NATIONAL ENERGY TECHNOLOGY LABORATORY

Life Cycle GHG Inventory Sensitivity to Changes in Natural Gas System Parameters

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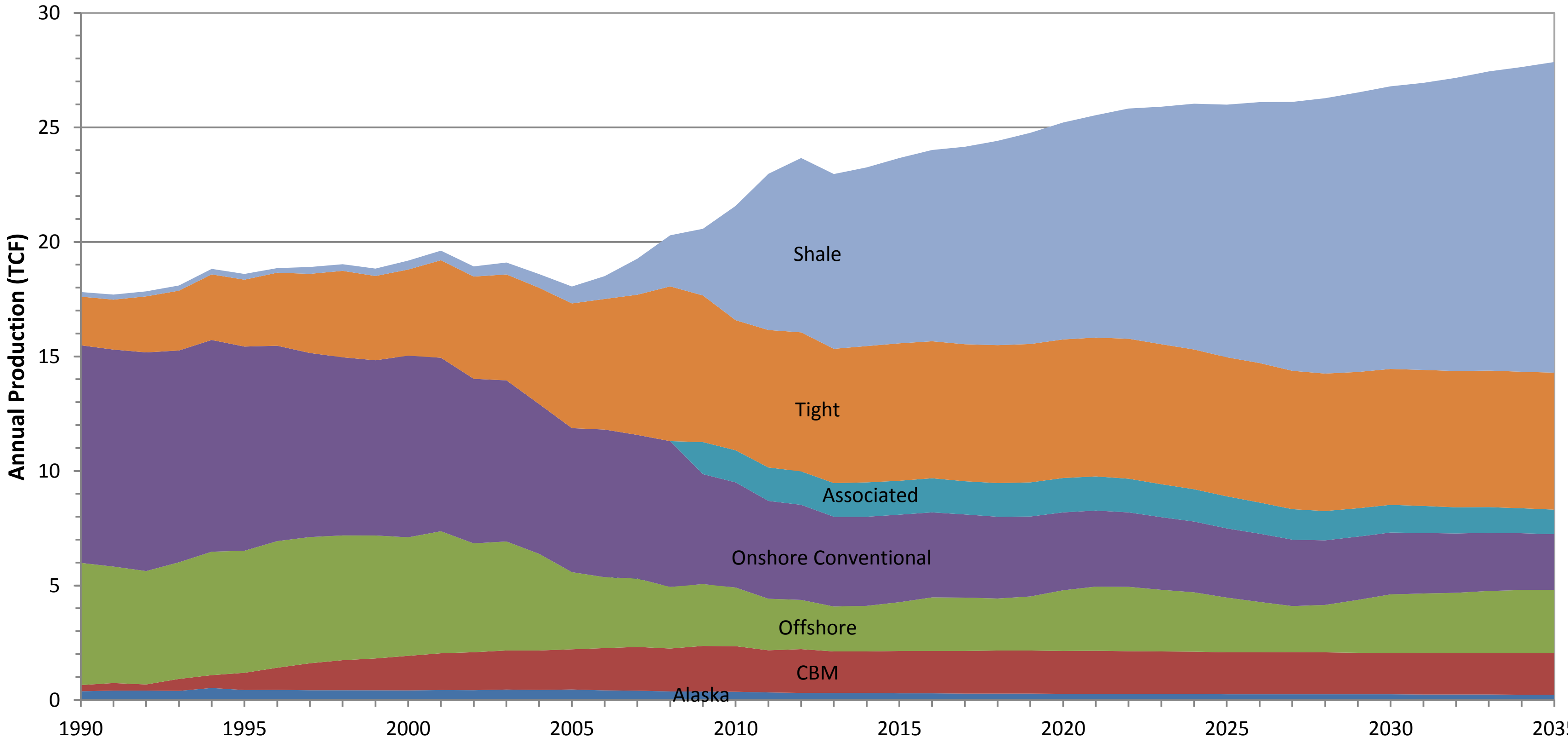
U.S. DEPARTMENT OF ENERGY

Agenda

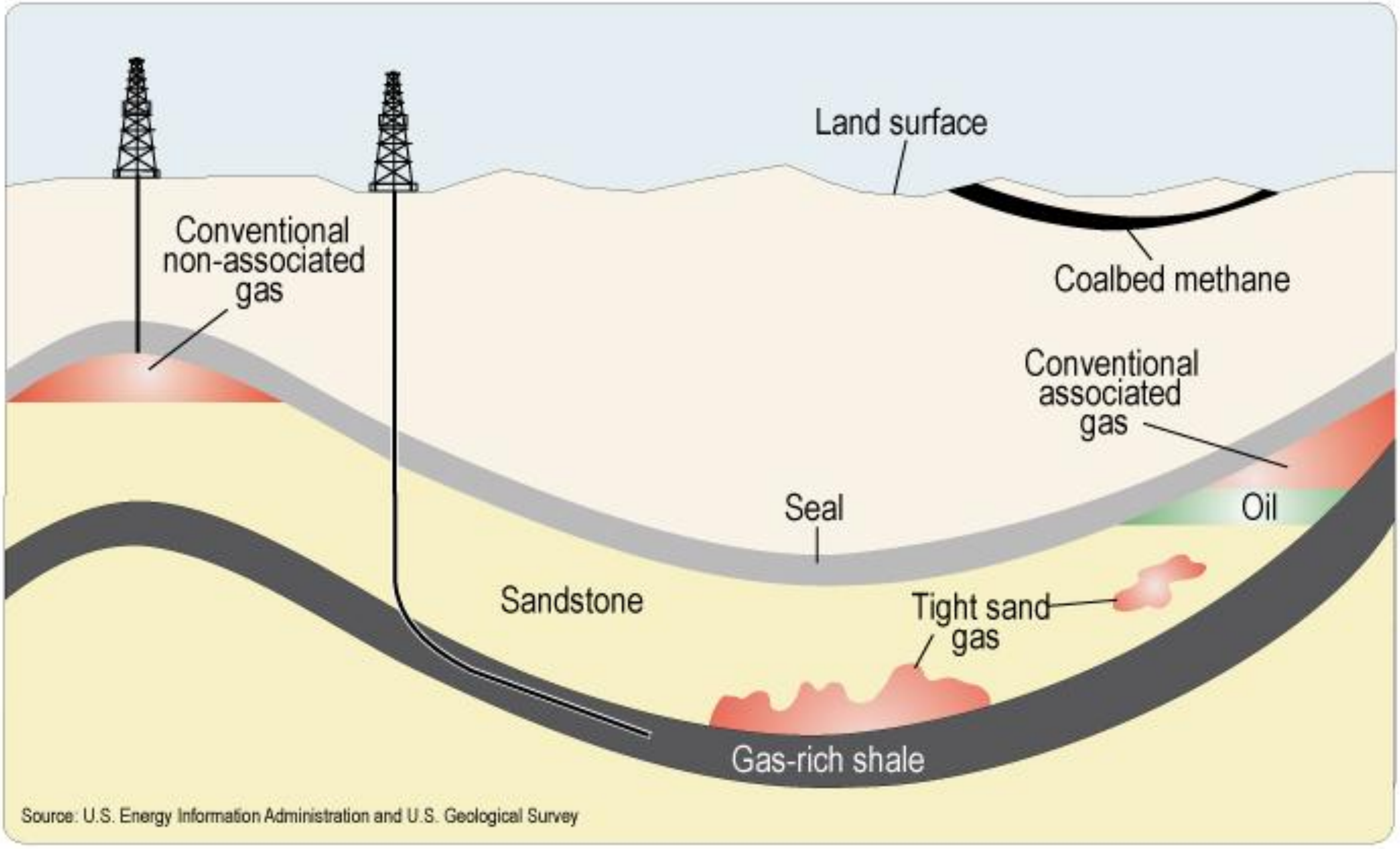
- Natural Gas Resource Growth
- LCA of Natural Gas
- Expected Results
- Sensitivity Analysis
- Role of Regulatory and Voluntary Emission Reductions
- Life Cycle Role of Power Generation

Unconventional sources of natural gas are changing the resource profile of natural gas production



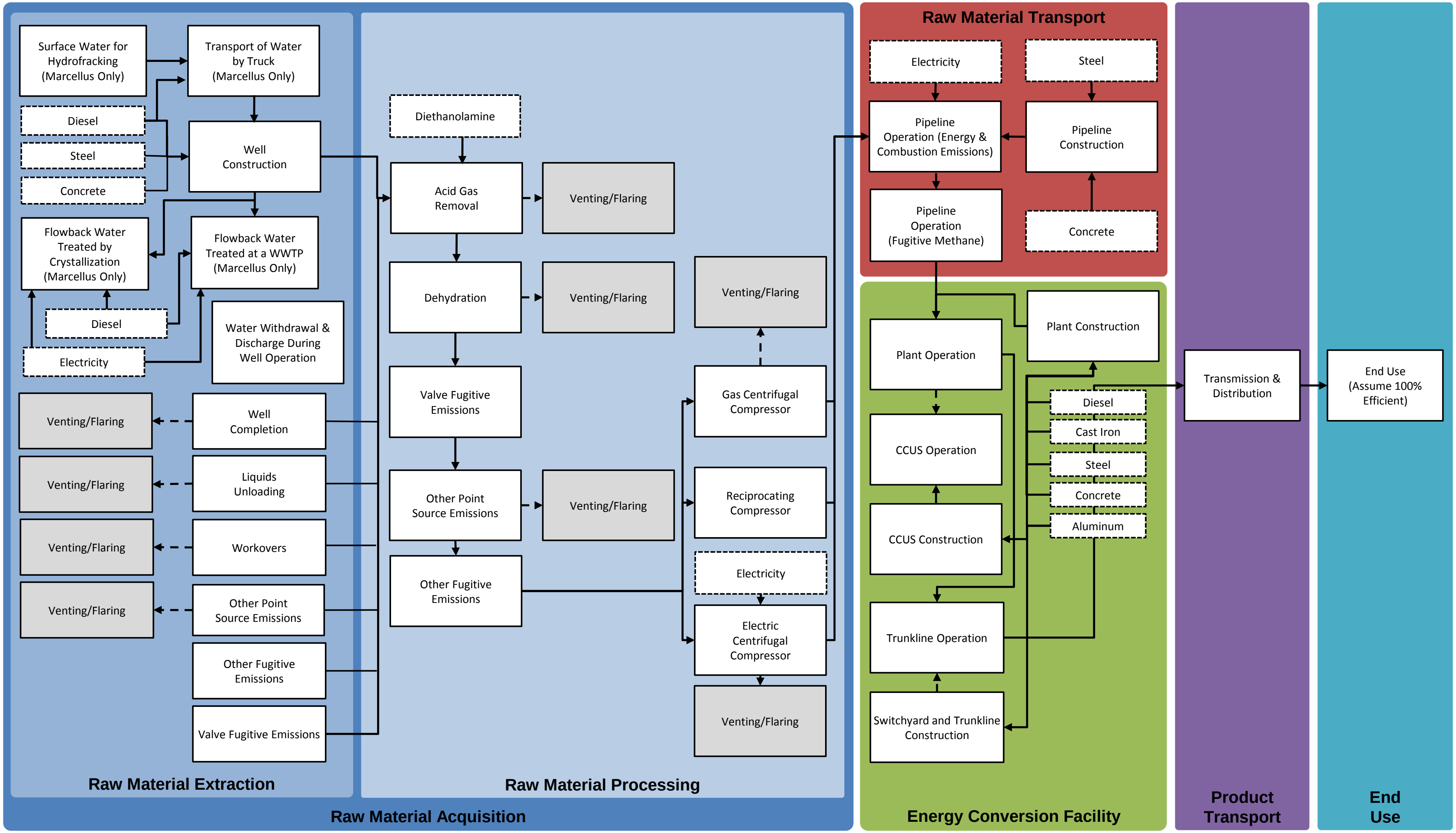
- Total U.S. demand for natural gas was 24.1 Tcf in 2010 and is projected to grow to 26.5 Tcf by 2035 (EIA, 2012a)
- Unconventional sources of natural gas are a growing share of U.S. production
- LCA is well suited to analyze the effect of shale gas growth on the environmental profile of natural gas systems

Geology of Onshore Natural Gas Sources



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.

NETL has built an LCA model that calculates environmental burdens of electricity from all types of NG sources

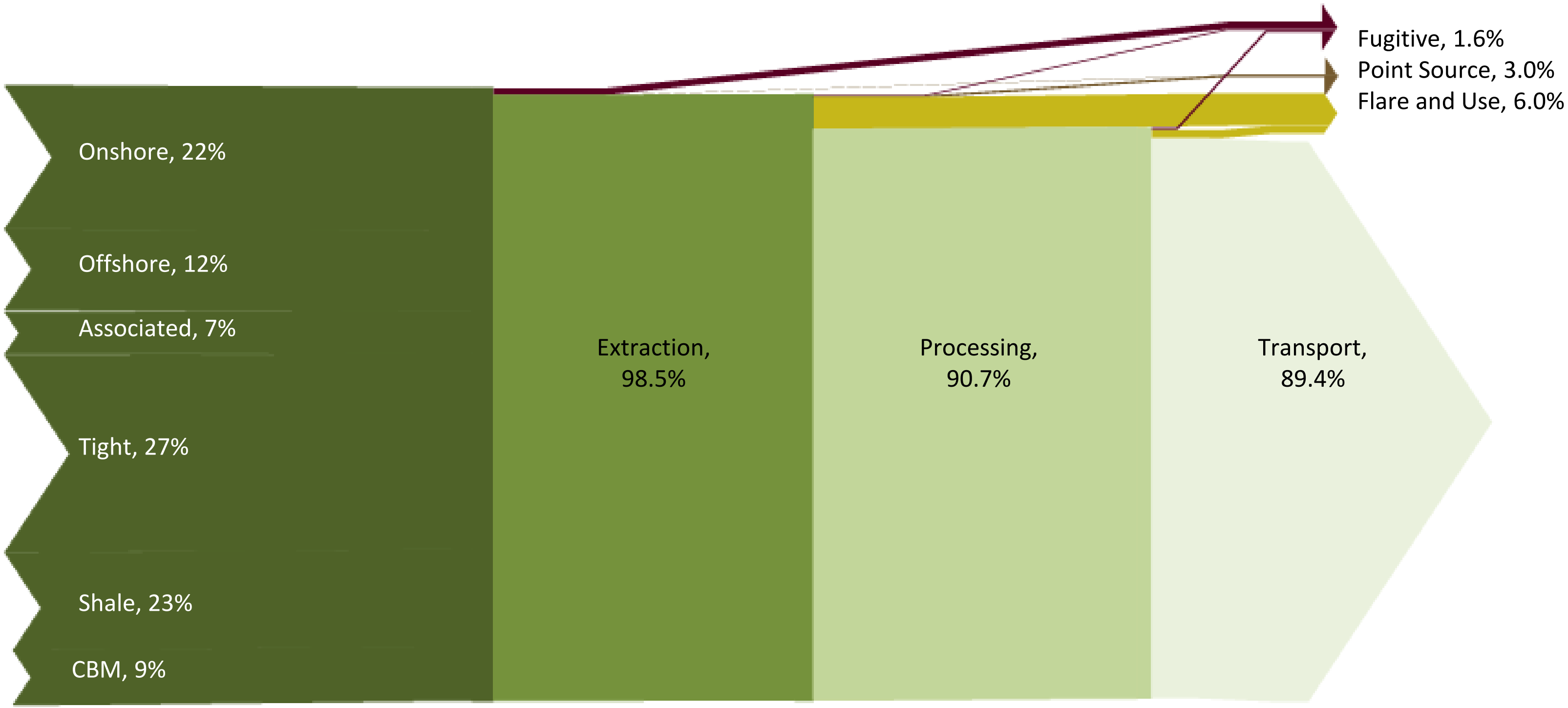


A detailed list of parameters allows modeling of natural gas from various extraction sources

Property (Units)		Onshore	Associated	Offshore	Tight Gas	Barnett Shale	Marcellus Shale	CBM
Natural Gas Source								
Contribution to 2010 U.S. Domestic Supply		22%	6.6%	12%	27%	21%	2.5%	9.4%
Average Production Rate (Mcf /day)	low	46	85	1,960	77	192	201	73
	expected	66	121	2,800	110	274	297	105
	high	86	157	3,641	143	356	450	136
Expected EUR (Estimated Ultimate Recovery) (BCF)		0.72	1.32	30.7	1.20	3.00	3.25	1.15
Natural Gas Extraction Well								
Flaring Rate (%)		51% (41 - 61%)			15% (12 - 18%)			
Well Completion (Mcf natural gas/episode)		47			3,670	9,175	9,175	49.6
Well Workover (Mcf natural gas/episode)		3.1			3,670	9,175	9,175	49.6
Lifetime Well Workovers (Episodes/well)		1.1			3.5			
Liquids Unloading (Mcf natural gas/episode)		23.5	n/a	23.5	n/a	n/a	n/a	n/a
Lifetime Liquid Unloadings (Episodes/well)		930	n/a	930	n/a	n/a	n/a	n/a
Valve Emissions, Fugitive (lb CH_4/Mcf natural gas)		0.11		0.0001	0.11			
Other Sources, Point Source (lb CH_4/Mcf natural gas)		0.003		0.002	0.003			
Other Sources, Fugitive (lb CH_4/Mcf natural gas)		0.043		0.01	0.043			

- These parameters include the expected values for production rates and emissions factors, as well as uncertainty ranges
- NETL's model uses a similar parameterization approach for other stages, including gas processing and transport

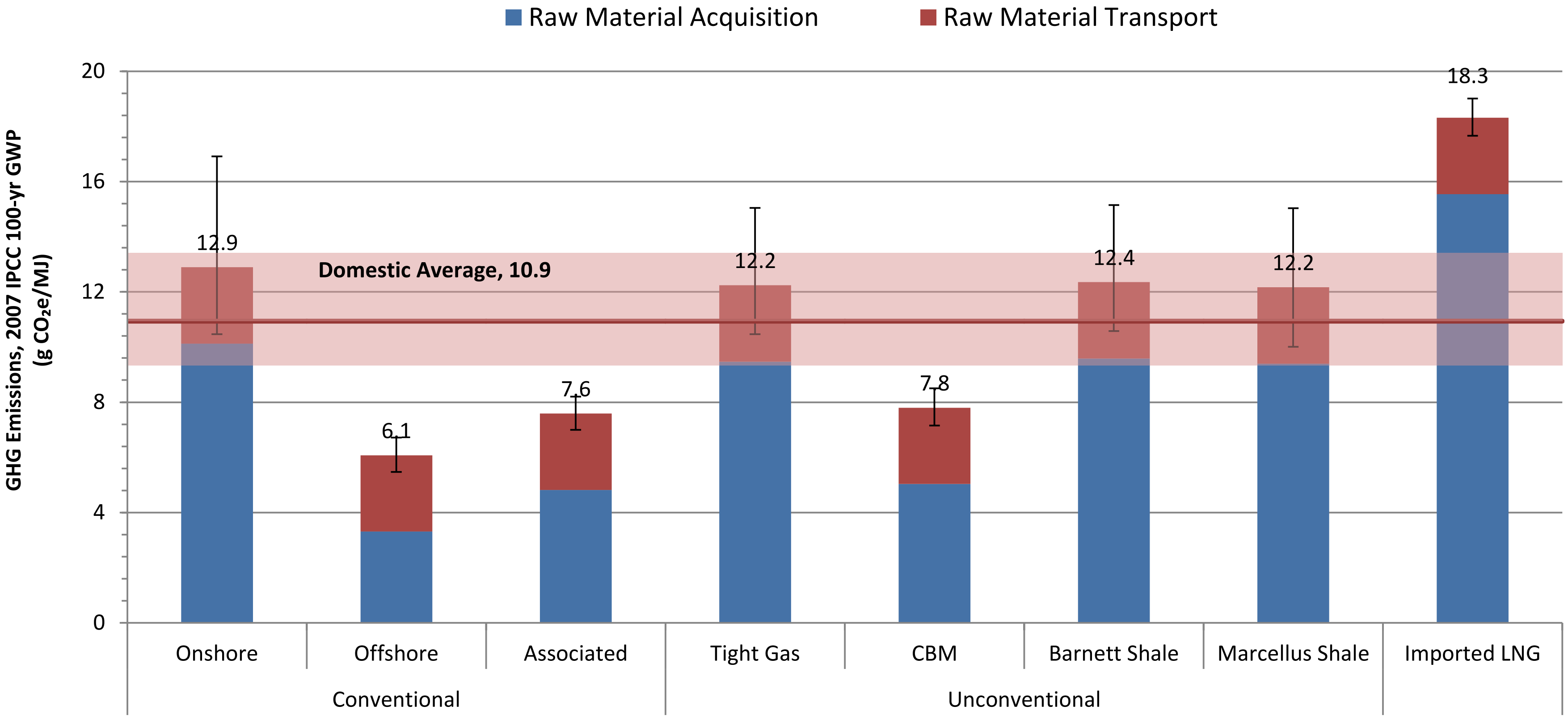
89% of natural gas extracted from the ground is delivered to the power plant or city gate



Of the 11% reduction:

- 57% is used to power various processing and transport equipment
- 28% is point source emissions that can be captured and flared
- 15% is fugitive emissions (spatially separated emissions difficult to capture or control)

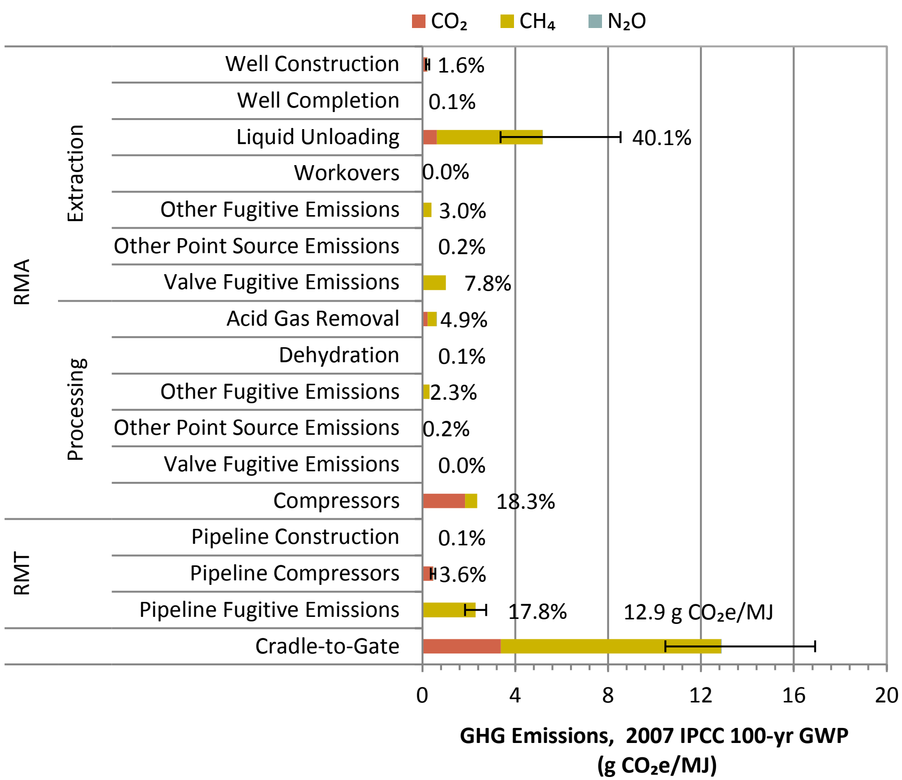
GHG results show variability among natural gas types



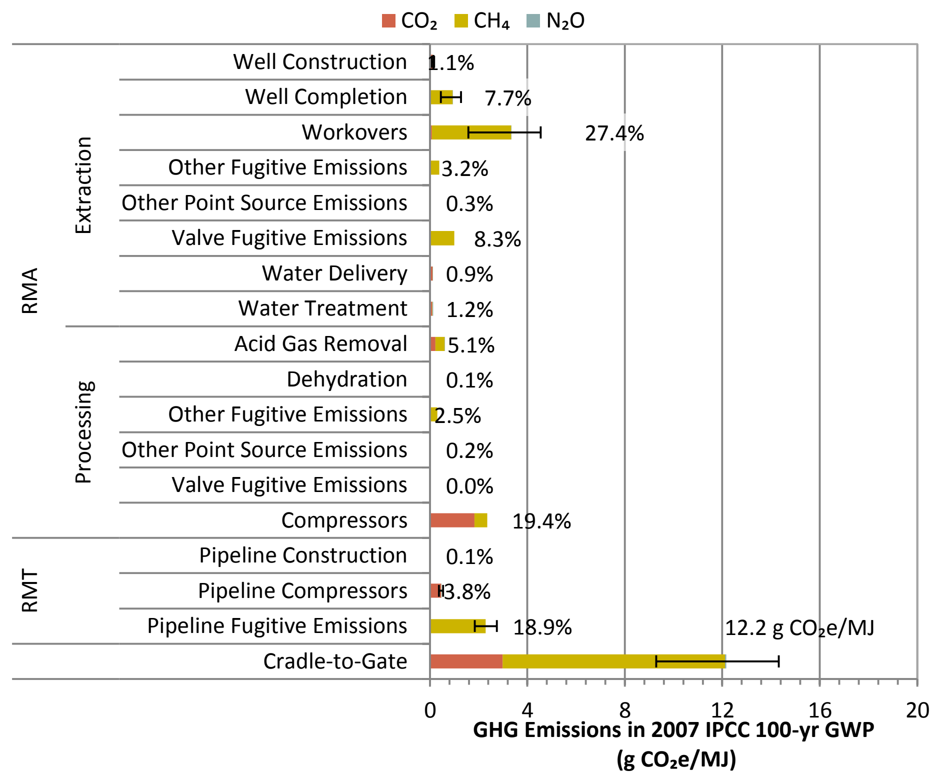
- Offshore natural gas has lowest GHGs of any source; it has a high production rate and offshore wells are motivated to control methane emissions for safety and risk-mitigation reasons
- Imported gas (LNG) has highest GHG emissions; liquefaction and regasification are energy intensive

Drilling down into the results shows the activities that contribute the most to the upstream GHG profiles

Onshore Natural Gas Extraction and Transport



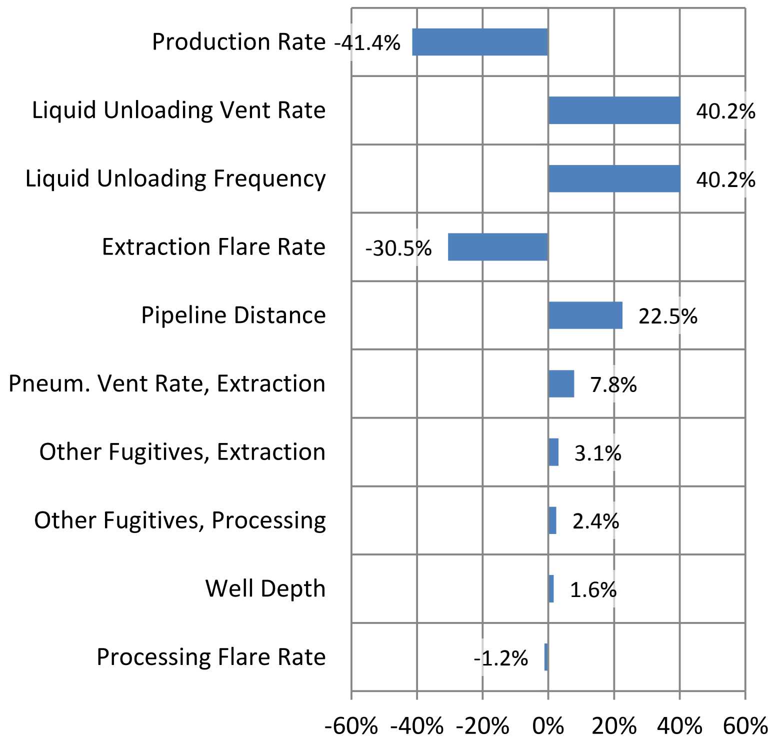
Marcellus Shale Natural Gas Extraction and Transport



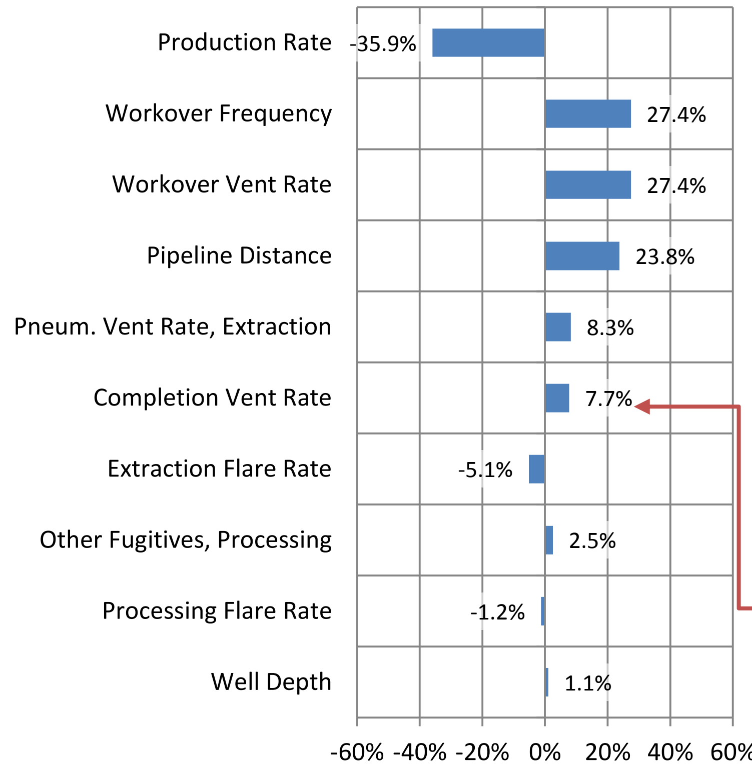
- Liquid unloading is a key episodic emission for onshore conventional natural gas; completion and workovers are key episodic emissions for unconventional natural gas
- Compressors (processing and pipeline) are a significant source of CO_2
- Hydrofracking water delivery and treatment is 2.1% of upstream GHG from Marcellus Shale natural gas

Production rate is the top driver of GHG sensitivity, followed by episodic emissions and pipeline distance

Onshore Natural Gas Extraction and Transport



Marcellus Shale Natural Gas Extraction and Transport



These graphs show all sensitivities relative to a 100% increase in the input parameter.

A positive percent change indicates a direct relationship.

A negative percent change indicates an inverse relationship.

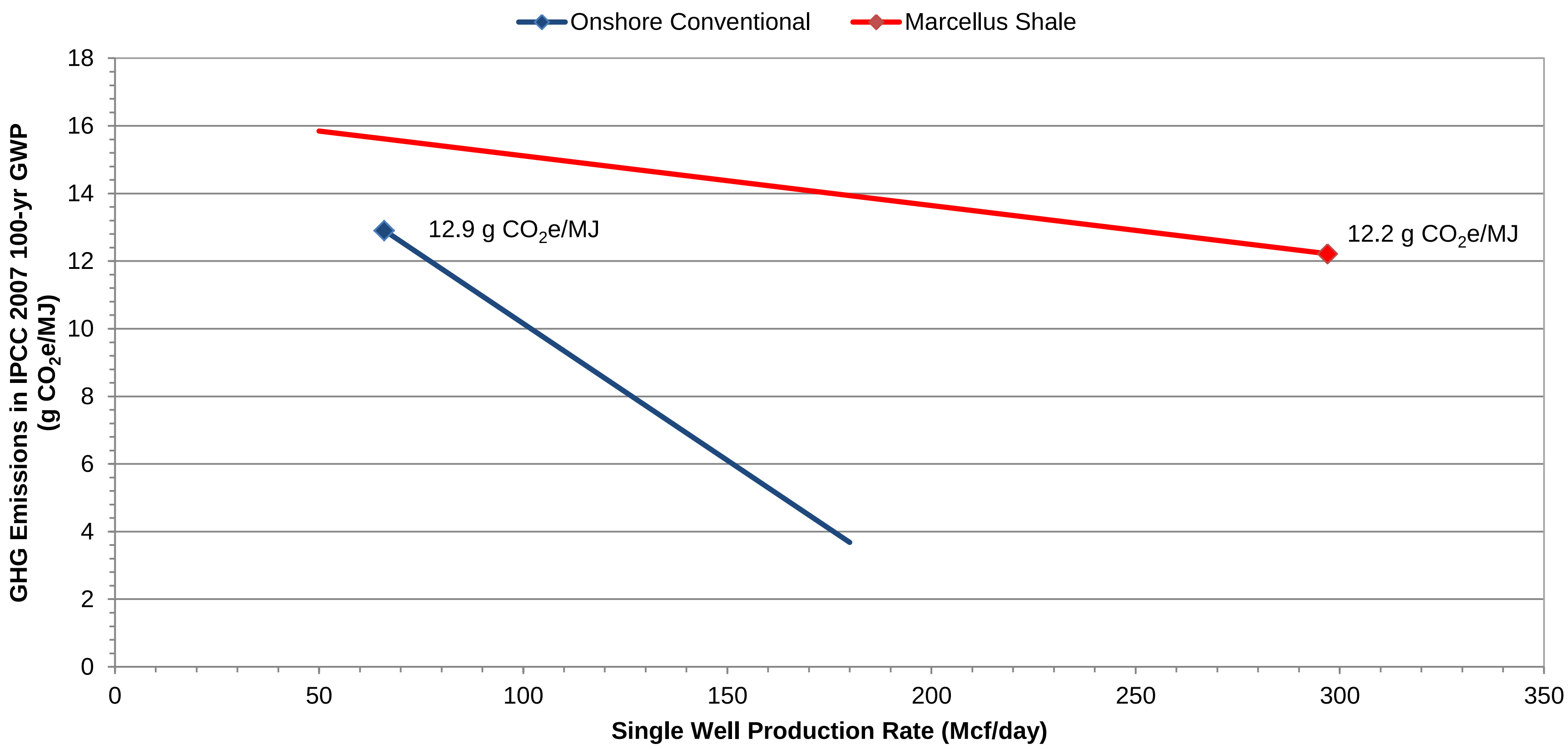
For example, a 100% increase in completion vent rate causes a 7.7% increase in upstream GHG emissions for Marcellus Shale natural gas.

- Emission factors for episodic emissions are a greater driver of GHG emissions than emission factors for routine operations
- Production rate is a key factor in apportionment of environmental burdens

Production rates for onshore conventional wells are variable, while Marcellus performance is uncertain

- **What's a typical well for onshore conv. production?**
  - 479,000 conventional onshore wells in the U.S.
  - With respect to *well count*, the average well produces 70 Mcf/day
  - With respect to contribution to *total production*, the average well produces ~500 Mcf/day
- **There's no historical data for Marcellus production**
  - Current data support estimated ultimate recoveries of 3.2 BCF/ well life
  - Recent USGS data suggest that ultimate recoveries could be closer to 2.0 BCF/well life

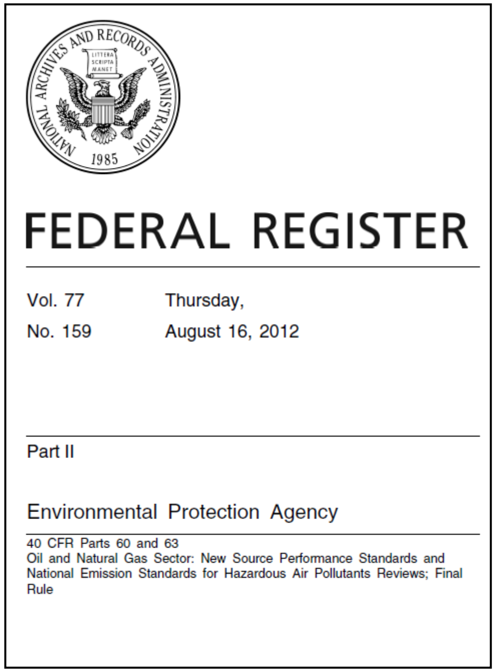
All natural gas types show an inverse relationship between production rate and upstream GHG emissions



- The retirement of older wells will improve the overall GHG profile of conventional onshore natural gas
- Lower-than-expected production from Marcellus Shale will increase the GHG profile of Marcellus Shale natural gas

EPA New Source Performance Standards (NSPS) regulate VOC emissions from the oil and gas sector

- **Final Oil & Gas Sector NSPS rule under CAA established August 16, 2012**
- **Methane is a key component of the VOC category for the oil and gas sector**
- **NSPS regulates emissions from:**
  - Well completions and workovers
  - Centrifugal compressors
  - Reciprocating compressors
  - Storage tanks
  - Pneumatic controllers
- **NSPS does not regulate emissions from:**
  - Liquid unloading from conventional wells
  - Compressors used for pipeline transmission



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Part II

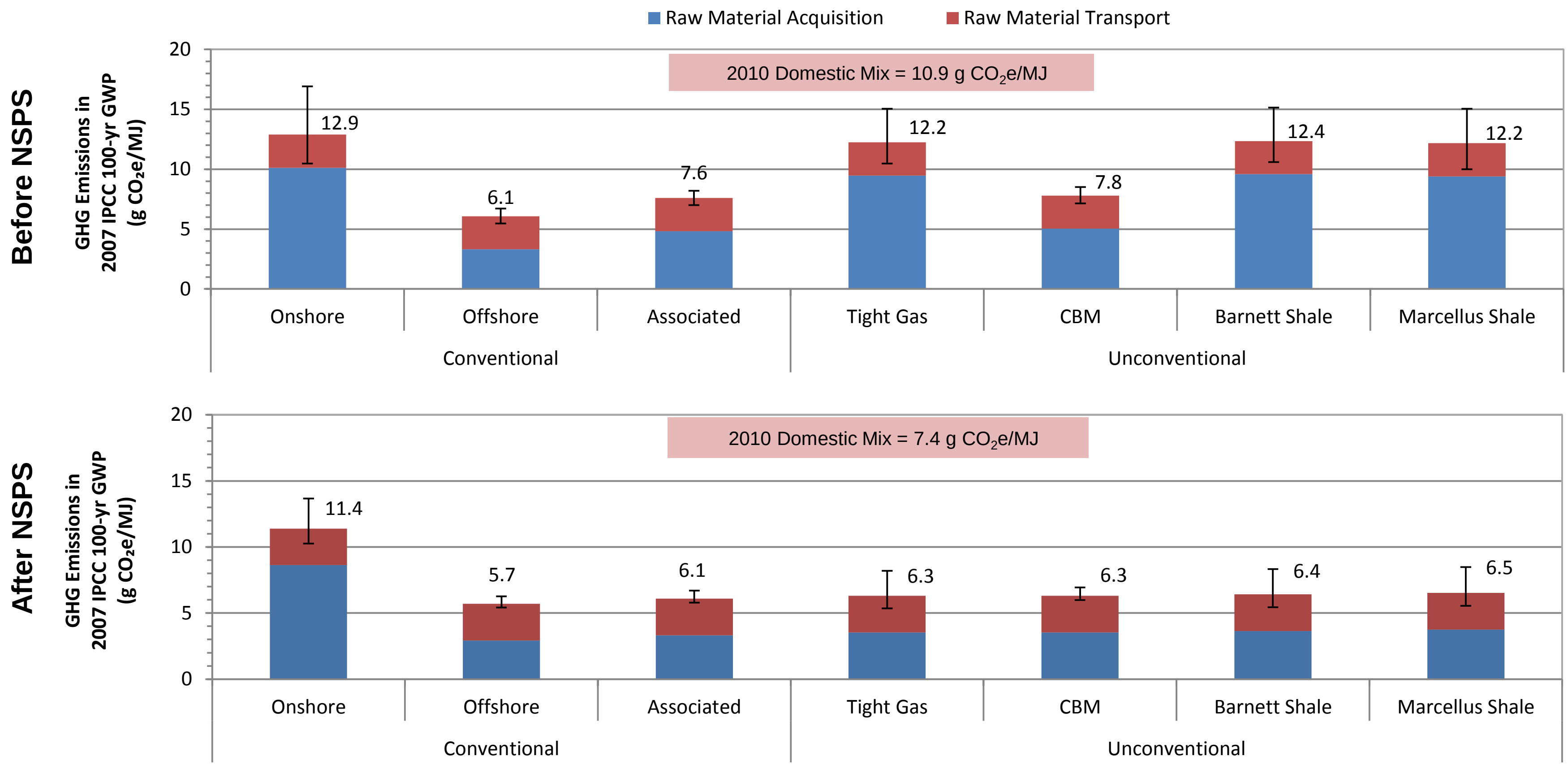
Environmental Protection Agency

40 CFR Parts 60 and 63
Oil and Natural Gas Sector: New Source Performance Standards and National Emission Standards for Hazardous Air Pollutants Reviews; Final Rule

NETL's parameterized modeling approach can estimate the GHG changes caused by NSPS

- **Reduced emission completions (RECs) for unconventional wells**
  - Can reduce unconventional completion emissions by 95% (NSPS, 2012)
  - New completion and workover emission factor = 9,175*(100% - 95%)
    = 459 Mcf natural gas/episode
  - A higher extraction flaring rate is also expected for RECs, so increase unconventional flaring rate from 15% to 51%
- **Replacement of compressor wet seals with dry seals**
  - Can reduce centrifugal compressor CH_4 emissions 95% (NSPS, 2012)
  - New emission factor for centrifugal compressors (at processing site)
    = 0.0069 kg CH_4/kg natural gas compressed * (100% - 95%)
    = 0.00035 kg CH_4/kg natural gas compressed
- **Routine replacement of compressor rod packings**
  - Can reduce reciprocating compressor CH_4 emissions 95% (NSPS, 2012)
  - New emission factor for reciprocating compressors (at processing site)
    = 0.0306 kg CH_4/kg natural gas combusted * (100% - 95%)
    = 0.00153 kg CH_4/kg natural gas combusted
- **Replacement of pneumatic controllers**
  - High bleed controllers have leak rates of 6 - 42 scf/hr (EPA, 2006b)
  - Low bleed controllers have leak rates less than 6 scf/hr and are used by offshore gas wells (EPA, 2006b)
  - New emission factor for onshore conventional and unconventional valves = existing emission factor for offshore valves = 0.0001 lb CH_4/Mcf

NSPS can reduce emissions from all natural gas sources, but brings greatest improvements to unconventional sources



- NSPS reduces GHG emissions of the domestic mix by 32 percent
- Greatest reductions are driven by reduced emission completions (RECs)
- NSPS overlooks the opportunity for liquid unloading emission reductions and does not address pipeline emissions

Some important emission sources are not addressed by NSPS or are outside the scope of NSPS

- **NSPS does not propose reductions in emission factors for liquids unloading from conventional wells**
  - New options for liquid unloading can reduce NG emissions at least 500 Mcf/yr per well (EPA, 2011b)
  - New liquid unloading emission factor

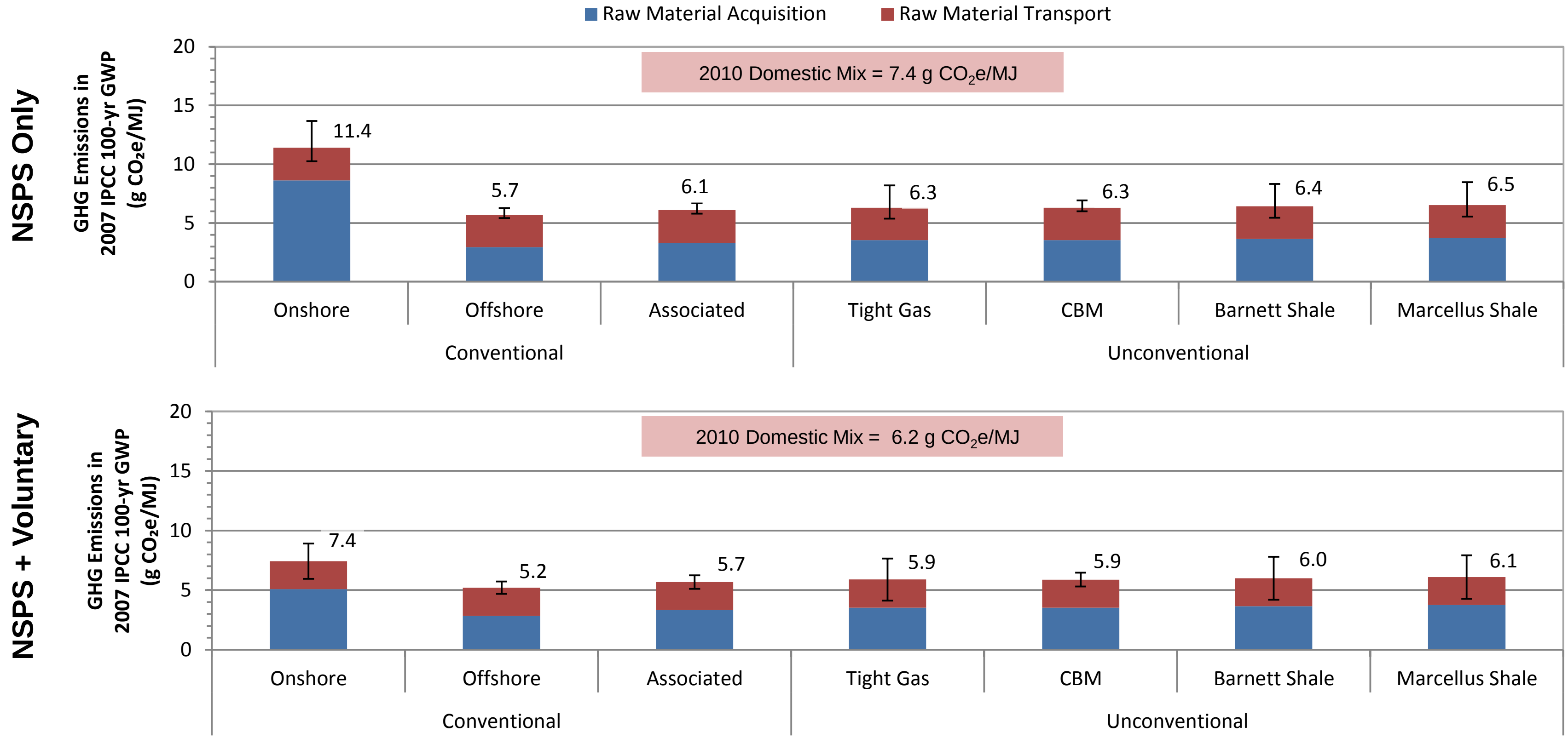
    = 23.5 Mcf/episode - (500 Mcf/yr)/(31 episodes/yr)

    = 7.4 Mcf natural gas/episode
- **NSPS boundaries stop after the gas processing plant and do not include natural gas pipeline transmission**
  - Natural gas transmission pipelines could replace centrifugal compressor wet seals with dry seals
  - Centrifugal compressors are 19 percent of transmission pipeline compressors
  - New pipeline emission factor

    = 5.37E-06 kg CH_4/kg-km * ((100% - 95%) * 19% + 81%)

    = 4.40E-06 kg CH_4/kg-km

Voluntary emission reductions, in addition to NSPS regulations, could further reduce upstream emissions



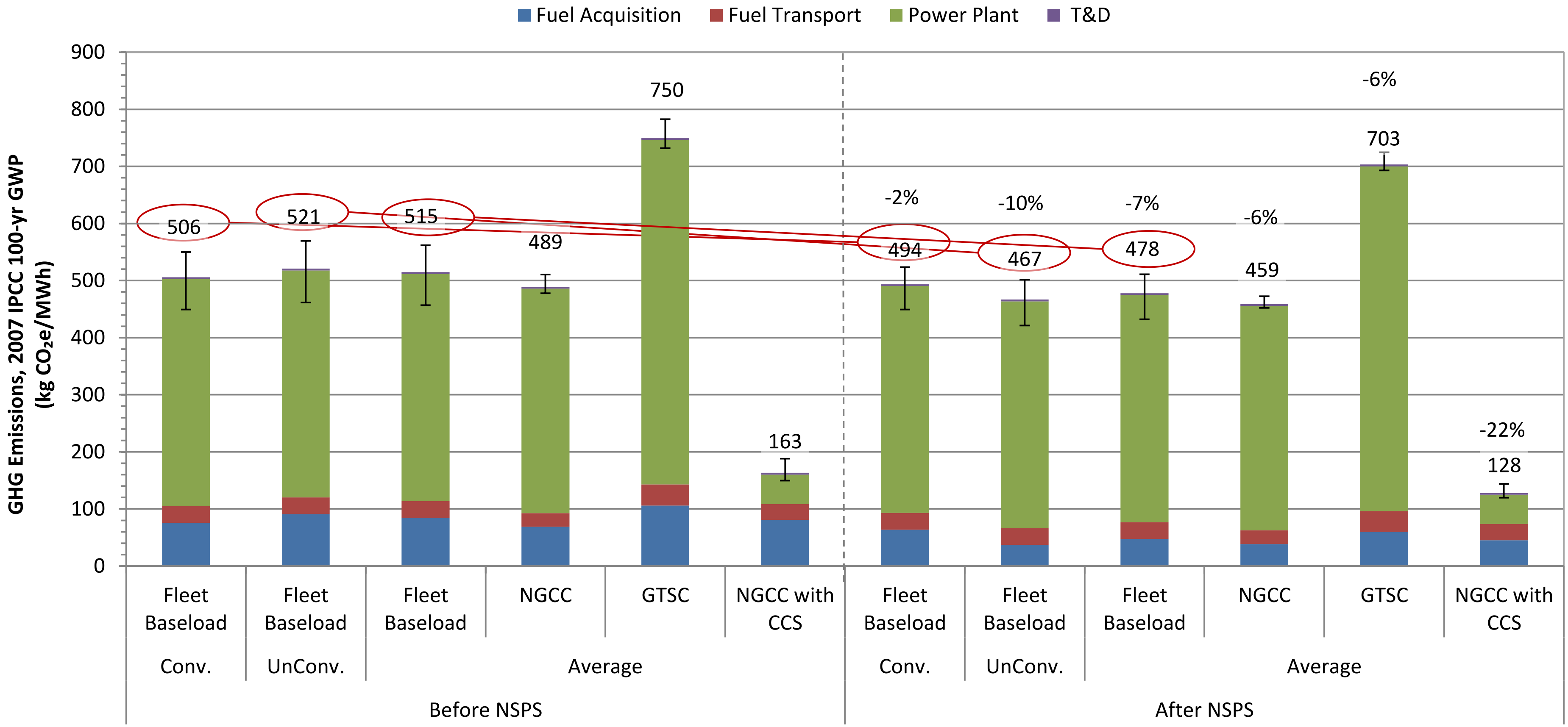
- Voluntary actions lead to an additional 16% reduction in the upstream GHG emissions of domestic natural gas (from 7.4 to 6.2 CO_2e/MJ)
- Total GHG emission reductions from NSPS and voluntary action are 43% (from 10.9 to 6.2 CO_2e/MJ)

Conclusions

- LCA is a valuable tool for identifying opportunities for improvement in a supply chain
- Methane emissions from natural gas acquisition and delivery can be reduced with existing technologies
- Greatest opportunities for upstream GHG emission reductions are the development of productive wells, capture of episodic emissions, and prevention of pipeline emissions
- Some emission reductions will be achieved through regulations, while others will be voluntary
- If new wells are not developed and methane capture technologies are not implemented, the average GHG profile of natural gas will increase

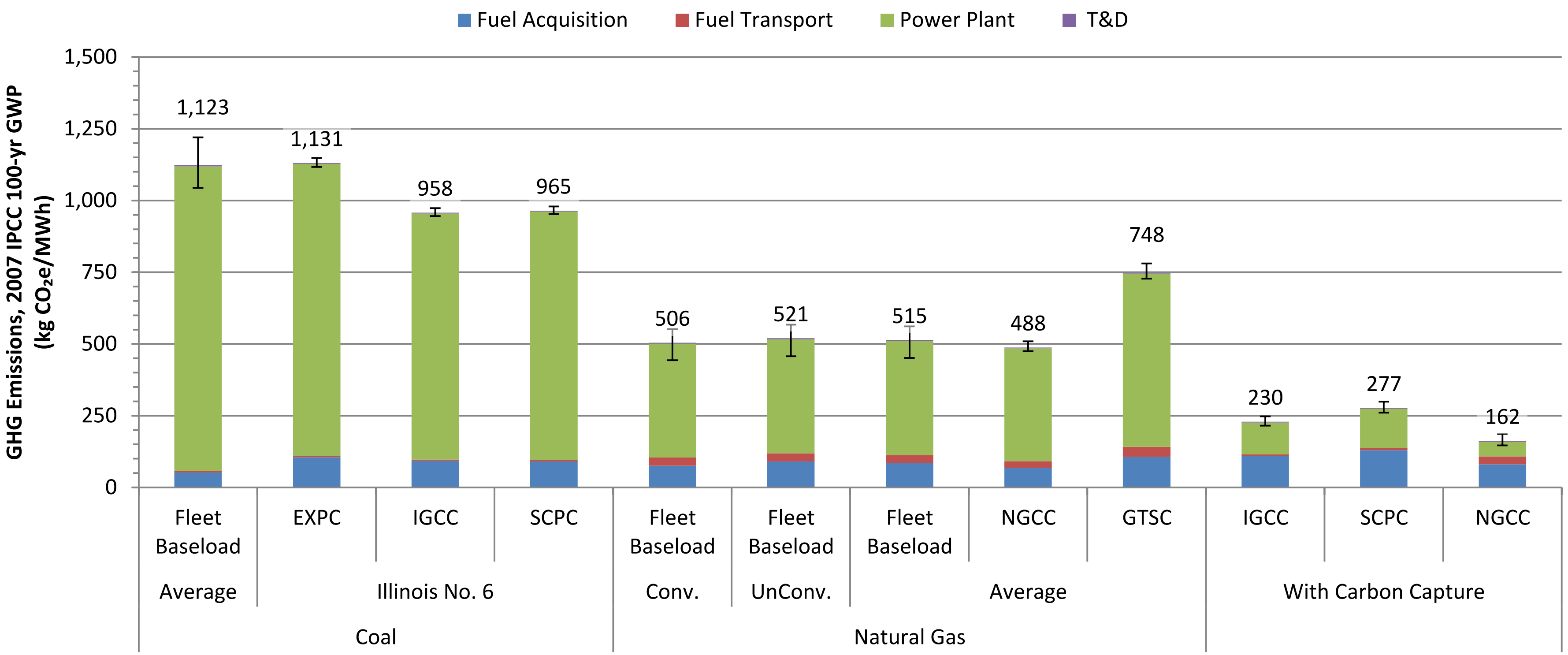
These conclusions focus on upstream natural gas burdens – a life cycle perspective is necessary

There are opportunities for improving the upstream profile of natural gas, but combustion dominates the GHG profile



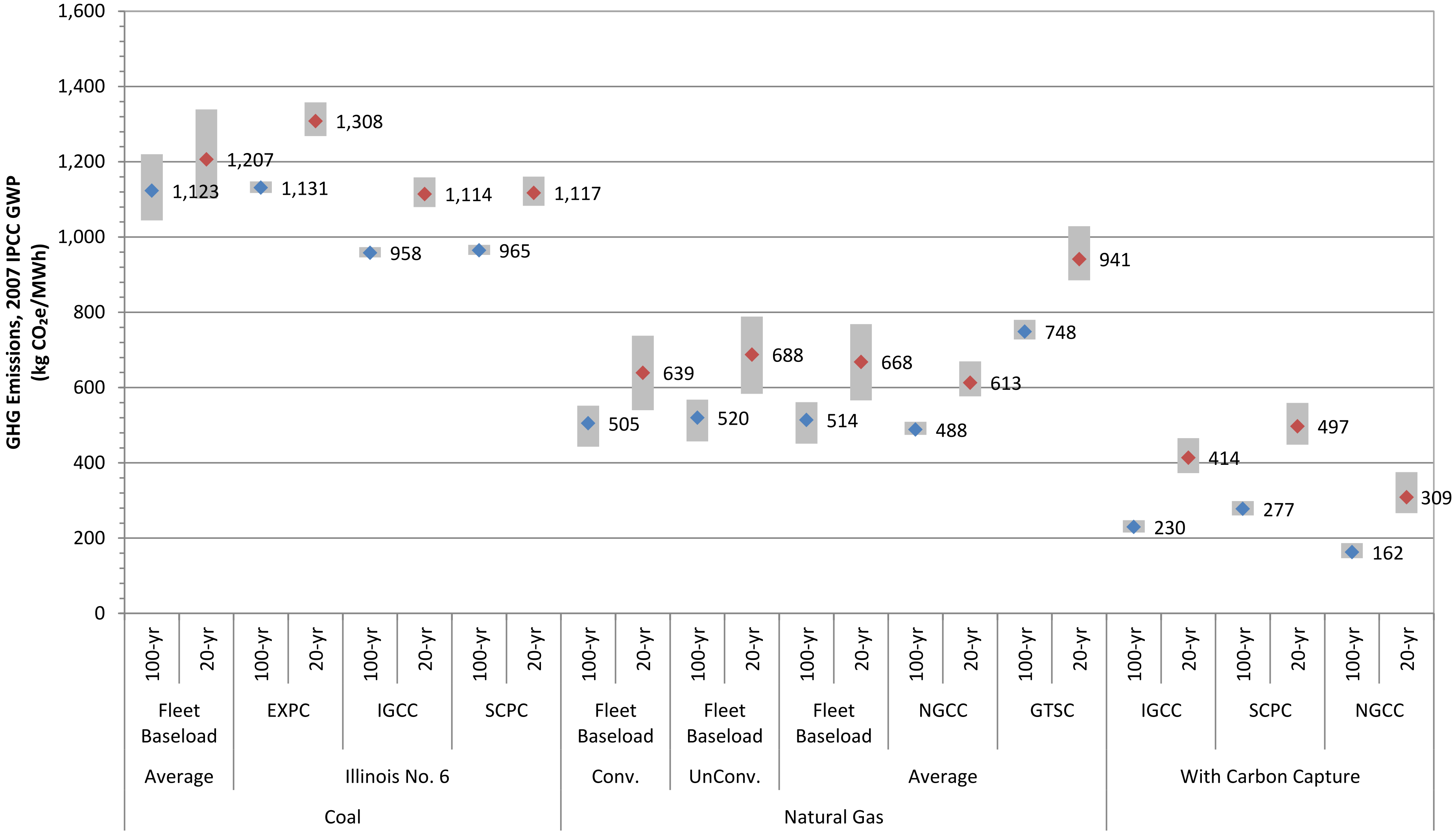
- **NSPS reductions to fleet baseload power:**
  - 12 kg CO_2e/MWh when using conventional natural gas (2% reduction)
  - 54 kg CO_2e/MWh when using unconventional natural gas (10% reduction)
  - 37 kg CO_2e/MWh when using domestic mix of natural gas (7% reduction)

On a life cycle basis for electricity, the power plant generates more GHG emissions than fuel acquisition and transport



- On a 100-yr IPCC GWP basis, natural gas power has a lower impact than coal power
- Because of their similar roles, the fairest comparison is the domestic mix of coal through an average baseload coal power plant vs. the domestic mix of natural gas run through an average baseload natural gas plant (1,123 vs. 514 kg CO_2e/MWh)
- Fuel acquisition and transport is 22% of life cycle GHG emissions from average NG fleet baseload – it is only 5.2% of life cycle GHG emissions from average coal fleet baseload

GHG results are more sensitive for natural gas than for coal when changing from 100- to 20-year GWPs



Bottom Line: Combustion Emissions Still Matter Most

- Upstream emission reductions are a near term opportunity, but CO_2 from combustion remains the largest contributor to the GHG emissions from natural gas power
  - Best case regulatory and voluntary approaches reduce life cycle GHG emissions of baseload natural gas power by only 7%
  - Difficult to improve upon efficiency of combined cycle power plants
  - After upstream GHG reductions have been made, CO_2 capture, utilization and storage (CCUS) will be the next step toward reductions in the life cycle GHGs from natural gas power

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In contrast to the unit processes for extraction and processing, pipeline transport is based on national data

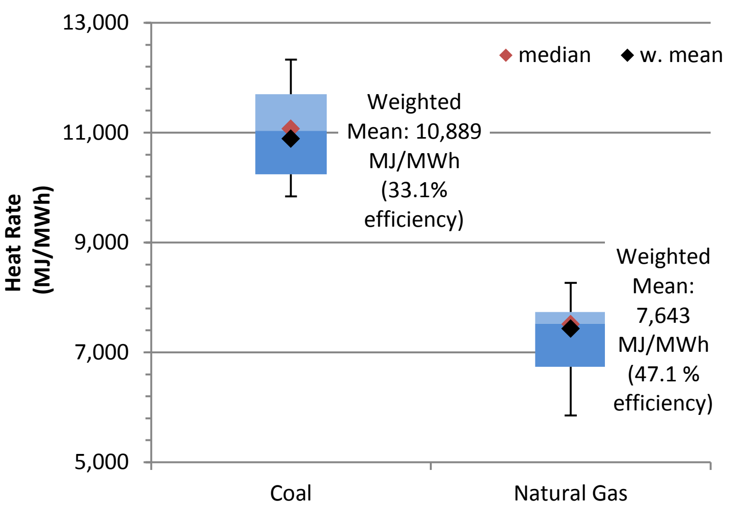
- **National methane emissions from natural gas pipeline transmission (EPA, 2011)**
  - $E_{methane}$ = 2.12 billion kg CH_4/yr
- **National natural gas consumption (EIA, 2011)**
  - $NG_{consumption}$ = 21.8 Quads/yr (21.8 x 10^{15} Btu/yr)
- **Methane emission factor from pipeline operations**
  - National ton-miles of natural gas transmission (Dennis, 2005 and EPA, 2011)
  - Fuel consumed by pipeline companies (FERC, 2010)
  - Methane emission factor for natural gas combustion in reciprocating compressors and gas turbines used by centrifugal compressors (EPA, 1995)
  - Percent split between pipeline compressor types (Hedman, 2008)
  - $EF_{methane}$ = 9.97E-05 kg CH_4/MMBtu-km

$$d = \frac{E_{methane}}{NG_{consumption} * EF_{methane}} = 971\ km$$

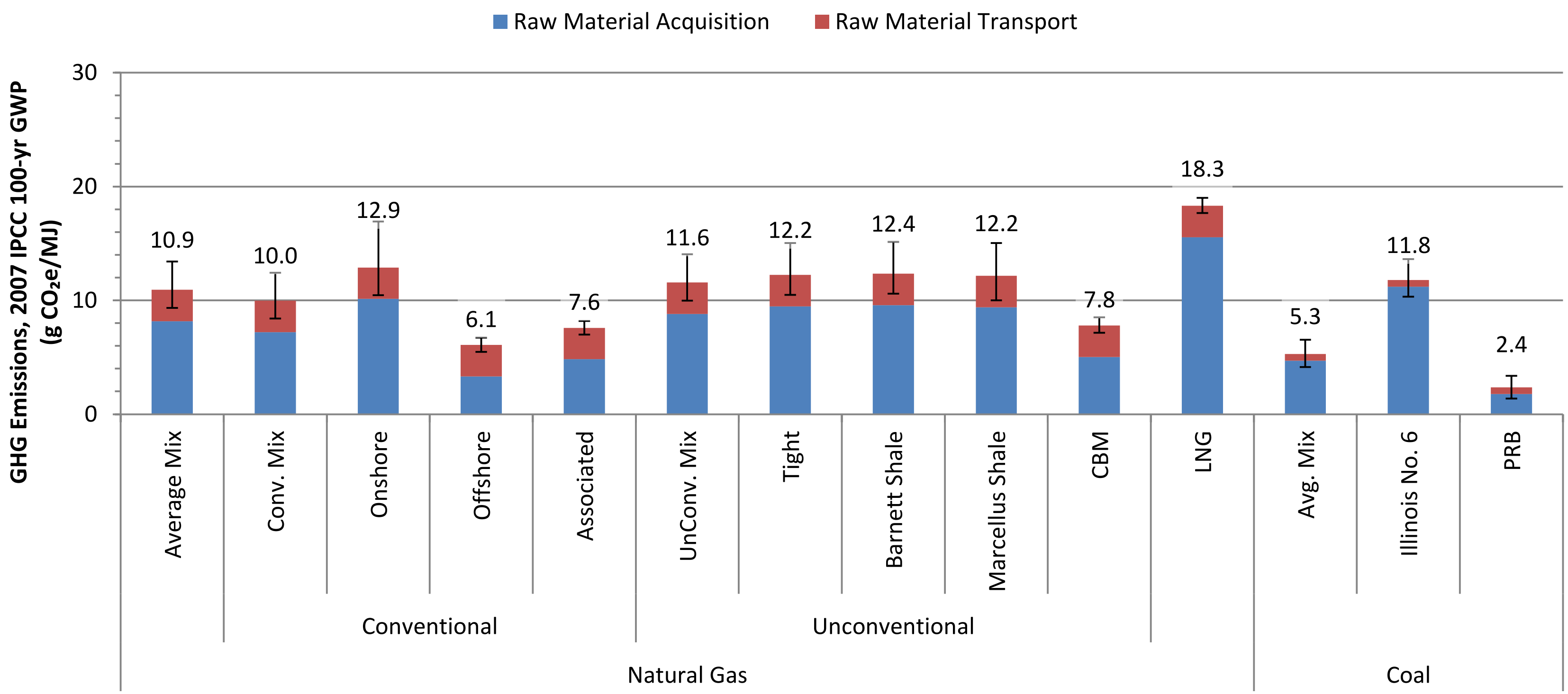
Supporting Material:
Natural Gas Power Performance

Power Plant Characteristic	NGCC	NGCC/ccs	GTSC	Fleet Baseload
Net Power, MWe	555	474	360	N/A
Net Plant Efficiency (HHV), %	50.2%	42.8%	30.0%	47.1%
Net Plant Heat Rate (HHV), MJ/MWh	7,172	8,406	11,983	7,643
Consumables				
Natural Gas Feed Flow, kg/hr	75,901	75,901	75,901	N/A
Raw Water Consumption, m^3/min	6.9	11.3	4.4	N/A
Air Emissions, kg/MWh				
Carbon Dioxide	362	46.3	560	379
Methane	7.40E-06	8.61E-06	N/A	N/A
Nitrous Oxide	2.06E-06	2.39E-06	N/A	N/A
Carbon Monoxide	2.70E-04	3.14E-04	4.59E-01	N/A
Nitrogen Oxides	2.80E-02	3.25E-02	4.24E-02	N/A
Sulfur Dioxide	1.93E-06	2.24E-06	N/A	N/A

- Performance of NGCC power plants (with and without CCS) is detailed in NETL's bituminous baseline (NETL, 2010a)
- GTSC performance is adapted from baseline by considering energy & material flows pertinent to gas turbine only
- Characteristic of U.S. natural gas (and coal) average baseload are based on eGRID (EPA, 2010) data

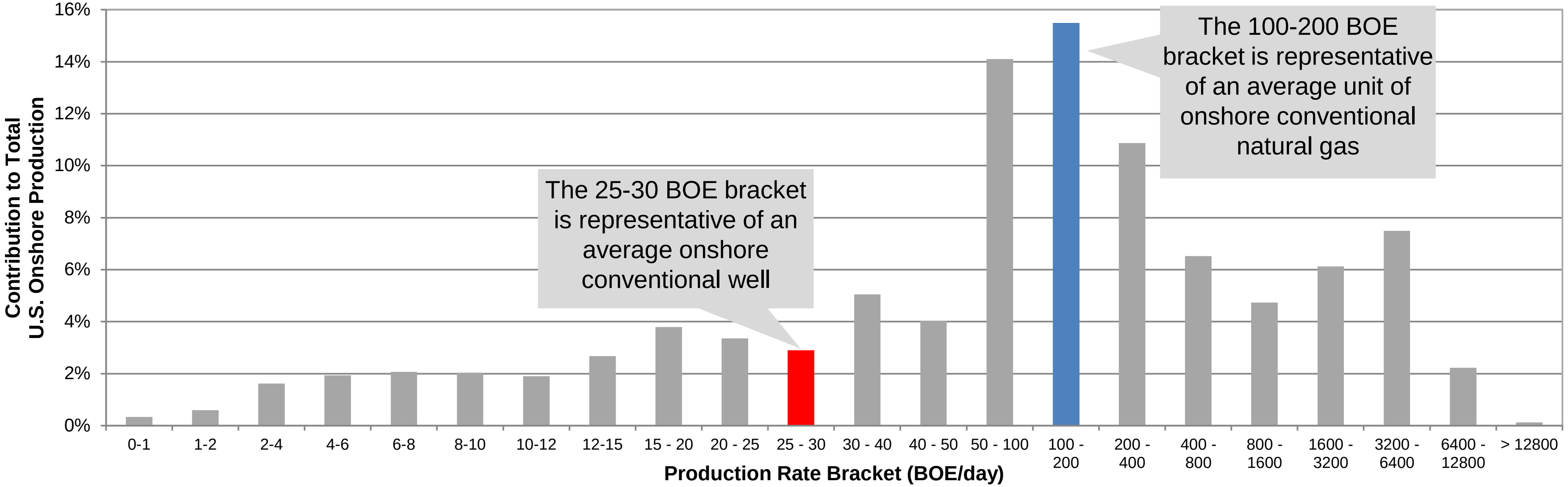


Supporting Material:
Upstream GHG Comparison of Natural Gas and Coal



- On an upstream energy basis, natural gas has higher GHG emissions than coal
- Bituminous coal with high amounts of entrained methane, such as Illinois No. 6, is more comparable to NG, but makes up only 31% of domestic coal consumption on an energy basis
- These results are not expressed on the basis of an equivalent service (i.e., 1 MWh of electricity)

Onshore conventional wells exhibit the most variability in production rates



Source: EIA, 2010 (United States Distribution of Wells by Production)

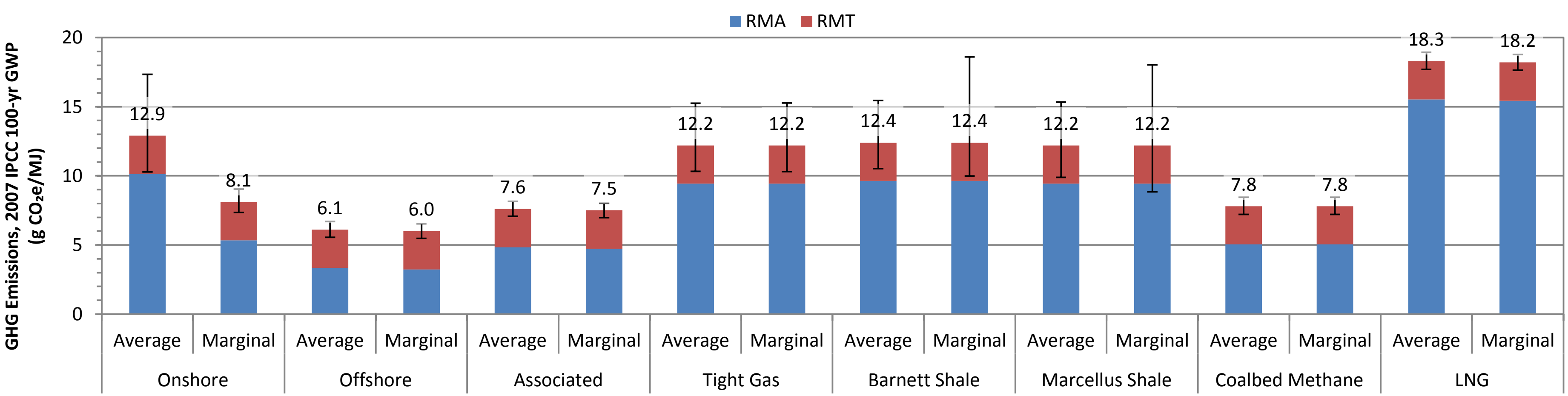
- *Low* production rate brackets have a *high* well count; *high* production rate brackets have a *low* well count
- As old wells are retired, the average production rate will be more representative of the higher production rate brackets

- Historical data not available for Marcellus Shale
- Current estimated ultimate recoveries (EUR) for Marcellus Shale wells are 3.2 BCF, but could be closer to 2 BCF (Pierce et al., 2012)

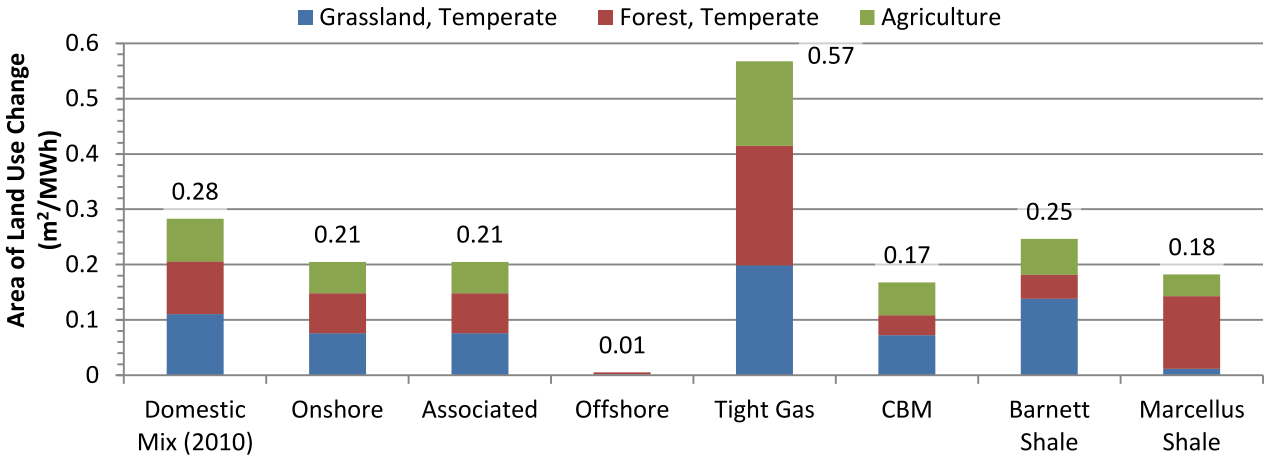
Supporting Material:
Upstream GHG for Average and Marginal Natural Gas

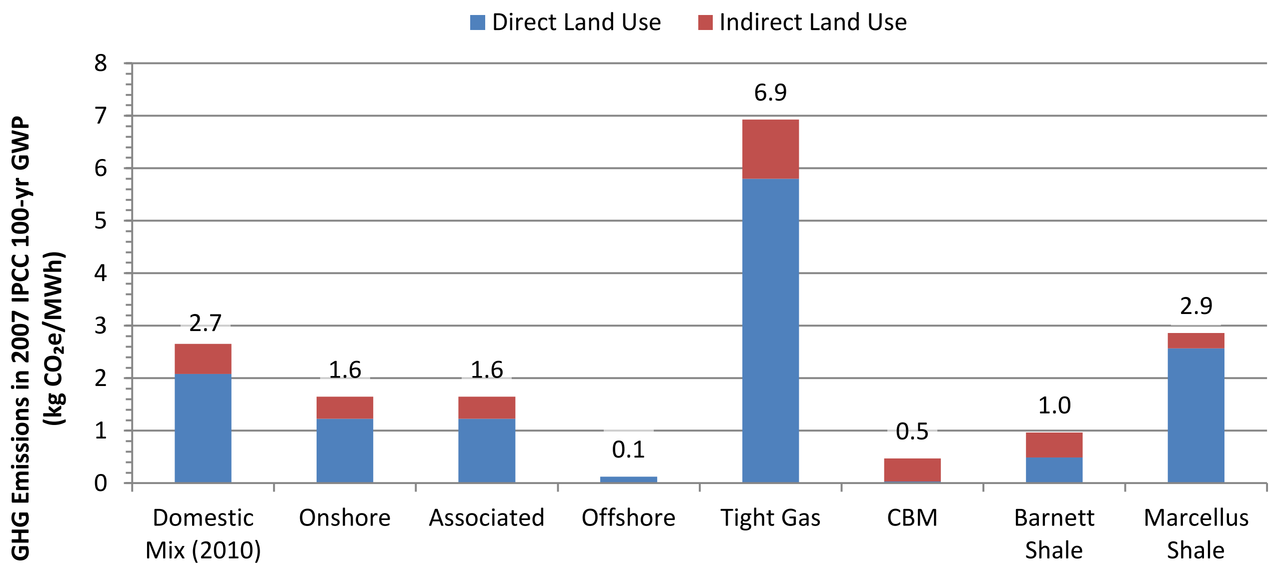
Source		Estimated Ultimate Recovery (BCF)						Greenhouse Gas Emissions ($g\ CO_2e/MJ$)		
		Average			Marginal					
		Expected	Low	High	Expected	Low	High	Average	Marginal	% Change
Conv.	Onshore	0.72	0.5	0.9	6.5	3.3	13.0	12.9	8.1	-37.1%
	Offshore	30.7	21.5	39.9	67.7	33.8	135.3	6.1	6.0	-1.6%
	Associated	1.32	0.9	1.7	4.4	2.2	8.7	7.6	7.5	-1.3%
UnConv.	Tight	1.20	0.9	1.6	1.2	0.8	1.6	12.2	12.2	0%
	Barnett Shale	3.00	2.1	3.9	3.0	1.5	4.5	12.4	12.4	0%
	Marcellus Shale	3.25	2.2	4.9	3.3	1.6	7.3	12.2	12.2	0%
	CBM	1.15	0.8	1.5	1.1	0.8	1.5	7.8	7.8	0%
LNG		30.7	21.5	39.9	67.7	33.8	135.3	18.3	18.2	-0.5%

- Error bars below represent uncertainty caused by likely ranges in all modeling parameters
- The most significant change is for onshore natural gas wells, which will have higher production rates as new wells are completed and poor performing wells are phased out



Supporting Material: Land Use Results for Natural Gas Power





- Marcellus results in highest loss of forest land, at 72% of total transformed land area, due to large proportion of forested area in Marcellus region
- Direct land use GHGs comprise majority of total land use GHG emissions; from 50% for Barnett up to 90% for Marcellus
- Indirect land use GHG emissions from Barnett are driven by higher proportion of agriculture loss for Barnett (26% of disturbed area was estimated to be agricultural), combined with relatively low proportion of forest area loss (18%)
- Marcellus GHG results indicate that indirect land use accounts for about 10% of total GHG emissions from land use, driven by reduced loss of agriculture (21%) combined with a high rate of forest loss (72%)