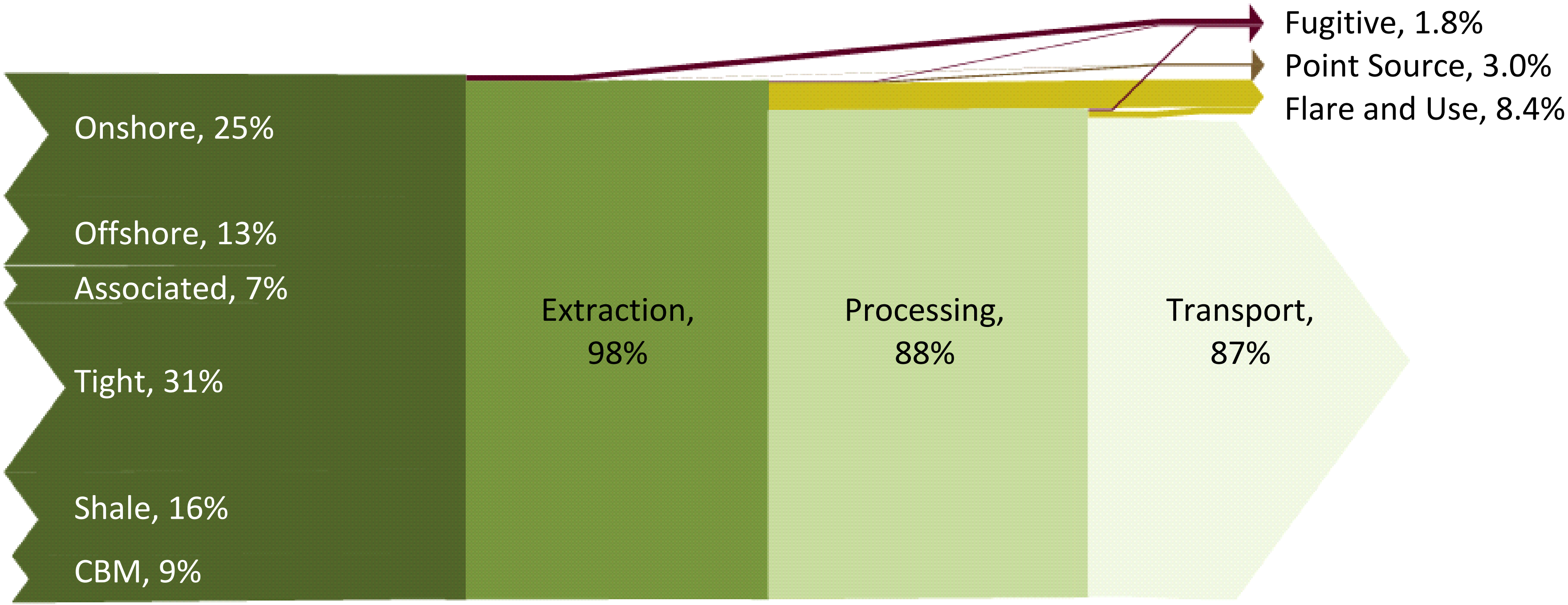
Property	Units	Conventional			Unconventional			
		Onshore	Associated	Offshore	Tight Gas	Barnett	Marcellus	Coal Bed Methane
Natural Gas Compression at Gas Plant								
Compressor, Gas-powered Combustion, Reciprocating	Percent	100%	100%		100%	75%	100%	100%
Compressor, Gas-powered Turbine, Centrifugal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

Natural Gas Transmission Modeling Properties

Property	Units	Conventional			Unconventional			
		Onshore	Associated	Offshore	Tight Gas	Barnett	Marcellus	Coal Bed Methane
Natural Gas Emissions on Transmission Infrastructure								
Pipeline Transport Distance (national average)	km	972 (777 – 1,167)						
Transmission Pipeline Infrastructure, Fugitive	g CH_4/MCF-km	0.219						
Transmission Pipeline Infrastructure, Fugitive (per 972 km)	g CH_4/MCF	81.65						
Natural Gas Compression on Transmission Infrastructure								
Distance Between Compressor Stations	km	121						
Compression, Gas-powered Reciprocating	Percent	78%						
Compression, Gas-powered Centrifugal	Percent	19%						
Compression, Electrical Centrifugal	Percent	3%						

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

(Percent Mass Basis)



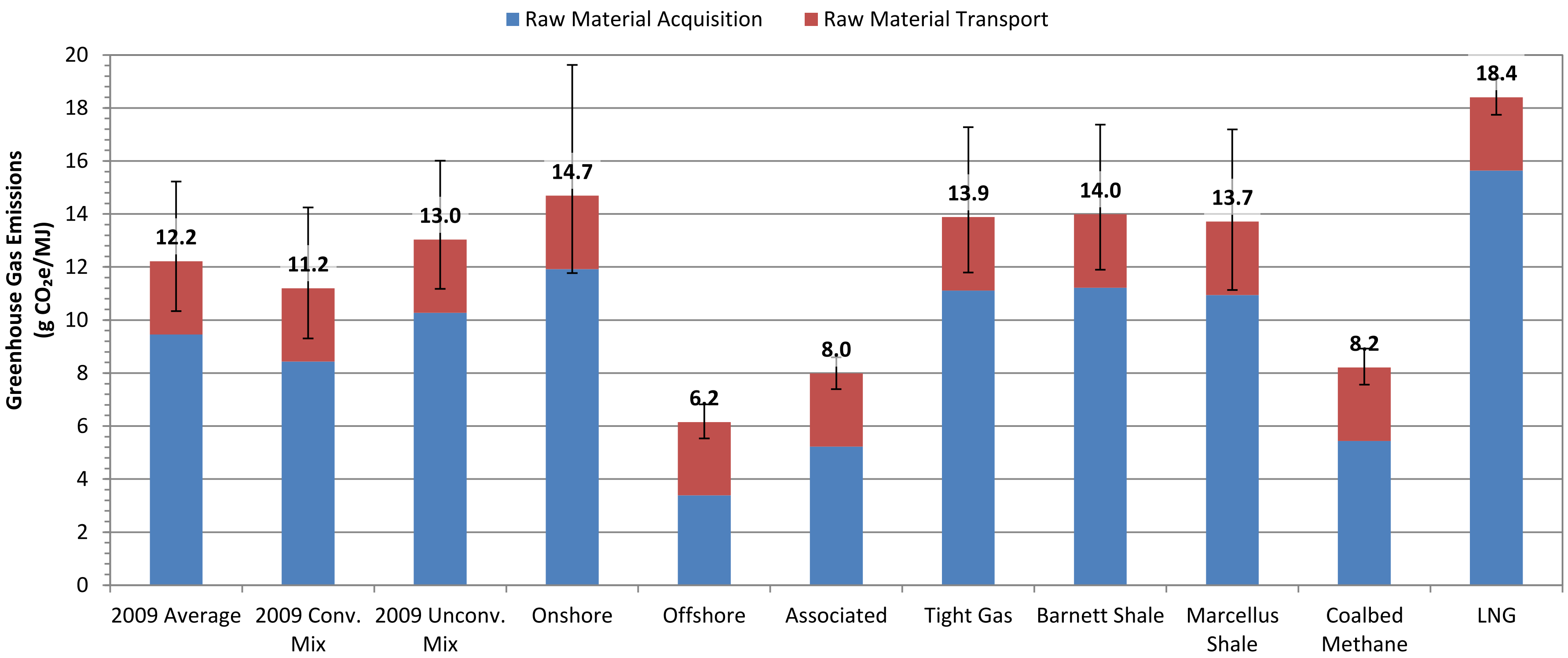
Natural Gas Resource Table	Raw Material Acquisition		Raw Material Transport	Cradle-to-Gate Total:
	Extraction	Processing		
Extracted from Ground	100.0%			100.0%
Fugitive Losses	1.2%	0.1%	0.5%	1.8%
Point Source Losses (Vented or Flared)	0.8%	2.2%	0.0%	3.0%
Fuel Use	0.0%	7.6%	0.8%	8.4%
Delivered to End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

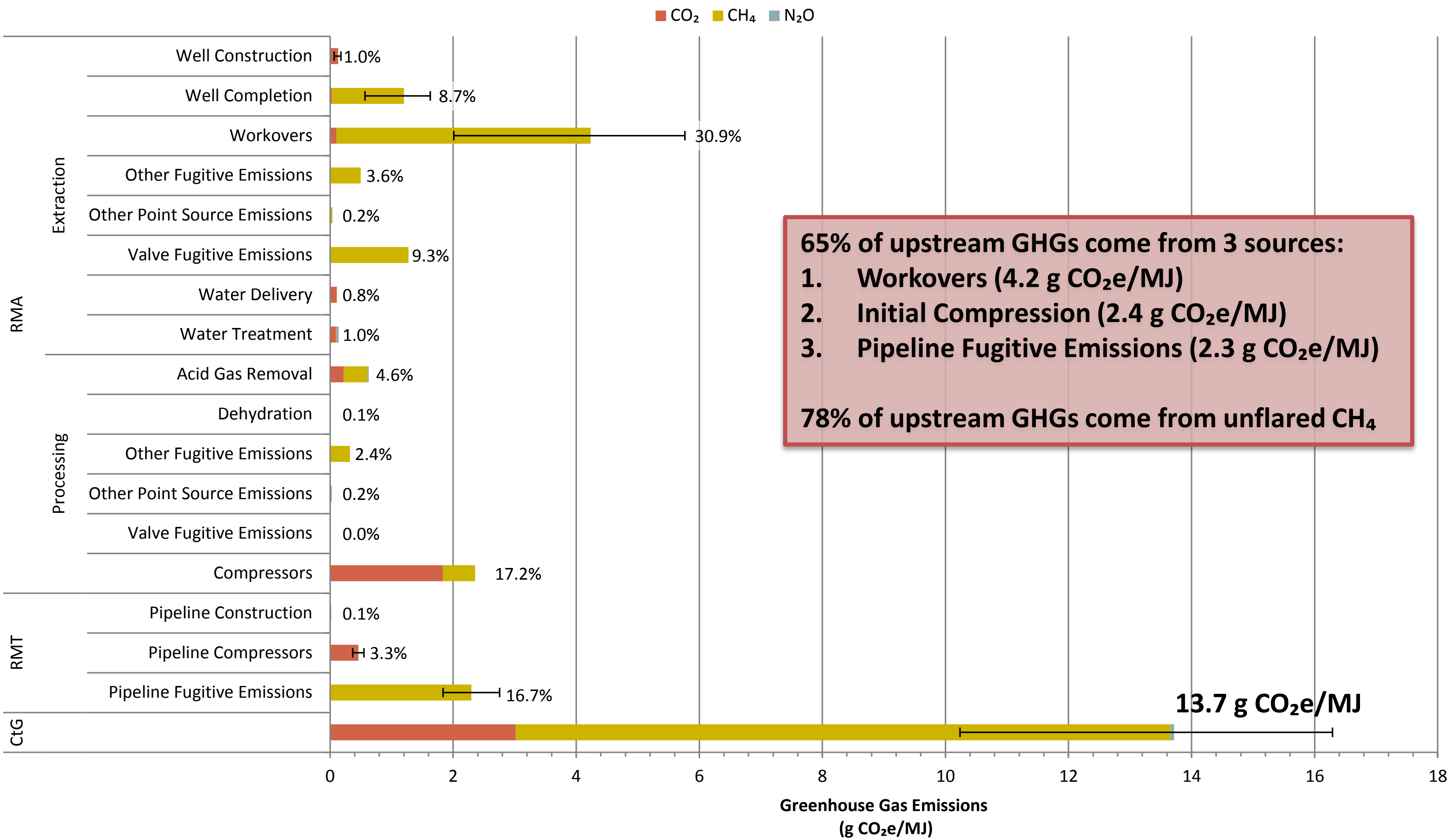
Life Cycle GHG Results for Average Natural Gas Extraction and Delivery to a Large End-User

- **Average conventional gas extraction produces fewer episodic emissions (liquids unloading), but produces less gas; unconventional extraction has more episodic emissions (workovers), but higher production rates**
- **GHGs from both conventional and unconventional sources of natural gas are dominated by unflared methane from episodic emissions**



Carbon dioxide equivalents calculated using 2007 IPCC 100-year GWP

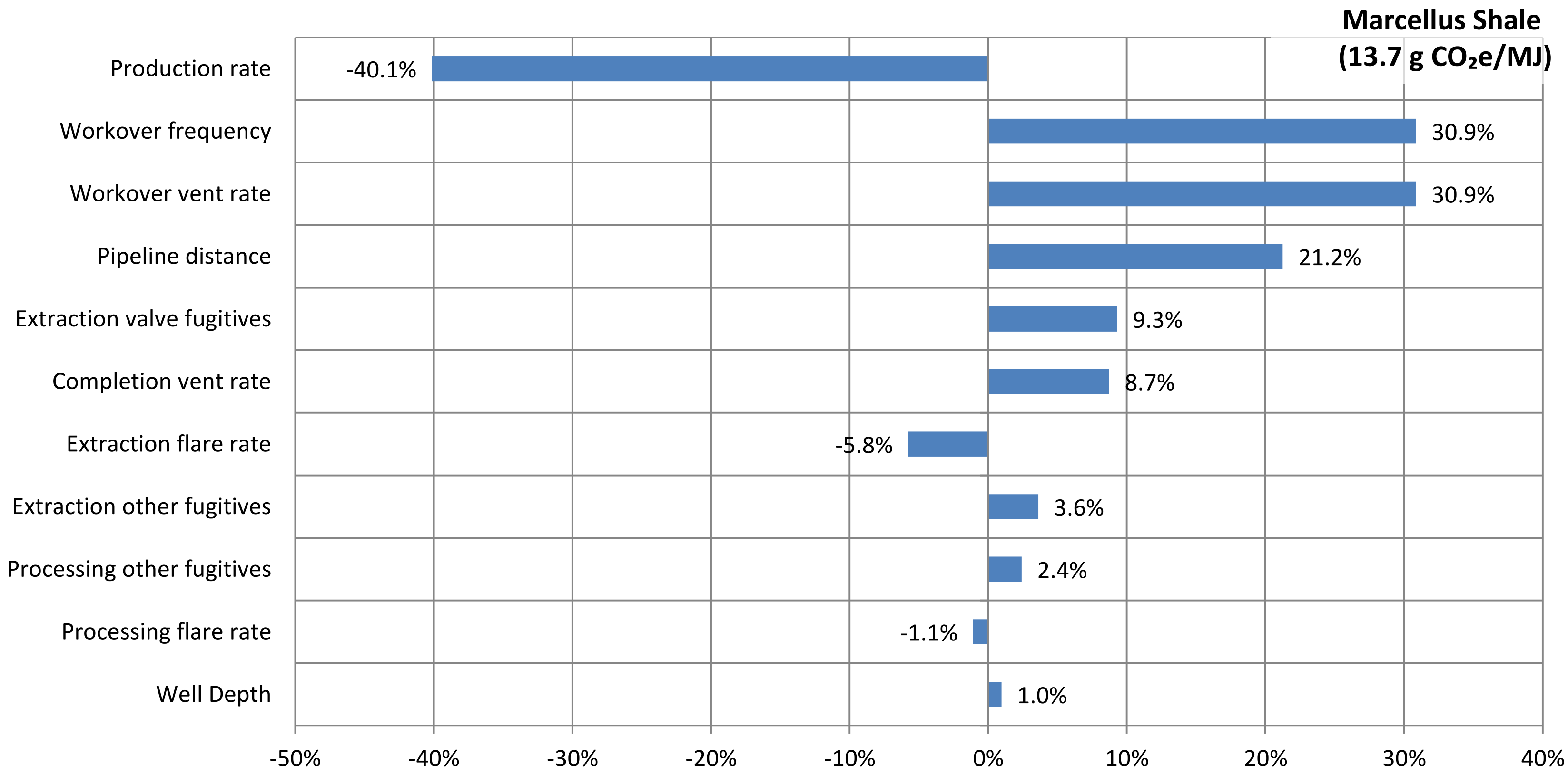
Marcellus Shale Upstream GHG Emission Profile



Carbon dioxide equivalents calculated using 2007 IPCC 100-year GWP

Marcellus Shale Upstream GHG Emission Profiles

Sensitivity of Model Result to Changes in Parameter Values



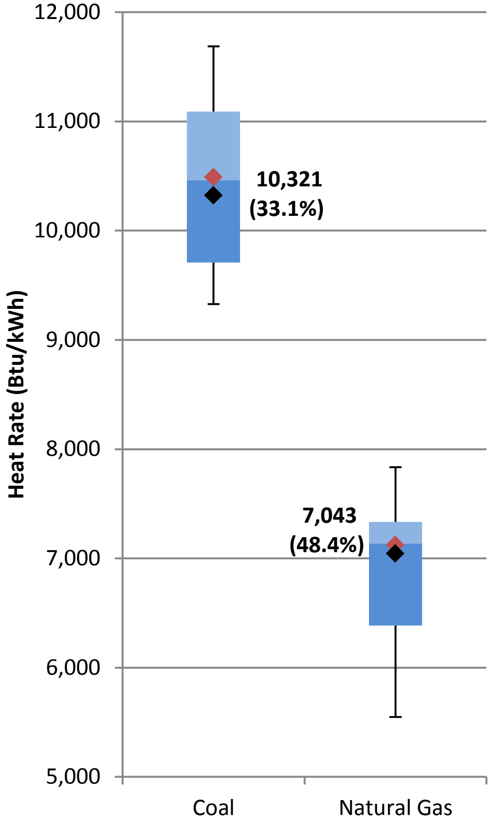
Percentages above are relative to a unit change in parameter value; all parameters are changed by the same amount, allowing comparison of the magnitude of change to the result across all parameters.

Example: A 10% *increase* in Marcellus Production Rate from 201 MCF/day to 221 MCF/day would result in a 4.01% (10% of 40.1%) *decrease* in cradle-to-gate emissions, from 13.7 to 13.2 g CO_2e/MJ.

Carbon dioxide equivalents calculated using 2007 IPCC 100-year GWP

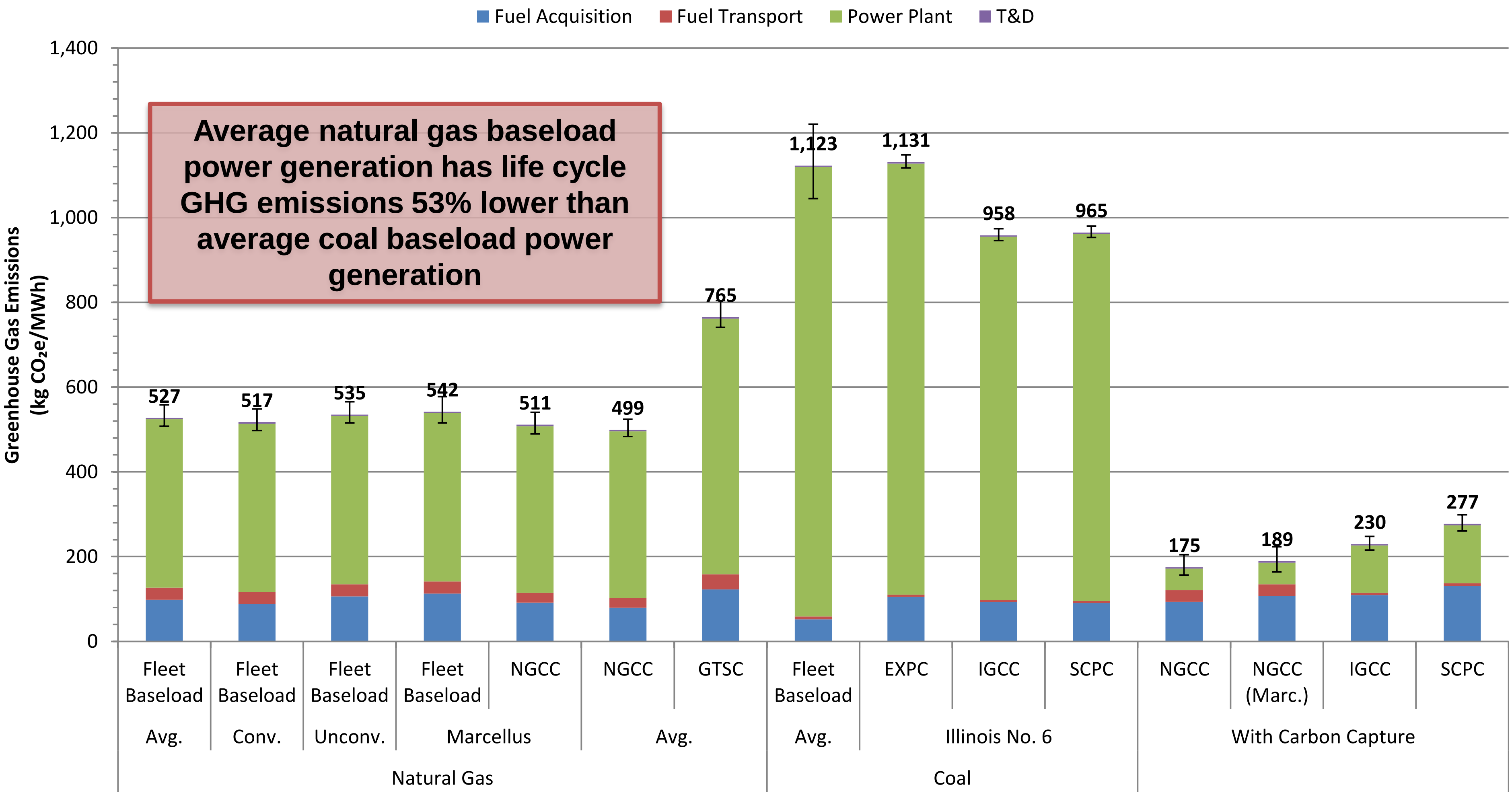
Power Technology and Coal Modeling Properties

Plant Type		Fuel Type	Capacity (MW)	Capacity Factor	Efficiency
Coal-fired	Fleet Baseload (2007 Average)	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	Fleet Baseload (2007 Average)	Varies	> 200	> 60%	48.4%
	Natural Gas Combined Cycle (NGCC)	Varies	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)	Varies	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%	

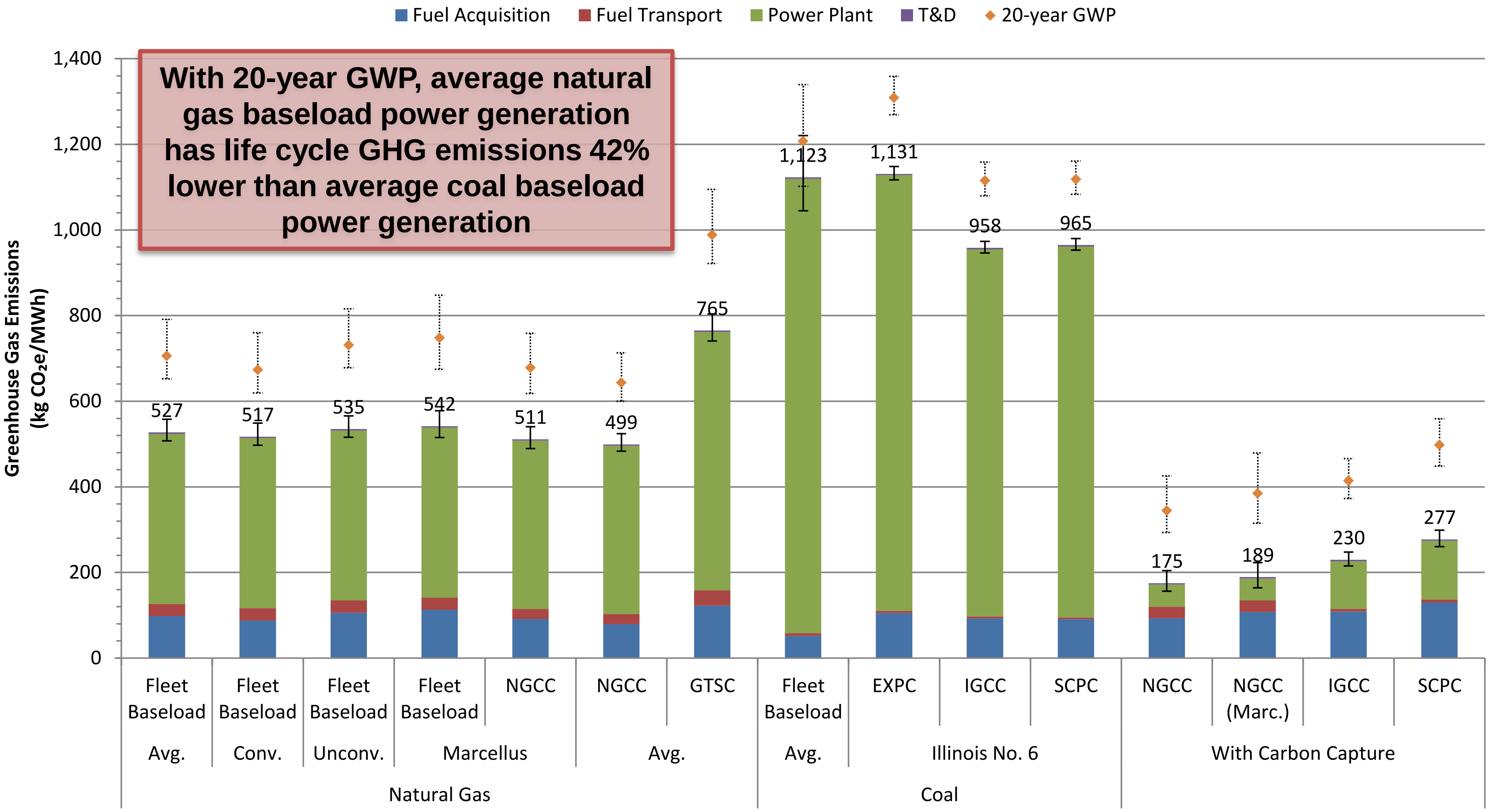
Comparison of Power Generation Technology Life Cycle GHG Footprints



Carbon dioxide equivalents calculated using 2007 IPCC 100-year GWP

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 (kg CO_2e/MWh)

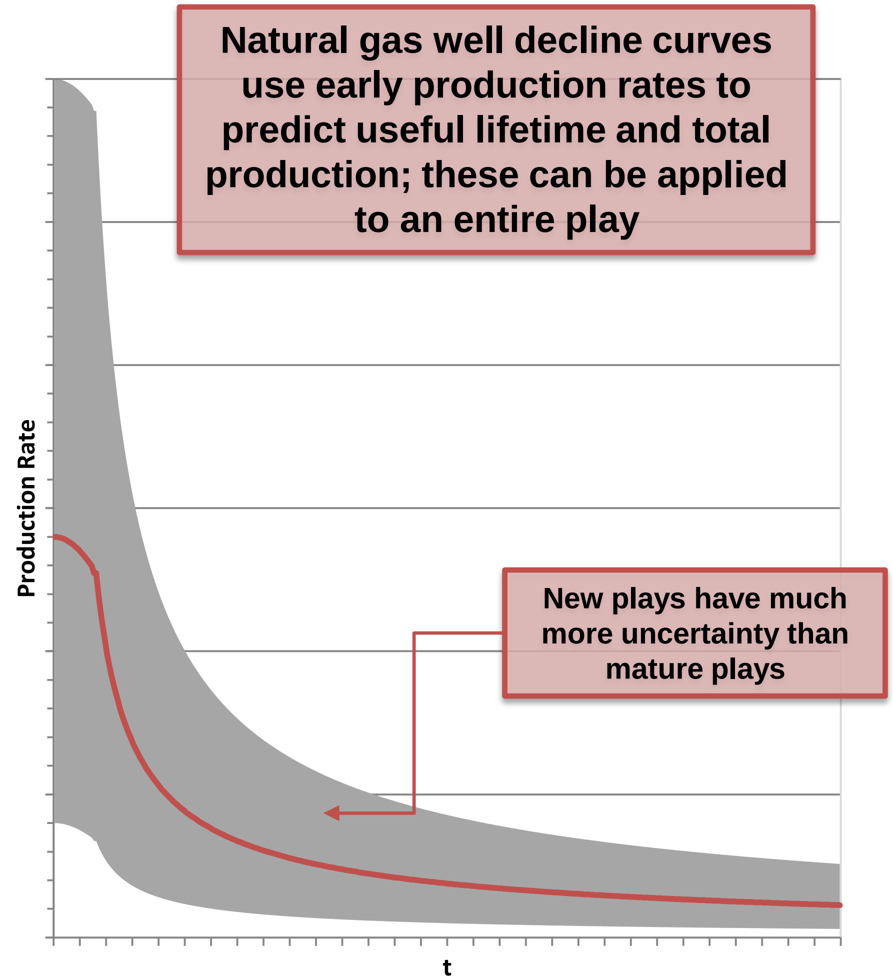


Carbon dioxide equivalents calculated using 2007 IPCC GWPs

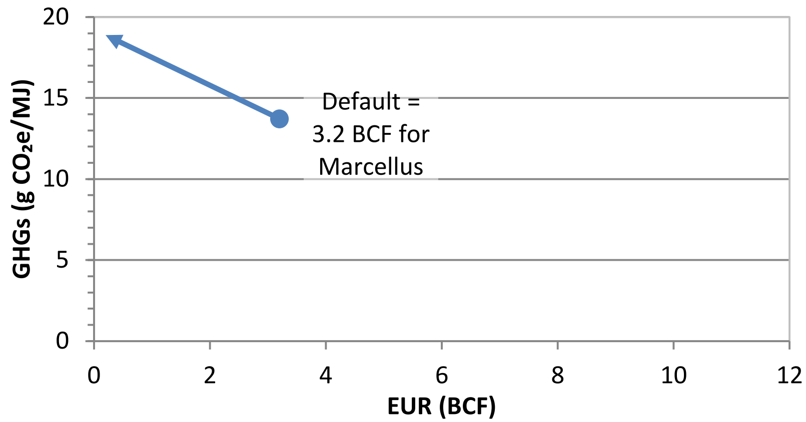
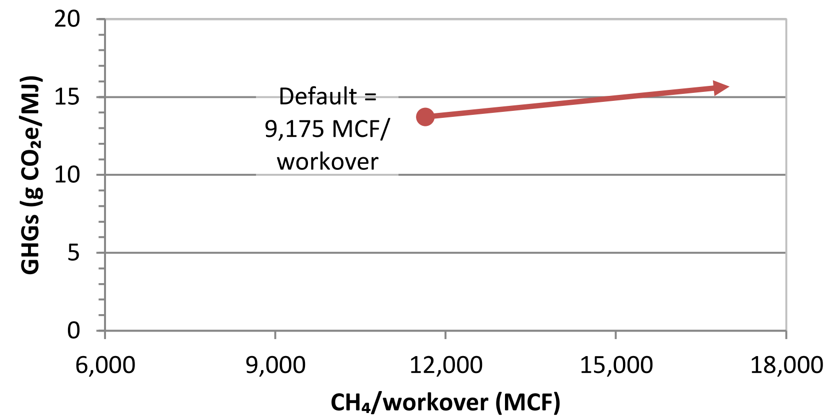
EXPC, IGCC, SCPC, and NGCC (combustion) results, with and without CCS, are based on scenario specific modeling parameters; not industry average data

Uncertainty About Future Production is a Key Driver of Upstream Results

- **Defining temporal and technological boundaries, and the associated uncertainty is critical**
  - *Average* represents what has occurred to this point, projected 30-years into the future
  - *Marginal* represents what will likely occur next, projected 30-years into the future – "What will the next well look like?"
- **Examples**
  - Mature play (onshore), stripper wells
    - Average production is low, so next well is likely better
    - Supported with lots of data
  - Young play (Barnett)
    - Average and marginal similar, but margin uncertain
  - New Play (Marcellus)
    - Average is high, direction of next well highly uncertain



Examples of Marginal GHG Results Drivers

<table>
<tr><th></th><th>Natural
(Parameters we cannot change)</th><th>Technological
(Parameters we can engineer)</th></tr>
<tr><td>Increase GHGs/MJ</td><td>Lower-than-expected technically recoverable resources (decreased denominator)

</td><td>Operators without the capital resources to invest in emission reduction technologies (increased numerator)

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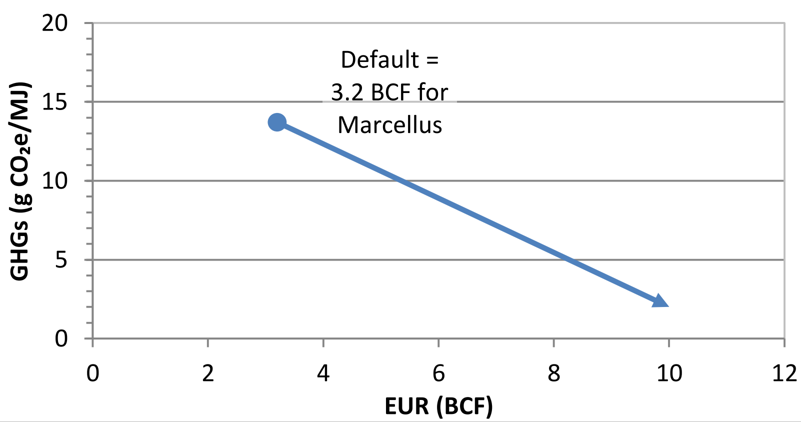
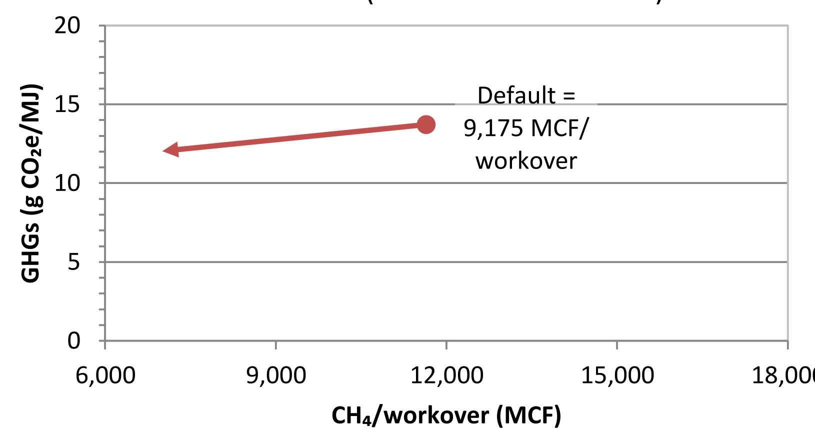
<tr><td>Decrease GHGs/MJ</td><td>Higher-than-expected technically recoverable resources (increased denominator)

</td><td>Advanced hydrofracking technology, green completions, and EPA Gas STAR (decreased numerator)

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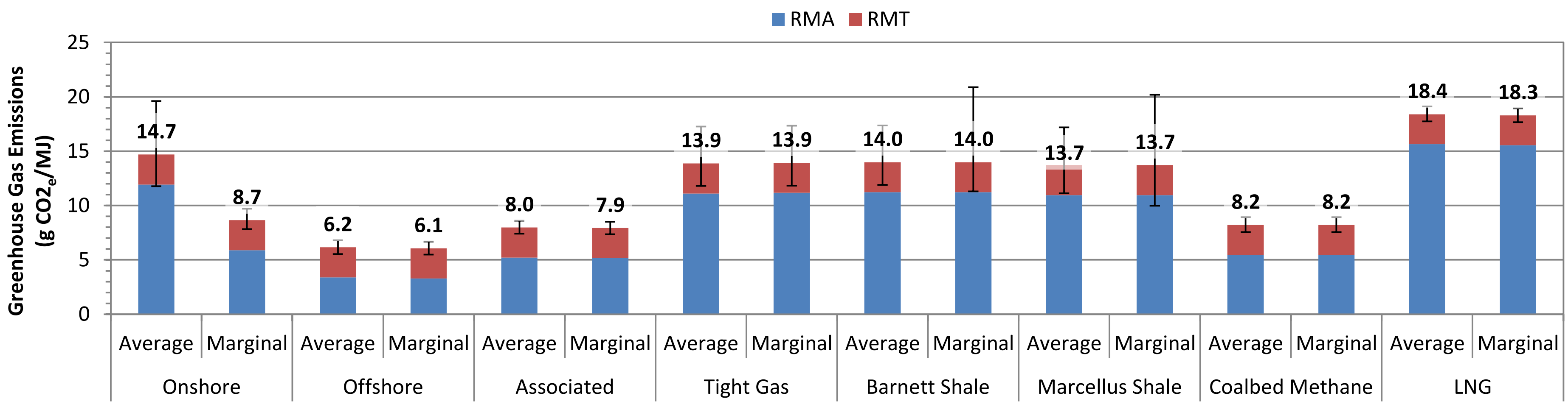
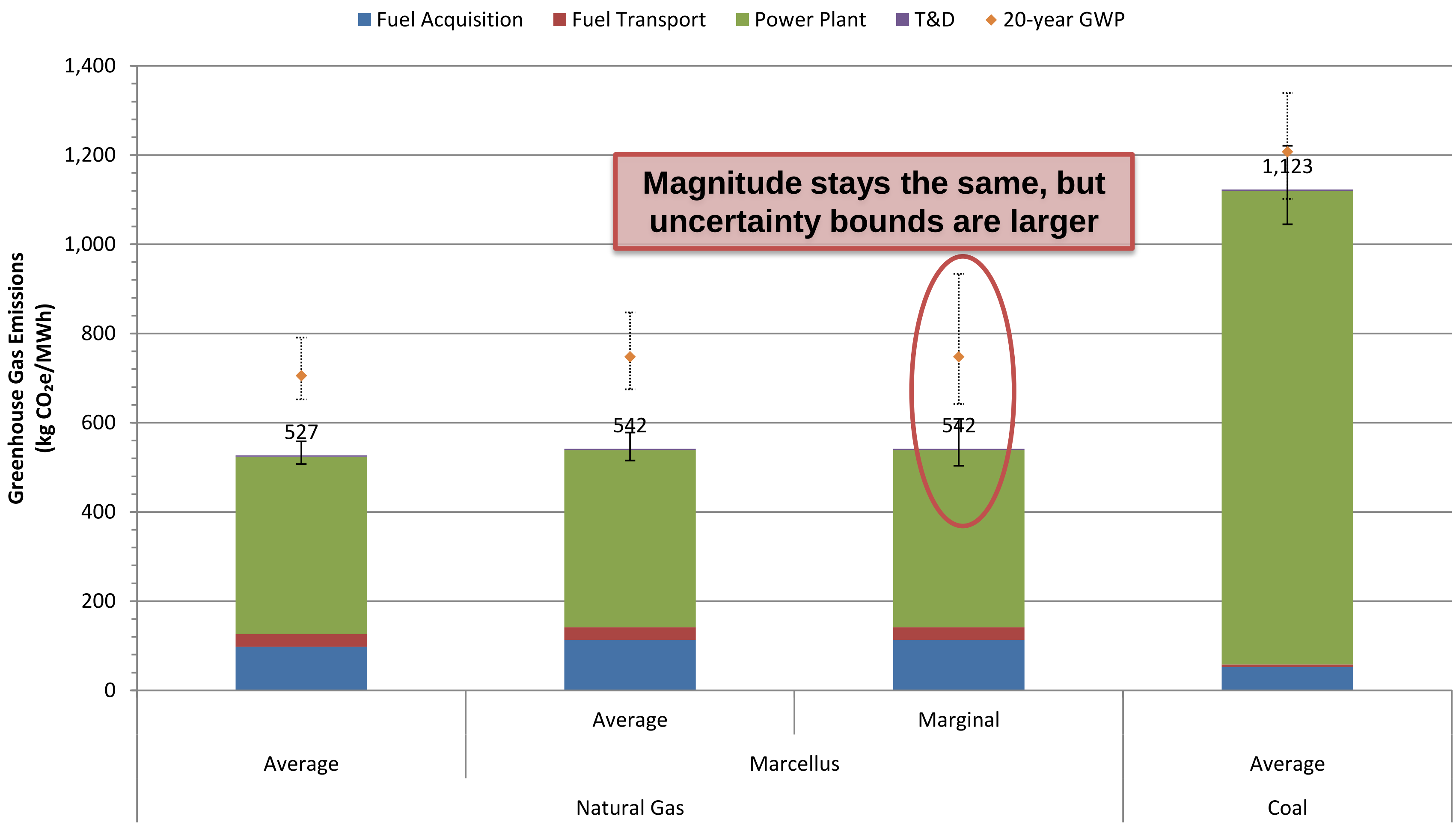
Average vs. Marginal Natural Gas Production Rates and Results

Source		Estimated Ultimate Recovery (BCF)						Greenhouse Gas Emissions (g CO_2e/MJ)		
		Average			Marginal					
		Nominal	Low	High	Nominal	Low	High	Average	Marginal	% Change
Conv.	Onshore	0.7	0.5	0.9	6.5	3.3	13.0	14.7	8.7	-40.80%
	Offshore	30.7	21.5	39.9	67.7	33.8	135.3	6.2	6.1	-1.60%
	Associated	1.3	0.9	1.7	4.4	2.2	8.7	8	7.9	-1.30%
Unconv.	Tight	1.2	0.9	1.6	1.2	0.8	1.6	13.9	13.9	0%
	Barnett Shale	3.0	2.1	3.9	3.0	1.5	4.5	14	14	0%
	Marcellus Shale	3.3	2.2	4.9	3.3	1.6	7.3	13.7	13.7	0%
	CBM	1.1	0.8	1.5	1.1	0.8	1.5	8.2	8.2	0%
LNG		30.7	21.5	39.9	67.7	33.8	135.3	18.4	18.3	-0.54%

- **Error bars below represent uncertainty caused by *likely* ranges in all modeling parameters**
- **This is in contrast to the previous slide, which showed *possible* results driven by selected parameters**



Marginal Marcellus through Power Production



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

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)

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