NATIONAL ENERGY TECHNOLOGY LABORATORY

Role of Alternative Energy Sources: Natural Gas Technology Assessment

Timothy J. Skone, P.E.

Senior Environmental Engineer

NETL Office of Strategic Energy Analysis and Planning

June 30, 2012

DOE/NETL-2012/1539

U.S. DEPARTMENT OF ENERGY

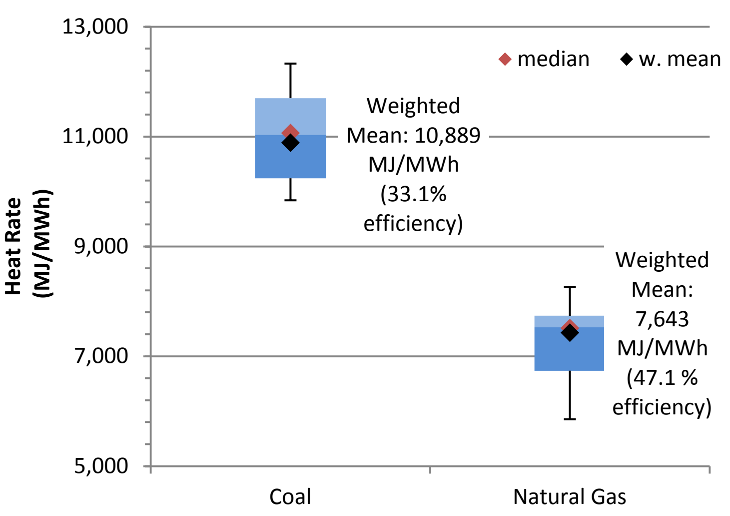
Agenda

- Technology Profile
- Resource Base
- Growth of Natural Gas Power
- Environmental Analysis
- Cost Analysis
- Barriers to Implementation
- Risks of Implementation
- Expert Opinions

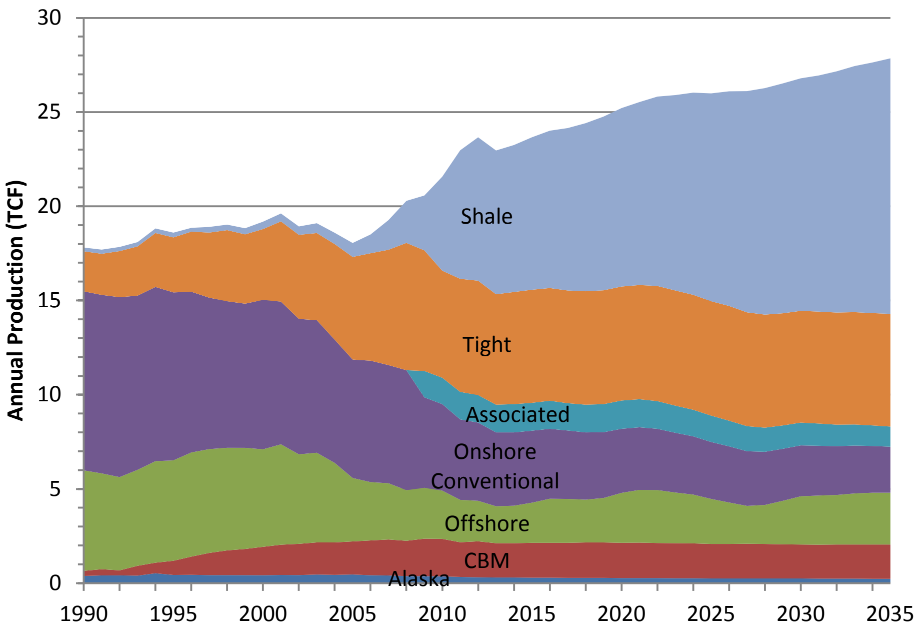
Natural Gas Power Technology Description

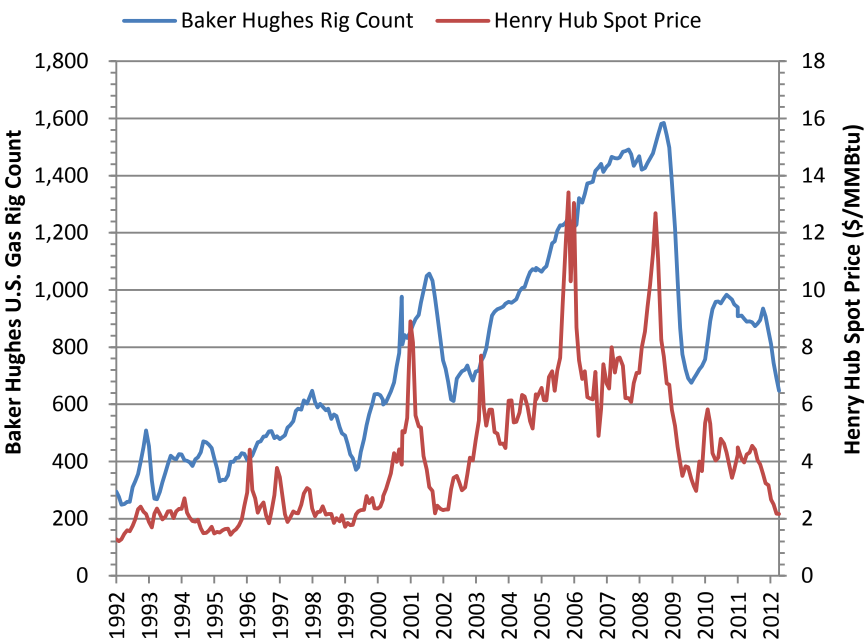
Power Plant Characteristic	NGCC	NGCC/ccs	GTSC	Fleet Baseload
Net Power, MWe	555	474	360	N/A
Net Plant Efficiency (HHV), %	50.2%	42.8%	30.0%	47.1%
Net Plant Heat Rate (HHV), MJ/MWh	7,172	8,406	11,983	7,643
Consumables				
Natural Gas Feed Flow, kg/hr	75,901	75,901	75,901	N/A
Raw Water Consumption, m^3/min	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



Natural Gas Resource Base and Growth



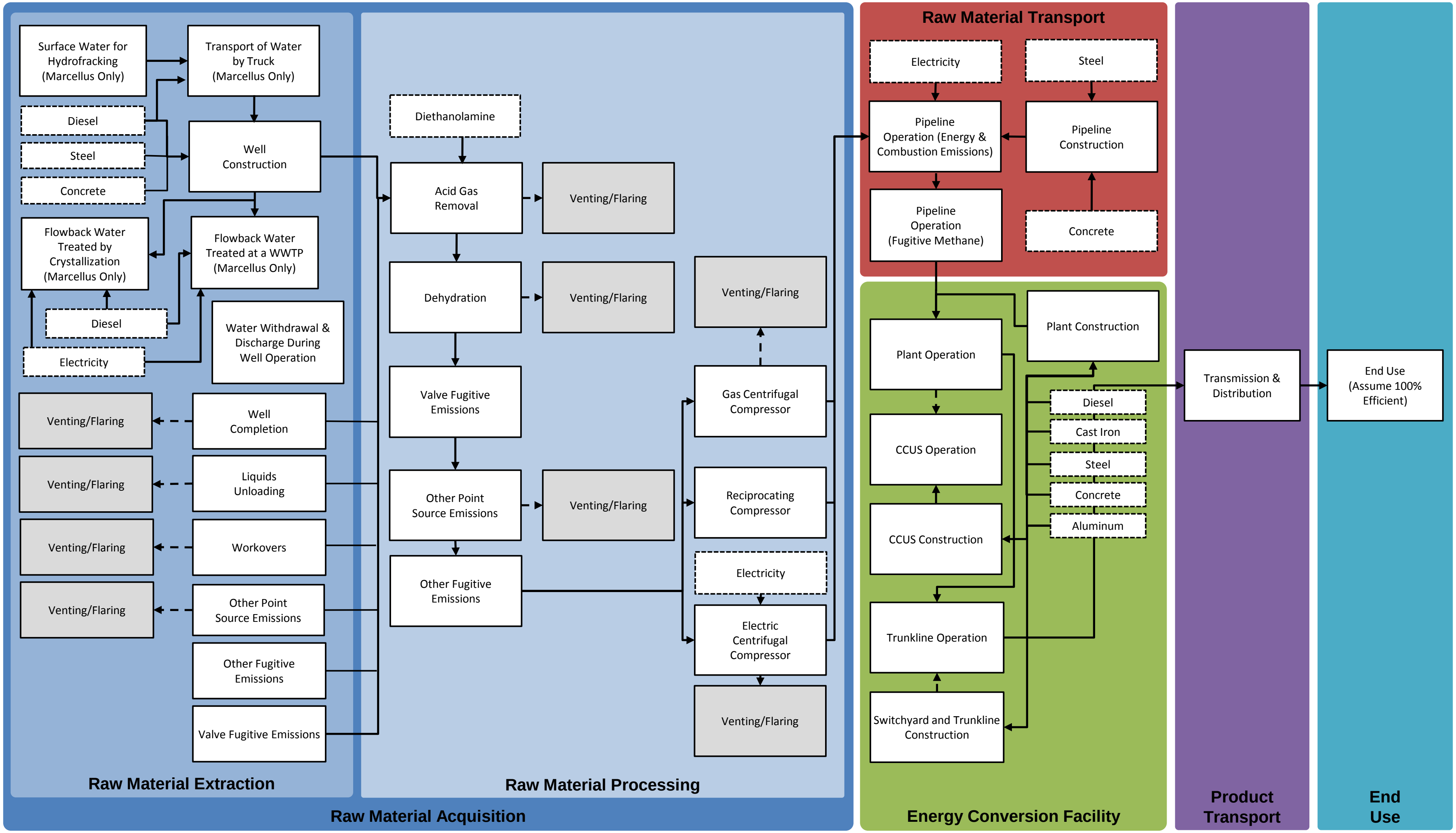


Source: EIA, 2012a

- 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)
- U.S. supply of natural gas consists of domestic and imported sources and includes conventional and unconventional extraction
- Marcellus Shale has an EUR (estimated ultimate recovery) of 489 Tcf (Engelder, 2009)

- Natural gas prices were low in 2010, but production climbed 4.8%, indicating an adherence to lease and drilling contracts Baker-Hughes, 2012; EIA, 2012a)
- Well development dropped quickly in 2011 as natural gas prices dropped toward $2/MMBtu
- U.S. natural gas in storage is relatively high, at 2.5 trillion cubic feet (Tcf) as of April 2012, a storage volume that is 51% higher than April 2011 (EIA, 2012b)

Boundaries for Natural Gas Life Cycle



Modeling Parameters for NG Extraction

<table>
<tr><th>Property (Units)</th><th></th><th>Onshore</th><th>Associated</th><th>Offshore</th><th>Tight Gas</th><th>Barnett Shale</th><th>Marcellus Shale</th><th>CBM</th></tr>
<tr><td colspan="9">Natural Gas Source</td></tr>
<tr><td colspan="2">Contribution to 2010 U.S. Domestic Supply</td><td>22%</td><td>6.6%</td><td>12%</td><td>27%</td><td>21%</td><td>2.5%</td><td>9.4%</td></tr>
<tr><td rowspan="3">Average Production Rate (Mcf /day)</td><td>low</td><td>46</td><td>85</td><td>1,960</td><td>77</td><td>192</td><td>201</td><td>73</td></tr>
<tr><td>expected</td><td>66</td><td>121</td><td>2,800</td><td>110</td><td>274</td><td>297</td><td>105</td></tr>
<tr><td>high</td><td>86</td><td>157</td><td>3,641</td><td>143</td><td>356</td><td>450</td><td>136</td></tr>
<tr><td colspan="2">Expected EUR (Estimated Ultimate Recovery) (BCF)</td><td>0.72</td><td>1.32</td><td>30.7</td><td>1.20</td><td>3.00</td><td>3.25</td><td>1.15</td></tr>
<tr><td colspan="9">Natural Gas Extraction Well</td></tr>
<tr><td colspan="2">Flaring Rate (%)</td><td colspan="3">51% (41 - 61%)</td><td colspan="4">15% (12 - 18%)</td></tr>
<tr><td colspan="2">Well Completion (Mcf natural gas/episode)</td><td colspan="3">47</td><td>3,670</td><td>9,175</td><td>9,175</td><td>49.6</td></tr>
<tr><td colspan="2">Well Workover (Mcf natural gas/episode)</td><td colspan="3">3.1</td><td>3,670</td><td>9,175</td><td>9,175</td><td>49.6</td></tr>
<tr><td colspan="2">Lifetime Well Workovers (Episodes/well)</td><td colspan="3">1.1</td><td colspan="4">3.5</td></tr>
<tr><td colspan="2">Liquids Unloading (Mcf natural gas/episode)</td><td>23.5</td><td>n/a</td><td>23.5</td><td>n/a</td><td>n/a</td><td>n/a</td><td>n/a</td></tr>
<tr><td colspan="2">Lifetime Liquid Unloadings (Episodes/well)</td><td>930</td><td>n/a</td><td>930</td><td>n/a</td><td>n/a</td><td>n/a</td><td>n/a</td></tr>
<tr><td colspan="2">Valve Emissions, Fugitive (lb CH_4/Mcf natural gas)</td><td colspan="2">0.11</td><td>0.0001</td><td colspan="4">0.11</td></tr>
<tr><td colspan="2">Other Sources, Point Source (lb CH_4/Mcf natural gas)</td><td colspan="2">0.003</td><td>0.002</td><td colspan="4">0.003</td></tr>
<tr><td colspan="2">Other Sources, Fugitive (lb CH_4/Mcf natural gas)</td><td colspan="2">0.043</td><td>0.01</td><td colspan="4">0.043</td></tr>
</table>

- 3 types of episodic emissions: completion, workover, liquids unloading
- Production rate a key driver of GHG results because it is used to apportion episodic emissions
- Routine emissions include valve emissions, other fugitives, and other point sources; offshore extraction has lowest rates for routine emissions
- Valve emissions & other fugitives are not recoverable; other point sources are recovered and flared

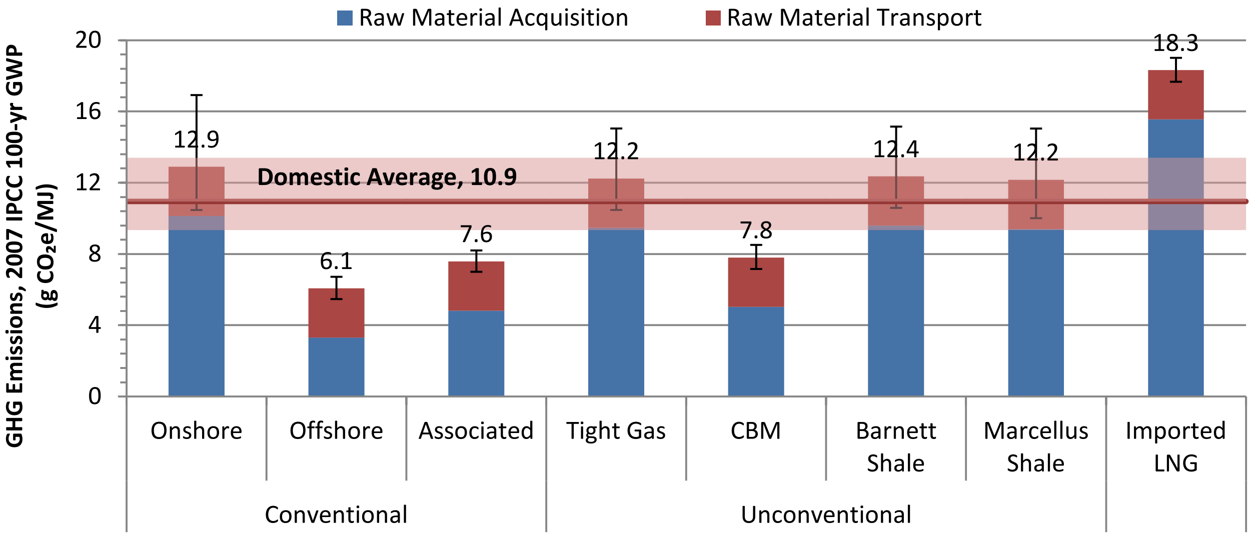
Modeling Parameters for NG Processing and Transport

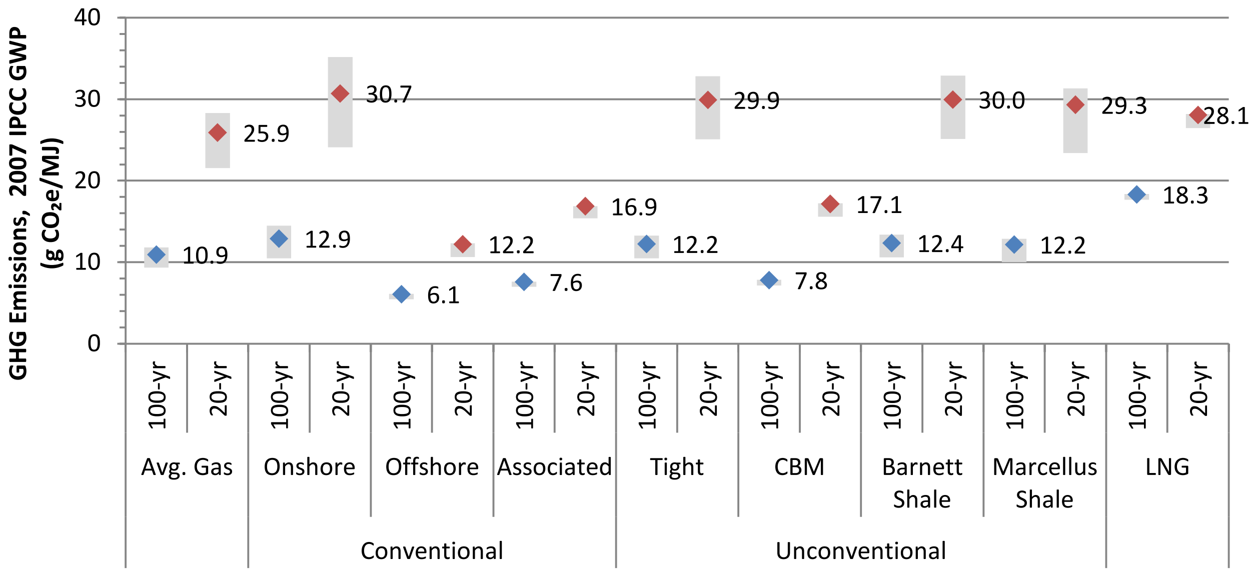
Property (Units)	On-shore	Assoc-iated	Off-shore	Tight Gas	Barnett Shale	Marcellus Shale	CBM
Acid Gas Removal (AGR) and CO_2 Removal Unit							
Flaring Rate (%)	100%						
CH_4 Absorbed (lb CH_4/Mcf natural gas)	0.04						
CO_2 Absorbed (lb CO_2/Mcf natural gas)	0.56						
H_2S Absorbed (lb H_2S/Mcf natural gas)	0.21						
NMVOC Absorbed (lb NMVOC/Mcf natural gas)	6.59						
Glycol Dehydrator Unit							
Flaring Rate (%)	100%						
Water Removed (lb H_2O/Mcf natural gas)	0.045						
CH_4 Emission Rate (lb CH_4/Mcf natural gas)	0.0003						
Valves & Other Sources of Emissions							
Flaring Rate (%)	100%						
Valve Emissions, Fugitive (lb CH_4/Mcf natural gas)	0.0003						
Other Sources, Point Source (lb CH_4/Mcf natural gas)	0.02						
Other Sources, Fugitive (lb CH_4/Mcf natural gas)	0.03						
Natural Gas Compression at Gas Plant							
Compressor, Gas-powered Reciprocating (%)	100%	100%		100%	75%	100%	100%
Compressor, Gas-powered Centrifugal (%)			100%				
Compressor, Electrical, Centrifugal (%)					25%		

- The same acid gas removal, dehydration, and emissions are used to model processing of all sources of natural gas
- NMVOC is a coproduct of natural gas processing; coproduct allocation is used to account for the two products (natural gas and NMVOC) of acid gas removal
- Offshore platforms require centrifugal compressors, but reciprocating compressors are most likely technology for other sources of natural gas
- Barnett shale uses electrically-powered, centrifugal compressors when extraction and processing is near a city

Transport of natural gas is modeled with the same parameters for all natural gas sources: 971 km of pipeline transmission with a 78/19/3 mix of reciprocating/centrifugal/electric compressors

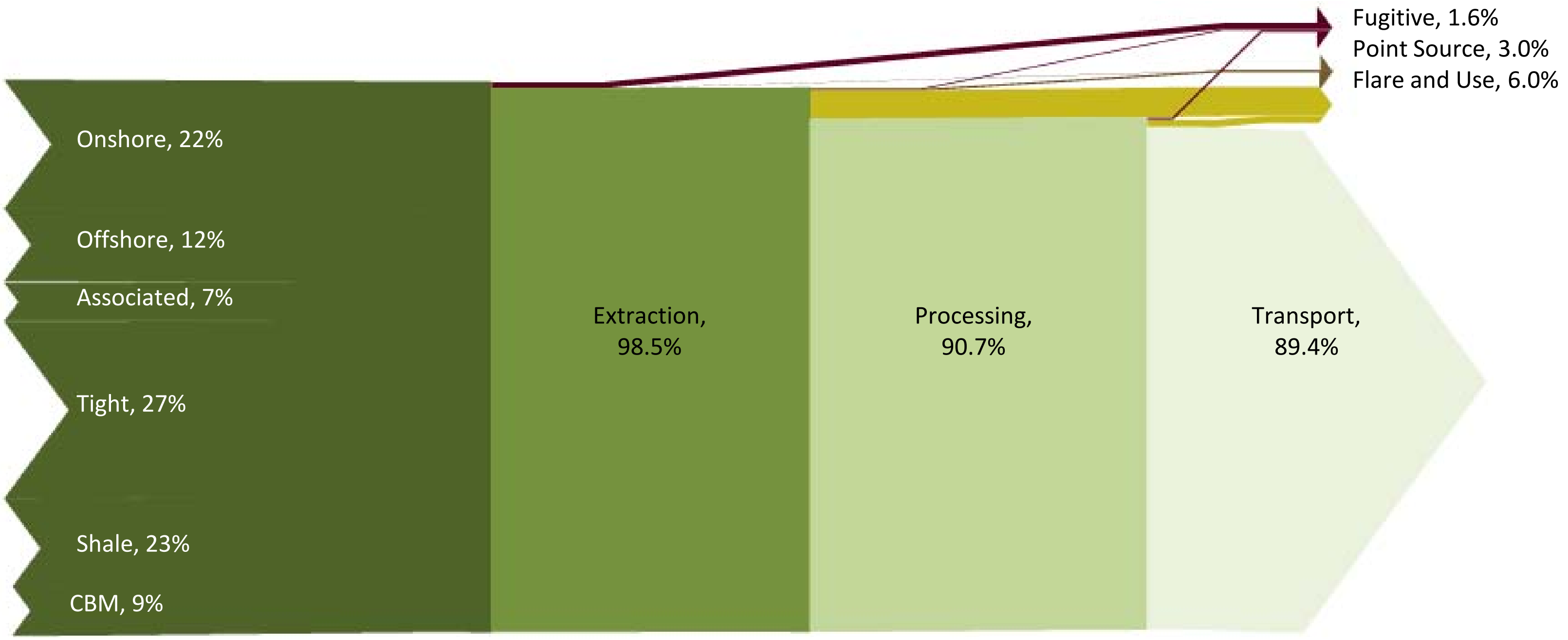
Upstream GHG Emissions from Natural Gas





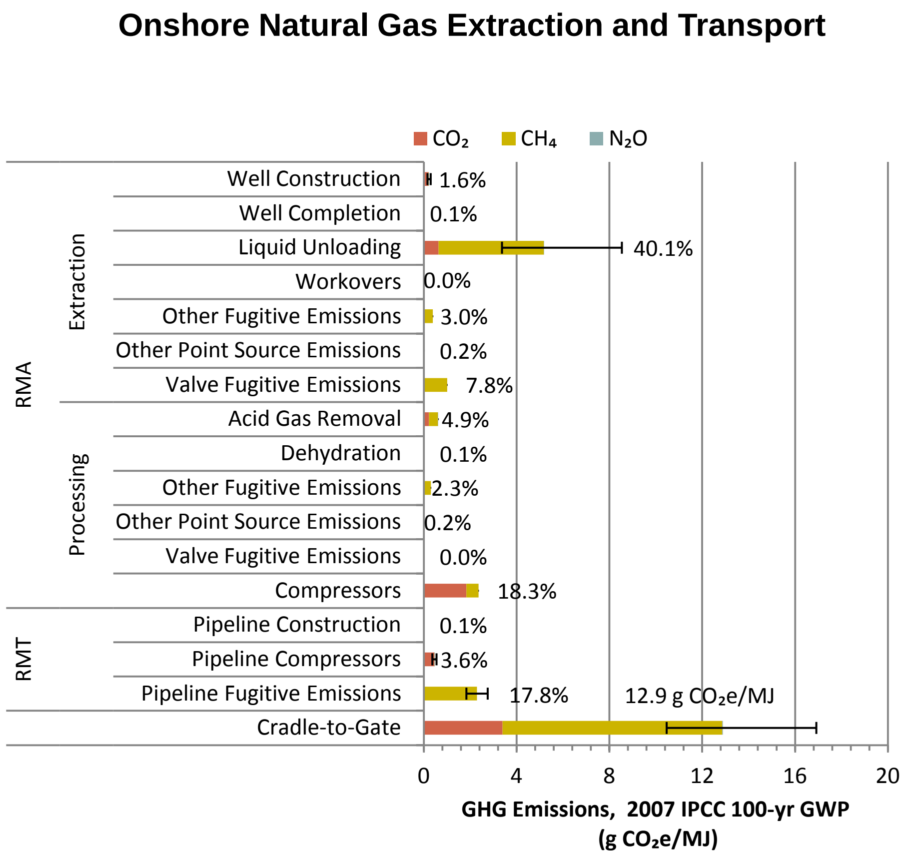
- Offshore natural gas has lowest GHGs of any source; it has a high production rate and offshore wells are motivated to control methane emissions for safety and risk-mitigation reasons
- Imported gas has highest GHG emissions; liquefaction and regasification is energy intensive
- RMT result is assumed the same for all types of natural gas because natural gas is a commodity that is indistinguishable once put on transport network
- Converting inventory of GHGs to 20-year GWP, where CH_4 factor increases from 25 to 72, magnifies difference between conventional and unconventional sources of natural gas, and importance of CH_4 losses to upstream GHG results

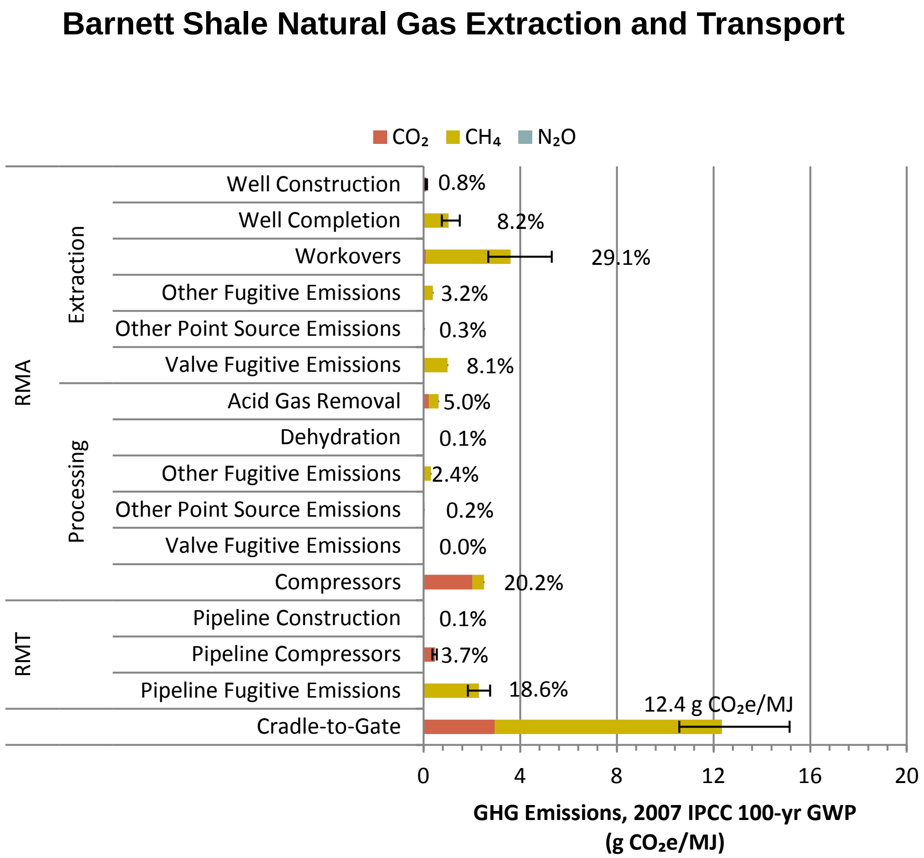
Natural Gas Upstream Reduction



- Of natural gas extracted from the ground, only 89% is delivered to 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)

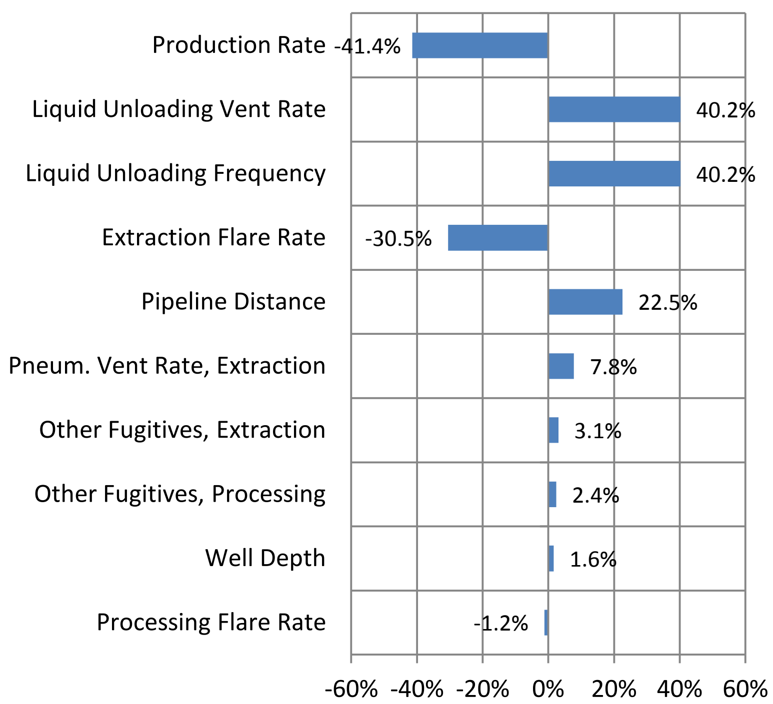
GHG Details for Natural Gas (RMA + RMT)

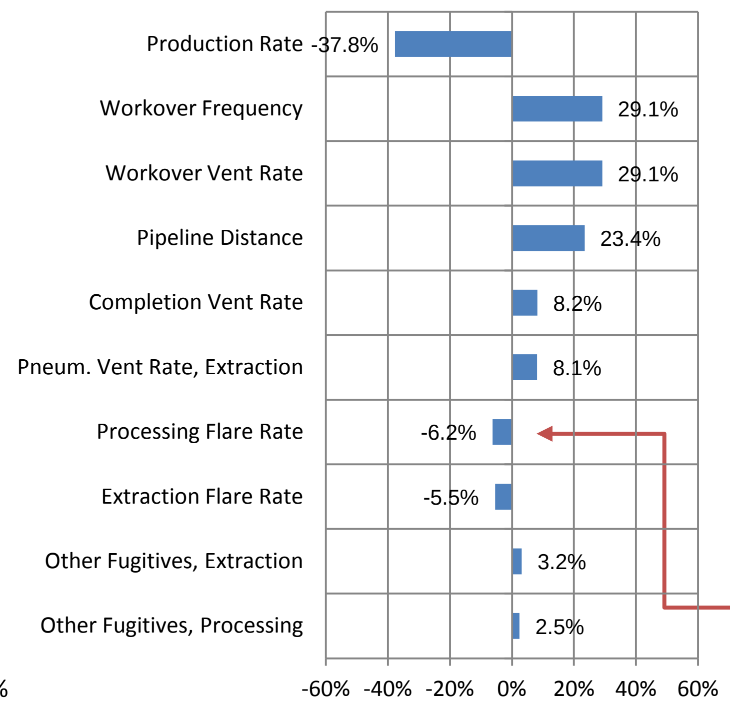




- Error bars represent uncertainty driven by ranges in production rates, flaring rates, and other parameters
- CH_4 is important to upstream GHGs and arises from episodic, point source, and fugitive emissions
- Liquid unloading is a key episodic emission for onshore conventional natural gas; completion and workovers are key episodic emissions for unconventional natural gas
- Compressors (processing and pipeline) are a significant source of CO_2
- Detailed results for Marcellus Shale (not shown) show hydrofracking water delivery and treatment is 2.1% of upstream GHG

GHG Sensitivity for Natural Gas (RMA + RMT)





Sensitivity analysis finds the parameters in the model that, when changed, have the greatest affect on the results.

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.

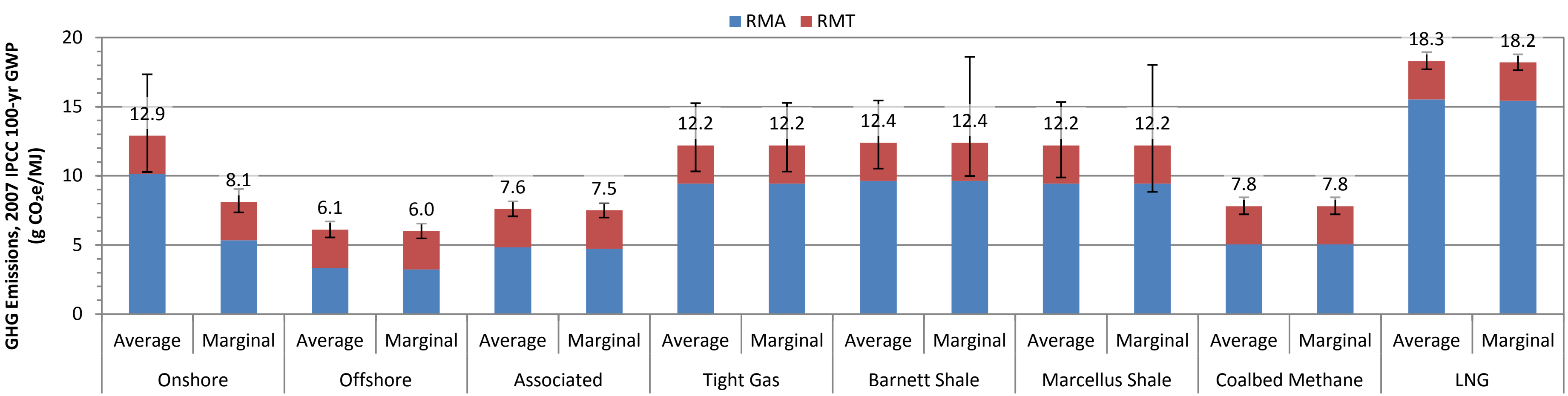
For example, a 100% increase processing flare rate causes a 6.2% decrease in upstream GHG emissions.

- Upstream GHG emissions are most sensitive to production rate, episodic emissions, and pipeline distance
- Upstream GHG results for all NG sources are sensitive to pipeline distance
- Changes to emission rates for routine emissions from extraction and processing do not significantly change upstream GHG results
- Sensitivity data can be generated for all natural gas types, but onshore and Barnett Shale extraction are shown above because they exemplify key sensitivities for conventional and unconventional sources

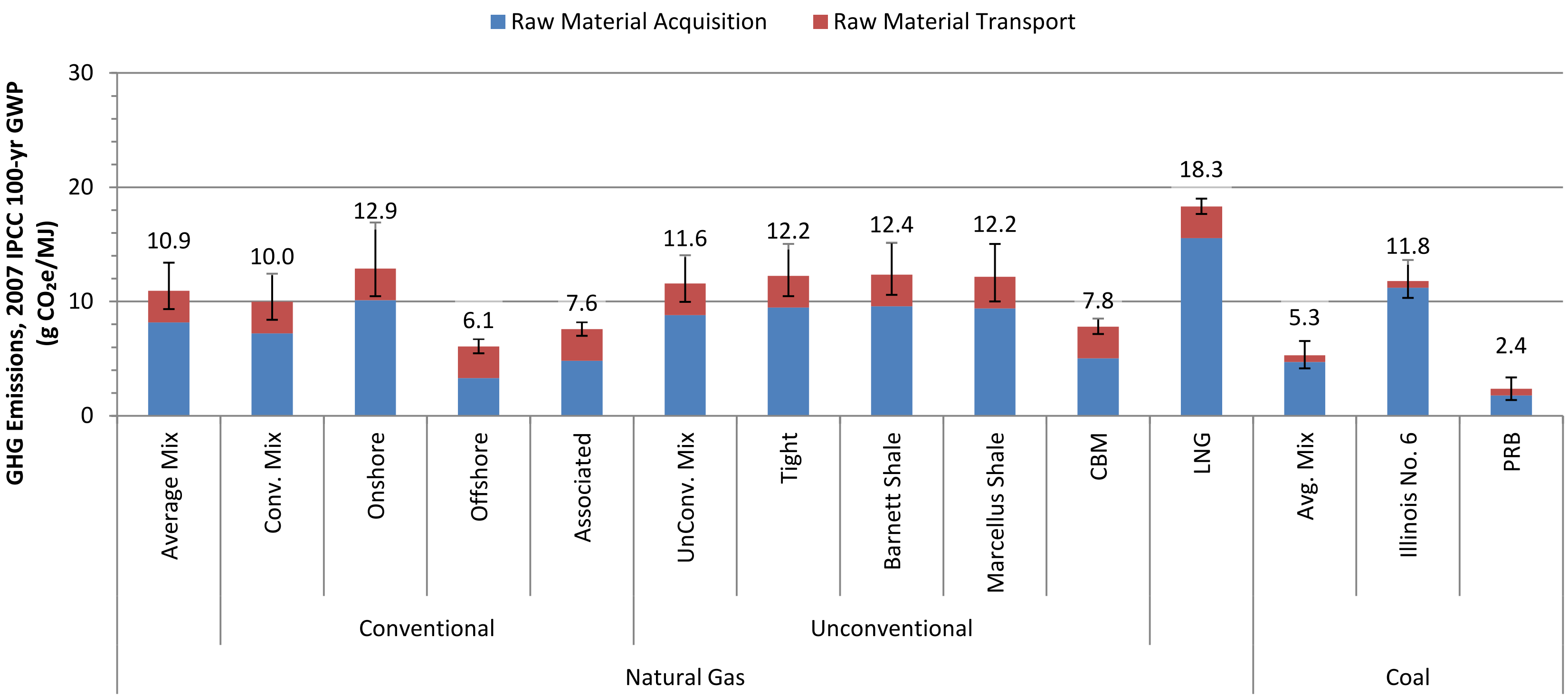
Average vs. Marginal Natural Gas Production Rates and Results

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

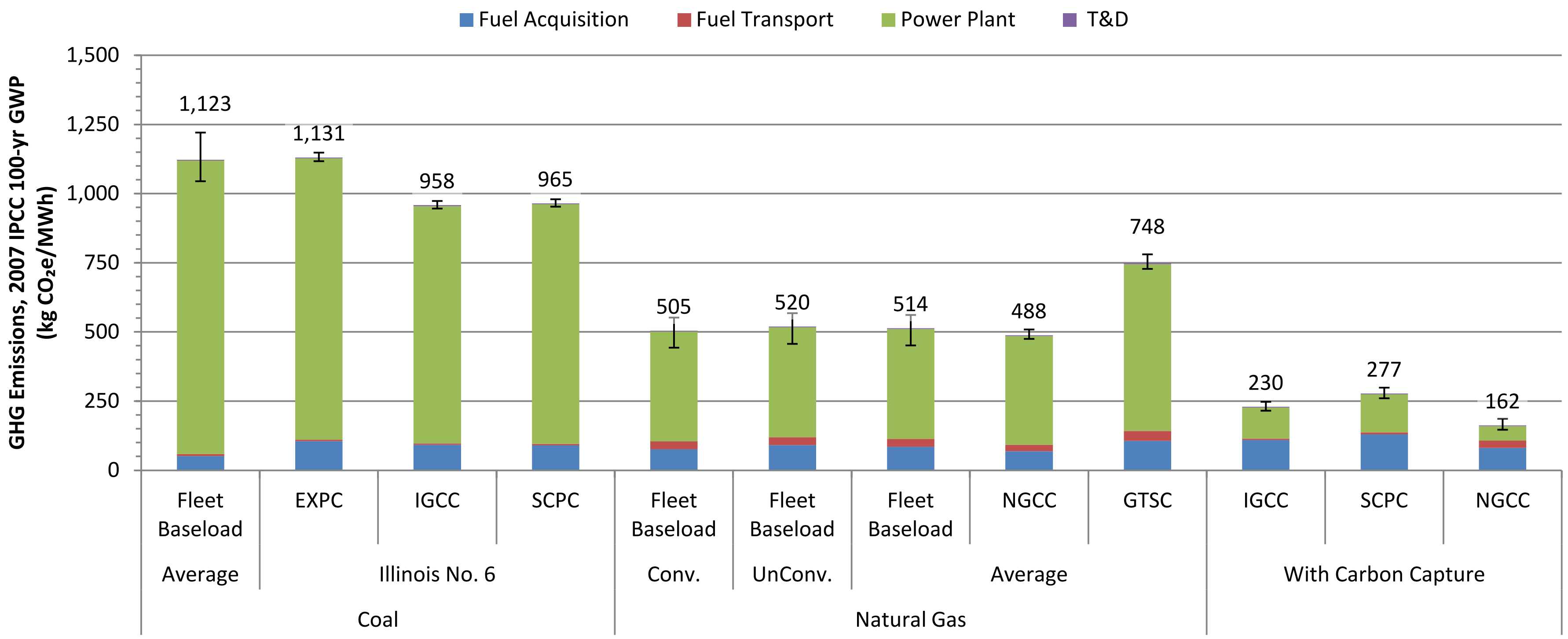


Upstream GHG Comparison of Natural Gas and Coal



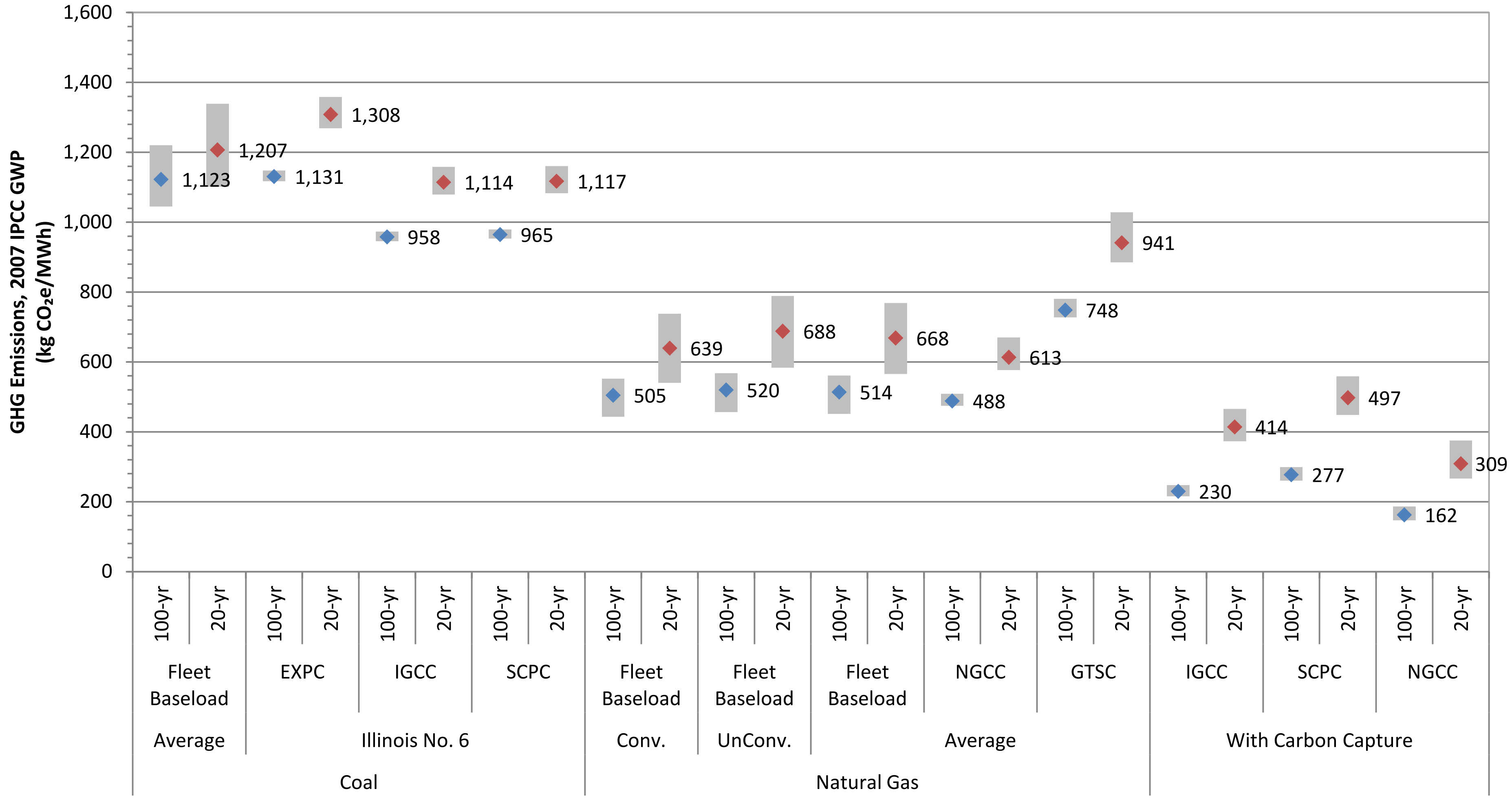
- On an upstream energy basis, natural gas has higher GHG emissions than coal
- Bituminous coal with high amounts of entrained methane, such as Illinois No. 6, is more comparable to NG, but makes up only 31% of domestic coal consumption on an energy basis
- These results are not expressed on the basis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

Life Cycle GHG Emissions of Natural Gas and Coal Power



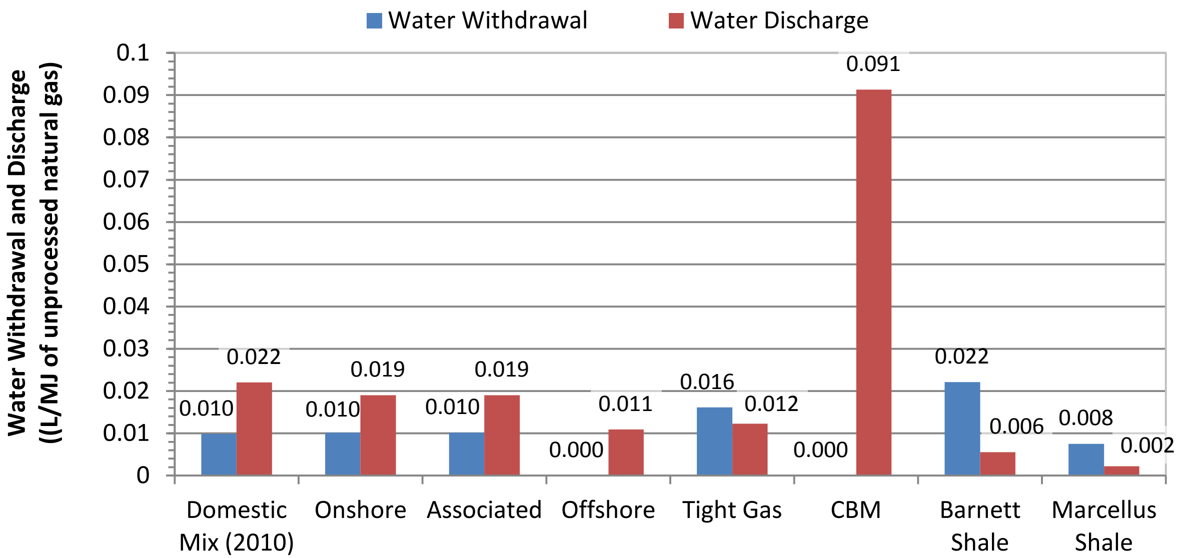
- On a 100-yr IPCC GWP basis, natural gas power has a lower impact than coal power
- Because of their similar roles, the fairest comparison is the domestic mix of coal through an average baseload coal power plant vs. the domestic mix of natural gas run through an average baseload natural gas plant (1,123 vs. 514 kg CO_2e/MWh)

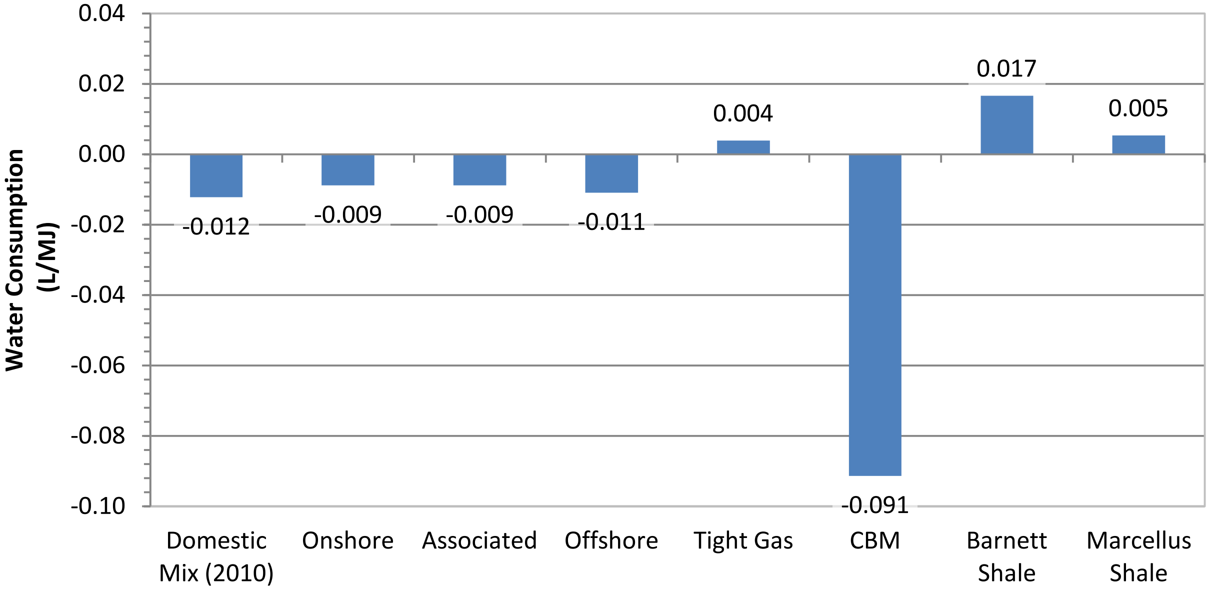
Importance of 20- and 100-yr GWP



Even when increasing the GWP of CH_4 from 25 to 72, the relative impact of upstream methane from gas-fired power still has lower GHGs than coal-fired power

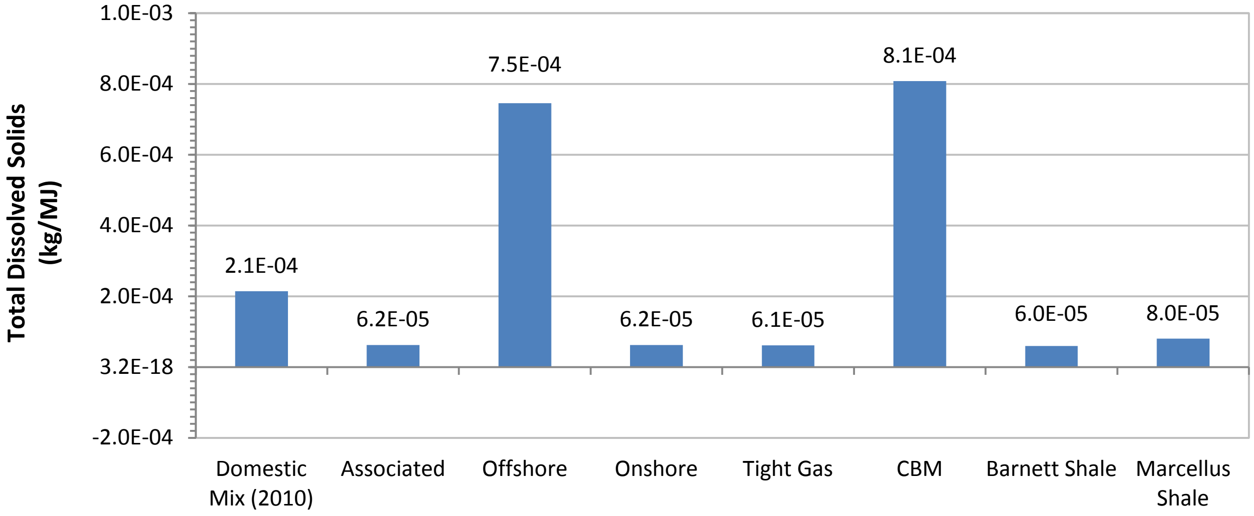
Water Use Results for Natural Gas Extraction

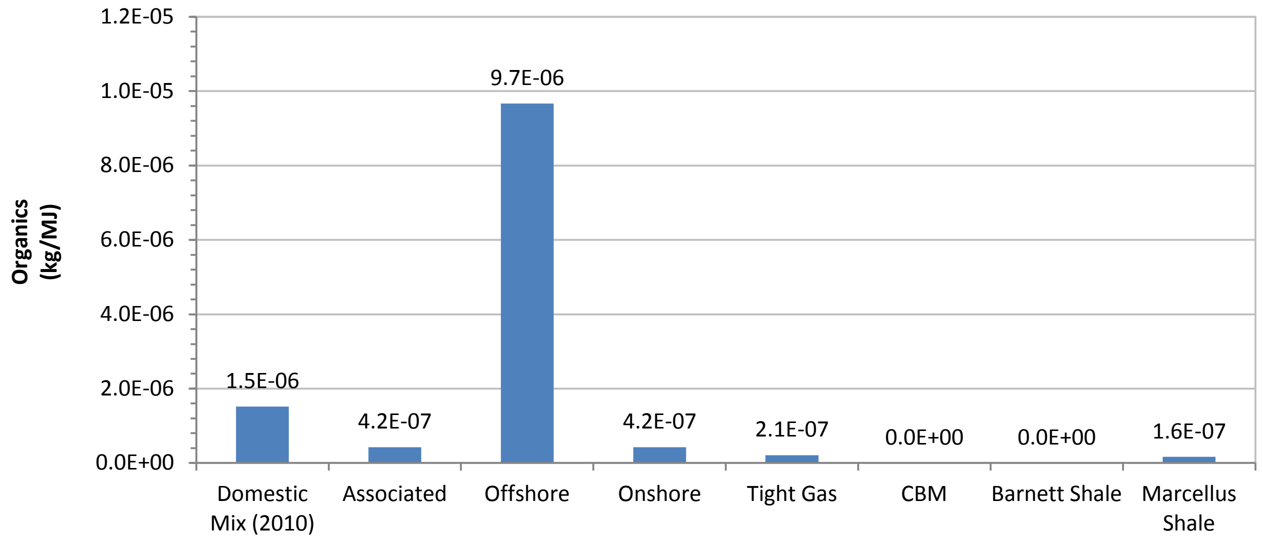




- Water withdrawal, discharge, and net consumption are accounted for based on primary data for each well type
- No water use data available for tight gas wells; water use characteristics of tight gas likely fall between those for onshore conventional and Barnett Shale wells
- Shale gas has higher water consumption than other wells due to hydrofracking
- CBM wells do not use water, but produce water at a rate of approximately 0.091 L/MJ (3.7 L/m^3)of natural gas extracted
- Results should also be considered on a life cycle perspective (through power)

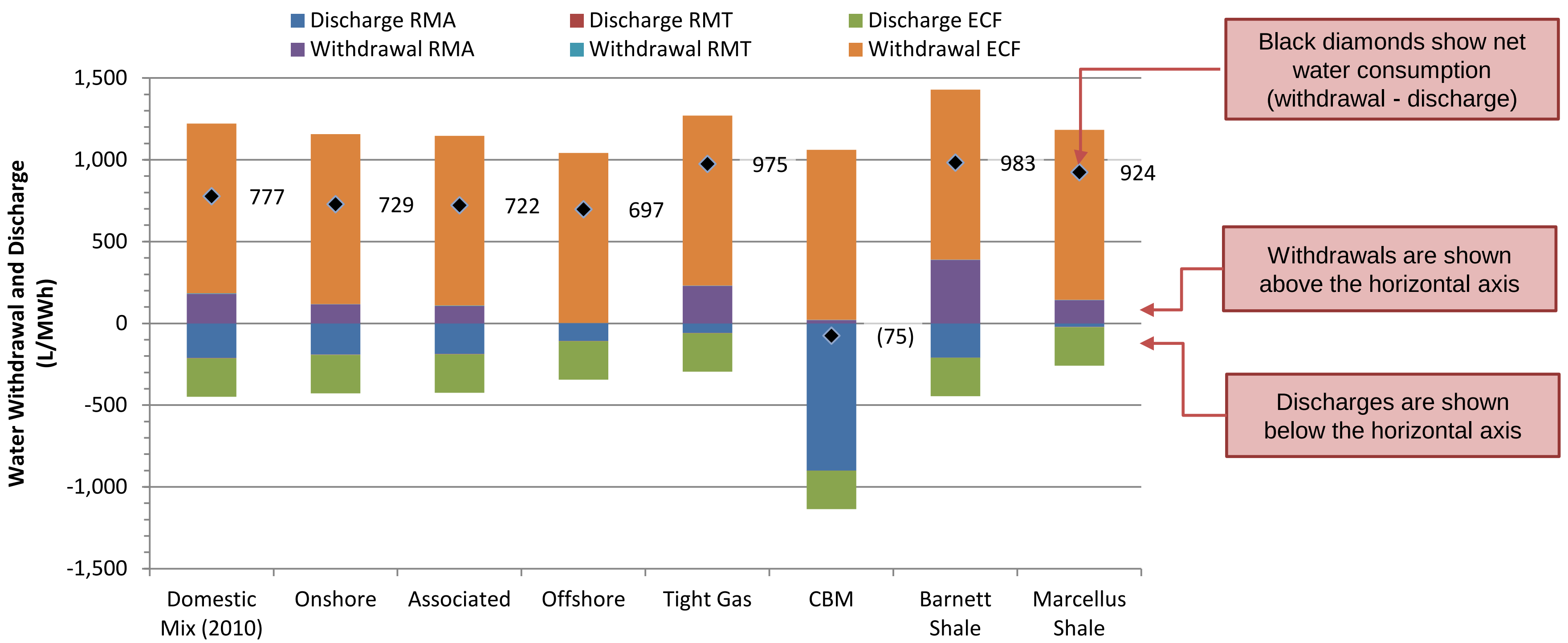
Water Quality Results for Natural Gas Extraction





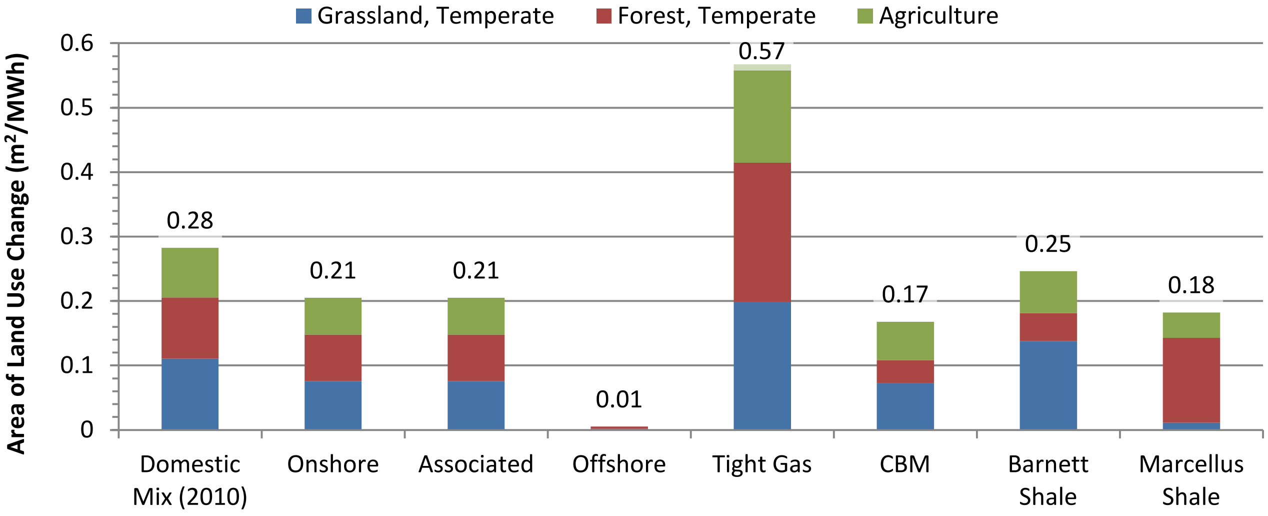
- TDS (total dissolved solids) are a measure of water quality and include salts and organics less than 2 μm
- Water discharged from offshore wells has high salinity that leads to high TDS per unit of natural gas produced; the high volumes of produced water from CBM wells lead to high TDS per unit of natural gas produced
- Organics include oil and grease as well as organic carbon
- Data quality for organics is lower than for TDS
- No data available to calculate organic effluents from CBM or Barnett Shale wells

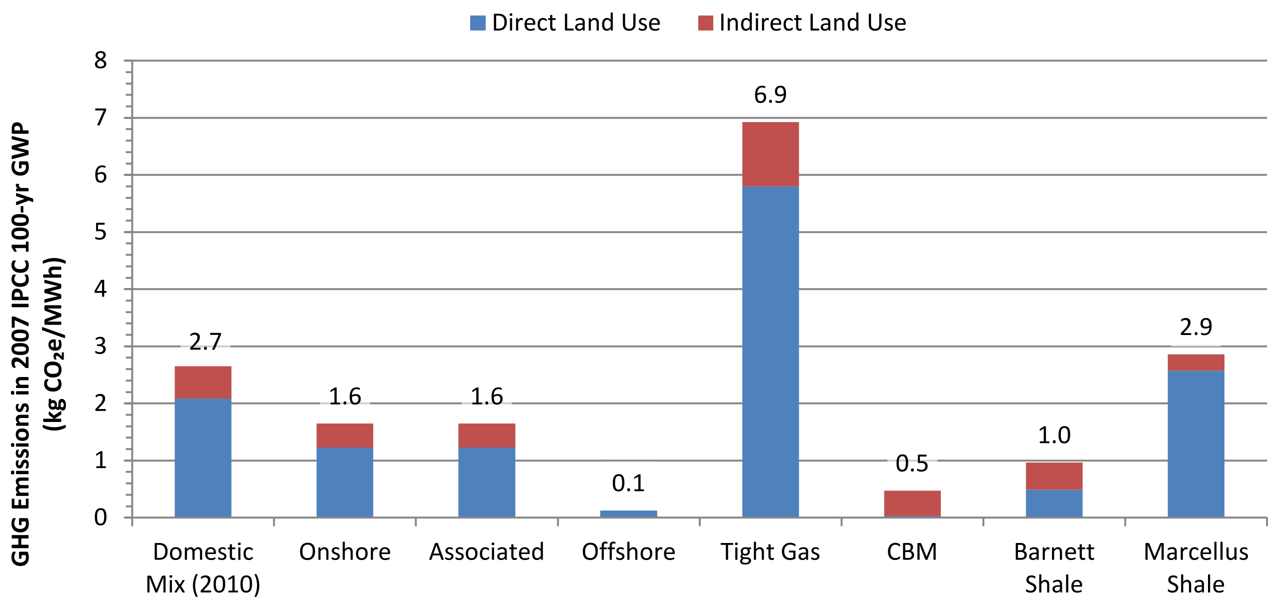
Life Cycle Water Use Results for Natural Gas Power (NGCC without CCS)



- Compared to other life cycle stages, the energy conversion facility has the highest magnitude of water flows
- Life cycle water consumption for NGCC power using CBM natural gas is lower than other unconventional scenarios due to water produced by CBM wells
- Life cycle water consumption for NGCC power *with CCS* (not shown) is approximately 1.8 times higher than NGCC without CCS

Land Use Results for Natural Gas Power

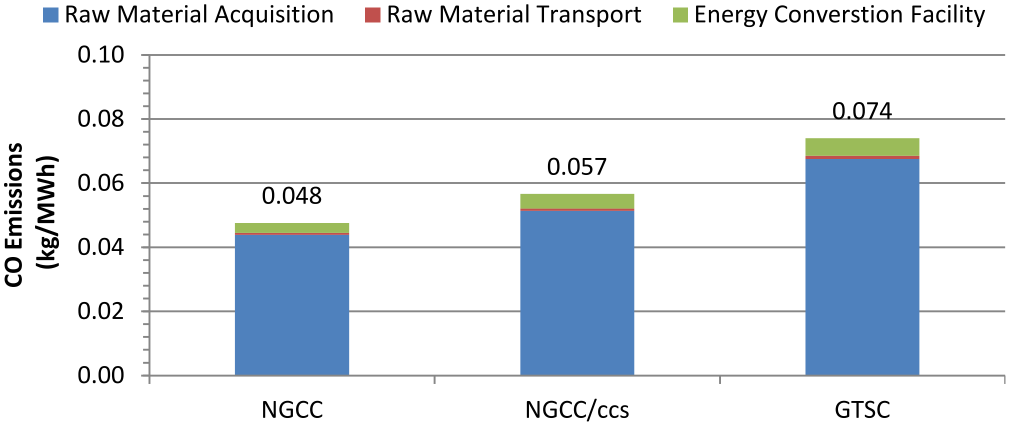


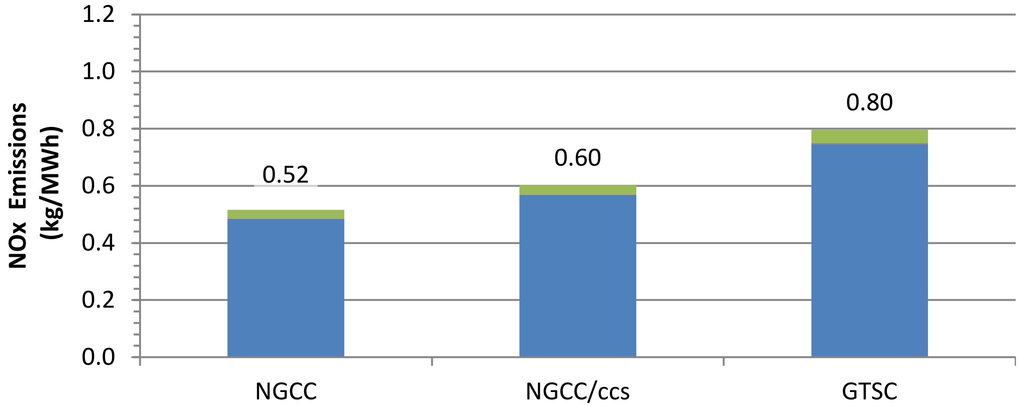


- Marcellus results in highest loss of forest land, at 72% of total transformed land area, due to large proportion of forested area in Marcellus region
- Direct land use GHGs comprise majority of total land use GHG emissions; from 50% for Barnett up to 90% for Marcellus
- Indirect land use GHG emissions 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%)

Other Air Emissions for NG Power

Technology	Emission (kg/MWh)	RMA	RMT	ECF	Total
NGCC	Pb	1.98E-06	1.65E-07	2.71E-06	4.86E-06
	Hg	6.80E-08	5.17E-09	2.46E-08	9.77E-08
	NH_3	8.98E-07	1.99E-06	1.88E-02	1.88E-02
	CO	4.38E-02	6.23E-04	3.12E-03	4.76E-02
	NOx	4.85E-01	7.80E-04	3.05E-02	5.16E-01
	SO_2	5.06E-03	3.18E-04	1.19E-03	6.56E-03
	VOC	4.73E-01	1.59E-05	3.72E-05	4.73E-01
	PM	4.80E-03	6.55E-05	2.17E-03	7.04E-03
NGCC/ccs	Pb	2.32E-06	1.94E-07	3.09E-06	5.61E-06
	Hg	7.97E-08	6.06E-09	3.50E-08	1.21E-07
	NH_3	1.05E-06	2.33E-06	2.03E-02	2.03E-02
	CO	5.14E-02	7.31E-04	4.50E-03	5.66E-02
	NOx	5.68E-01	9.14E-04	3.42E-02	6.03E-01
	SO_2	5.93E-03	3.72E-04	1.67E-03	7.97E-03
	VOC	5.55E-01	1.86E-05	4.74E-05	5.55E-01
	PM	5.63E-03	7.67E-05	2.47E-03	8.18E-03
GTSC	Pb	3.05E-06	2.55E-07	6.27E-07	3.94E-06
	Hg	1.05E-07	7.96E-09	7.08E-09	1.20E-07
	NH_3	1.38E-06	3.07E-06	2.90E-02	2.90E-02
	CO	6.75E-02	9.61E-04	5.48E-03	7.40E-02
	NOx	7.47E-01	1.20E-03	4.87E-02	7.97E-01
	SO_2	7.79E-03	4.89E-04	1.53E-03	9.81E-03
	VOC	7.29E-01	2.45E-05	1.64E-04	7.30E-01
	PM	7.40E-03	1.01E-04	2.75E-03	1.03E-02





- Life cycle emissions for most criteria air pollutants and other air emissions of concern are within the same order of magnitude
- In general, these emissions increase as power plant efficiency decreases

Energy Return on Investment (EROI)

Energy Flow	NGCC	NGCC/ccs	GTSC	Fleet Average NG Power
Useful Energy Produced, MJ	1.0	1.0	1.0	1.0
Total System Energy Input, MJ	2.6	3.1	4.1	3.2
Crude oil, MJ	< 0.1	< 0.1	< 0.1	< 0.1
Hard coal, MJ	< 0.1	< 0.1	< 0.1	< 0.1
Lignite, MJ	< 0.1	< 0.1	< 0.1	< 0.1
Natural gas, MJ	2.6	3.1	4.4	3.2
Uranium, MJ	< 0.1	< 0.1	< 0.1	< 0.1
Renewables	< 0.1	< 0.1	< 0.1	< 0.1
Total Energy Expended, MJ	1.6	2.1	3.1	2.2
EROI	0.6:1	0.5:1	0.3:1	0.4:1

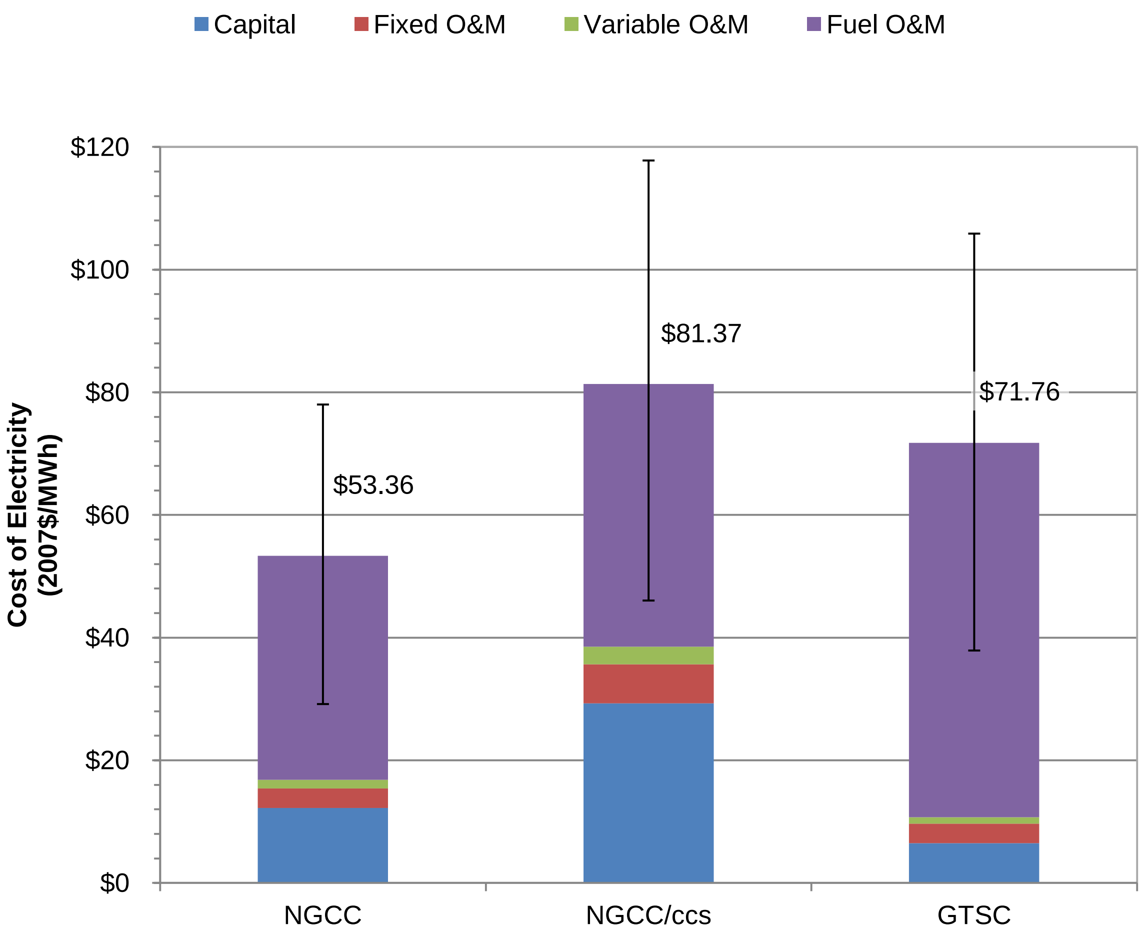
- The energy return on investment (EROI) is the ratio of energy produced to total energy expended
- EROI for electric power systems is less than 1 due to thermal-to-electric energy conversion
- The total energy inputs are accounted for by factoring the mass of all resources (crude oil, coals, natural gas, uranium, and renewable resources) by their heating values
- The resource energy of natural gas accounts for over 99% of total resource energy for all power cases in this analysis
- The NGCC power plant is the most efficient energy conversion facility of this analysis, so it has the highest EROI
- The EROI for upstream natural gas (2010 domestic mix) is 7.6

Cost Analysis of Natural Gas Power

Parameter	Units	NGCC	NGCC/ccs	GTSC
Total Capital (Total Overnight Cost)	**$/kW**	**802**	**1,913**	**428**
Capital (power plant)	$/kW	718	1,497	299
Capital (trunkline & switchyard)	$/kW	84	98	129
Capital (CO_2 pipeline)	$/kW	NA	265	NA
Capital (CO_2 injection)	$/kW	NA	52.2	NA
Fuel Costs (Natural Gas)	**$/MWh**	**34.0**	**39.9**	**56.9**
Total Variable O&M (Not Including Fuel Costs)	**$/MWh**	**1.32**	**2.68**	**0.96**
Variable O&M (power plant)	$/MWh	1.32	2.56	0.96
Variable O&M (CO_2 pipeline)	$/MWh	NA	0	NA
Variable O&M (CO_2 injection)	$/MWh	NA	0.0034	NA
Variable O&M (CO_2 monitoring)	$/MWh	NA	0.116	NA
Total Fixed O&M	**$/MW-yr**	**22,065**	**44,222**	**22,065**
Fixed O&M (power plant)	$/MW-yr	22,065	42,104	22,065
Fixed O&M (CO_2 pipeline)	$/MW-yr	NA	1,821	NA
Fixed O&M (CO_2 injection)	$/MW-yr	NA	297	NA
Net plant capacity	MW	555	474	360
Capacity factor	%	85%	85%	85%
Daily net electricity (at 100% capacity)	MWh/day	13,320	11,366	8,640
Annual Electricity Production (including capacity factor)	MWh/yr	4,132,530	3,526,426	2,680,560

- All power plant costs from bituminous baseline report (NETL, 2010a)
- CO_2 pipeline capital costs are $126 million for 100 miles (NETL, 2010b)
- CO_2 injection and monitoring costs estimated from background data to the bituminous baseline report (NETL, 2010a)
- 7% T&D loss
- Nominal fuel cost is $5.00/MMBtu natural gas (2007$)
- Financial assumptions include a 50/50 debt/equity ratio, 20-year MACRS depreciation, 38% total tax rate, and 12.0% internal rate of return on equity (IRROE)
- Modeled with NETL's Power Systems Financial Model (PSFM)

Life Cycle Cost of Natural Gas Power



- NGCC has lowest life cycle COE
  - Relatively high capital costs are offset by high power plant efficiency
  - COE of NGCC power is increased by 52% when a CCS system is added
- GTSC has low capital costs, but its relatively low efficiency results in high fuel costs per unit output
- Error bars represent uncertainty caused by ranges in capital costs, natural gas price, capacity factor, and variable O&M

Barriers to Implementation

- **Public concerns regarding water quality if poor practices are used for the completion of unconventional wells**
- **Unconventional natural gas has completion and workover activities that release GHG emissions**
- **Limited capacity of existing pipeline transmission network is a possible barrier to growth of new natural gas extraction sources**

Water quality and greenhouse gas emissions should be viewed from a life cycle perspective.

NETL's LCA results show:

- Water quality results for Marcellus Shale natural gas extraction are similar to those for conventional natural gas extraction
- When natural gas is used for power production, power plant emissions account for the majority of life cycle greenhouse gas emissions

Risks of Implementation

- **Legislation Focused on Shale Gas Development**
  - In December 2010, Governor Paterson vetoed legislation that would have placed a six-month moratorium on hydrofracking in New York (NYSDEC, 2010). New York’s hydrofracking ban was lifted in 2012, but there is still debate among citizens and policy makers
  - After months of controversy, in February 2012, Pennsylvania approved legislation that taxes the shale gas industry and sets standards for developing gas wells (Tavernise, 2012)
- **Industry vs. Citizens**
  - Industry in favor of unconventional extraction methods, while some citizens want to stop hydrofracking (Applebome, 2010)

Expert Opinions

- **Different estimates of technically recoverable gas in Marcellus Shale**
  - USGS estimates 84 TCF (Pierce et al., 2011)
  - Engelder estimates 489 TCF (Engelder, 2009)
- **Water quality concerns supported by research from Duke (Osborn, Warner, & Jackson, 2011)**
- **Pipeline companies claim that natural gas pipelines can be easily expanded**
  - Compressors can be added to existing pipelines to increase gas transport capacity (Langston, 2011)
  - There is enough room in existing pipeline right-of-ways for installation of additional pipelines (Langston, 2011)

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Contact Information

Office of Fossil Energy

www.fe.doe.gov

NETL

www.netl.doe.gov

Timothy J. Skone, P.E.
Senior Environmental Engineer
Office of Strategic Energy Analysis and Planning
(412) 386-4495
timothy.skone@netl.doe.gov

Robert James, Ph.D.
General Engineer
Office of Strategic Energy Analysis and Planning
(304) 285-4309
robert.james@netl.doe.gov

Joe Marriott, Ph.D.
Lead Associate
Booz Allen Hamilton
(412) 386-7557
marriott_joe@bah.com

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