A Strategy for Exploiting Unconventional Gas Resources and Mitigating Greenhouse Gas Emissions

or Getting From Here to There

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Department of Geophysics

The Energy Seminar
May 20, 2009
Getting from Here to There?

Significant Utilization of Unconventional Natural Gas – With Carbon Capture and Storage – During the Transition Away From Fossil Fuels Over the Next ~20-30 Years

Goal (in this presentation) is to Consider Fully Replacing Coal in the U.S. for Electrical Power Generation*

- Dramatically Reduce CO$_2$ Emissions
- Reduce Other Pollutants Associated With Coal
- Provide Required Energy With Domestic Sources
- Achieve This Using Existing Technologies**
- Provide Economic Incentives for CCS

* Other uses of natural gas (transportation) not considered
## Air Pollution and Energy Source*

*Pounds/Billion BTU

<table>
<thead>
<tr>
<th></th>
<th>CH(_4)</th>
<th>Oil</th>
<th>Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{CO}_2)</td>
<td>117,000</td>
<td>164,000</td>
<td>208,000</td>
</tr>
<tr>
<td>\text{CO}</td>
<td>40</td>
<td>33</td>
<td>208</td>
</tr>
<tr>
<td>(\text{NO}_x)</td>
<td>92</td>
<td>448</td>
<td>457</td>
</tr>
<tr>
<td>(\text{SO}_2)</td>
<td>0.6</td>
<td>1,122</td>
<td>2,591</td>
</tr>
<tr>
<td>Particulates</td>
<td>7.0</td>
<td>84</td>
<td>2,744</td>
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<tr>
<td>Formaldehyde</td>
<td>0.75</td>
<td>0.22</td>
<td>0.221</td>
</tr>
<tr>
<td>Mercury</td>
<td>0</td>
<td>0.007</td>
<td>0.016</td>
</tr>
</tbody>
</table>

*EIA, 1998*
Switching from Coal to Gas Reduces Emissions by 1 GT C/y

Pacala and Socolow (2004)

Potential Wedge #5. Use Gas baseload power for coal baseload power

1 GT C/y wedge

Switching from coal to gas with CCS – 2 wedges!
Getting from Here to There with Unconventional Gas

- An Unconventional Gas Primer
  - Shale Gas
  - Coal Bed Methane
  - Tight Gas

- Adequate Unconventional Gas Resources

- Carbon Sequestration in Coal and Shale Gas

- Opportunities of Enhanced Methane Recovery

- Some Outstanding Technical Questions

- Unconventional Gas Production is Going to Happen
Gas Shale Reservoirs

- Large, unconventional natural gas resource
- Organic-rich, low porosity, very low permeability
- Technology, economics, and trial and error exploration and development have led to success in Barnett
Gas Shale Basins Align with Pipeline Grid

Sources: EIA, US Natural Gas Pipeline Nework
Organic Source Rock
Extremely Low Permeability

Organic Shales - Deep Water - Anaerobic / Clay Matrix
2008

IT'S SHALE MADNESS!!!

March 08

July 08
Gas Shales Are Booming

> $40B invested in past 3-5 years!

2.3 Trillion Cubic Feet Produced Since 2000!

Barnett Production Through 2006
Drilling/Completion Technology Key To Barnett Shale Development

Horizontal Drilling and Multi-Stage **Slick-Water** Hydraulic Fracturing Induces Microearthquakes (M ~ -1 to M~ -3) To Create a Permeable Fracture Network
Many Technological Challenges Remain

1. Identifying frac intervals.

2. Designing frac jobs

3. Interpreting Clouds of Microseismicity

4. Assess Impact on the Field
SPE Shale Gas Production Conference - Survey

- 101 ballots returned of 400 distributed

![Bar Chart](chart.png)

Questions:
1. I am confident that I understand reservoir drainage.
2. I am confident in our estimated ultimate recovery number.
3. I think shale gas is free gas dominated.
4. I think new completion technology is needed.
5. I think new drilling technology is needed.

Options:
- Yes
- No
- Unsure
Geologically, the shales in question are quite Diverse in composition.

The Barnett shale is not really a shale.
Current Drilling and Stimulation Schemes

Multi-lateral completions

Microseisms from various hydro-frac stages

Getting from Here to There
Gas Shales Are Were Booming

> $40B invested in past 3-5 years!

2.3 Trillion Cubic Feet Produced Since 2000!

Barnett Production Through 2006

May 20, 2009
Decline in Gas Prices/Rate of Development – Opportunity!

Rig Counts Standard Report

Copyright oilenergy.com, 2009
Coal Bed Methane Potential
Biogenic Origin of CBM

Photos courtesy Luca Technologies
Desorption of Biogenic Gas and Flow In Coal

- Adsorption on internal coal surfaces
  - Adsorption on internal coal surfaces

- Diffusion through matrix and micropores
  - Diffusion through the matrix and micropores

- Bulk flow in the fracture network
  - Bulk flow in the fracture network

Biogenic Gas

Desorption

Flow
Adsorption Isotherms

Kovscek and Tang, 2004

Desorption By Depressurization

Kovscek and Tang, 2004
Depressurization of coal beds causes desorption of methane.

Pumping continues during the lifetime of the well.

Significant amounts of water and gas are produced.
Currently ~18,000 active CBM wells.

~50,000 more to be drilled in next decade.
• The Potential Gas Committee estimates recoverable CBM resources of 24 Tcf.

• 75% of the growth in CBM production in the US over the next 10 years is expected to occur in the Powder River Basin.
Significant Environmental Impacts of CBM Water Production

- Clabaugh Ranch Wild Horse Creek CBM Discharge Water Flooding – March 2005
- CBM Reservoirs Overflowing and Flooding Wild Horse Creek
- Clabaugh Ranch Salt & Iron Damage to Soil by CBM Waste Water
- Downstream Soil and Vegetation Damage from CBM Discharge in Dead Horse Creek on Barlow Ranch
- CBM Flooding in Spotted Horse Creek and on Meadows on the West Ranch
- West Ranch, Spotted Horse Creek Meadows: Salts Deposited and Leached from Soil Caused by CBM Flooding

Map of Powder River Basin with overlay of Coal Bed Methane development areas and existing CO₂ pipelines.
Consequences of Hydraulic Fracturing CBM Wells

If the hydraulic fracture propagates vertically from the coal seam and through a confining unit, water production may occur from overlaying strata.

Colmenares and Zoback (2007) 2/3 of water comes from problem wells
Tight Gas – Conventional Reservoirs with Extremely Low Permeability

Conventional Gas Sand Permeability Typically
$10^{-12}$ to $10^{-15}$ m$^2$
(1-1000 md)

Tight Gas Sand Permeability Typically
$< 10^{-16}$ m$^2$
$< 0.1$ md

Developed Using Horizontal Drilling and Extensive Hydraulic Fracturing
Sometimes in a Similar Manner as Shale Gas
Getting from Here to There with Unconventional Gas

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- Adequate Unconventional Gas Resources

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- Unconventional Gas Production is Going to Happen
Replacing Coal with Unconventional Gas

- 1 TCF \((10^{12} \text{ ft}^3)\) of \(\text{CH}_4\) \(\approx 10^{15}\) BTU \(\equiv 1\) Quad
- Current Annual Coal Consumption in U.S.  
  - \(\sim 23\) Quads (27 Quads in 2030*)
- Current Annual Gas Production in U.S.  
  - \(\sim 20\) Quads \(\approx 20\) TCF (23.7 TCF in 2030*)  
  - \(\sim 9\) TCF/Year from Unconventional Sources
- To Replace Coal with Natural Gas by 2030 Requires 39 TCF** Annual Gas Production

* EIA (2009) Estimates

** Takes into Account the Improved Efficiency (1.8) of Gas Plants
Total Gas Production Increase to ~39 TCF/y?

- Conventional Current Production ~11 TCF/y
  (Assumed to Remain ~Constant)
- Unconventional Current Production ~ 9 TCF/y
  - Shale Gas ~ 1.5 TCF/y
  - Tight Gas ~ 6 TCF/y
  - CBM ~ 1.5 TCF/y
- Is Increasing Unconventional Production to ~ 28 TCF/y Achievable Over the Next 20-30 Years?
### U.S. Recoverable Shale Gas ~ 650 TCF

<table>
<thead>
<tr>
<th>Shale Formation</th>
<th>Recoverable TCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barnett</td>
<td>44 TCF</td>
</tr>
<tr>
<td>Fayetteville</td>
<td>42 TCF</td>
</tr>
<tr>
<td>Haynesville</td>
<td>251 TCF</td>
</tr>
<tr>
<td>Marcellus</td>
<td>262 TCF</td>
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<td>Woodford</td>
<td>11 TCF</td>
</tr>
<tr>
<td>Antrim</td>
<td>20 TCF</td>
</tr>
<tr>
<td>New Albany</td>
<td>19 TCF</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>649 TCF</strong></td>
</tr>
</tbody>
</table>

Estimates Vary Significantly
- 274 TCF (Navigant Consulting, 2008)
- 842 TCF (maximum reported, 2008)

Most of the Variation in Estimates Comes from the Marcellus and the Haynesville

There is No Question that Shale Gas is an Extremely Large, Relatively Clean and Efficient Domestic Resource

- U.S. Lower 48 Tight Gas – 117 TCF*
- U.S. Lower 48 CBM – 88 TCF*

*Navigant Consulting (2008)
Is 28 TCF/y Achievable in 30 Years?

~1.2 TCF/y is Currently Produced from the Barnett Shale Mostly From Development Over Past ~5 Years

Reaching 28 TCF/y in 30 Years Requires that Shale Basins be Developed at 4-5 Times the Rate of the Barnett

As the Barnett Represents Only a Fraction of all Domestic Recoverable Shale Gas Reserves. Such Growth Should be Possible (Even Ignoring Growth in Production from CBM and Tight Gas Sands)

Barnett Production Through 2006
EIA Sees Little Growth of Unconventional Gas

The percent contribution of natural gas to the U.S. energy supply is expected to remain fairly constant for the next 20 years.

DOE, Modern Shale Gas, April 2009
EIA Has Always Been Wrong

In EIA’s Defense, Estimates of Recoverable Unconventional Gas Have Increased By a Factor of ~10 Between 1998 and 2008
Natural gas is going to be there for awhile. It’s got to be there to get us through this transition, which is going to take 30 or more years ...

Fortunately, we’ve got a lot of natural gas ...

The use of natural gas to produce electricity will continue and continue ...

We may not need any [new nuclear or coal plants] ever.

Jon Wellinghoff
Chairman, FERC
April, 2009
Industry View of Unconventional Gas Potential

Source: Modified from American Clean Skies, Summer 2008
Getting from Here to There with Unconventional Gas

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“Conventional” Carbon Sequestration

Overview of Geological Storage Options

1. Depleted oil and gas reservoirs
2. Use of CO₂ in enhanced oil and gas recovery
3. Deep saline formations — (a) offshore (b) onshore
4. Use of CO₂ in enhanced coal bed methane recovery

IPCC (2005)
CO₂ Sequestration Research Projects

**Powder River Basin**
- CBM Production
- ECBM/Environment/Sequestration
- Collab. with Western Res. Foundation

**Mountaineer, West Virginia**
- Deep aquifer injection
- Point source - Coal Burning power plant
- Collaboration with DOE, NETL, Battelle, AEP, BP, Schlumberger, Ohio Coal Development Office

**Michigan Basin**
- Deep aquifer injection
- Permeability enhancement

**Teapot Dome**
- Depleted Oil and Gas Reservoir
- Sequestration seal capacity
- Collaboration with LLNL, DOE. RMOTSI

Stanford University
Global Climate & Energy Project
Why Not Just Do It!

- 1996 to present
- 1 Mt CO₂ injection/yr
- Seismic monitoring

X 3500!
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Relative Adsorption of CO\textsubscript{2} and CH\textsubscript{4}

Kovscek and Tang, 2004
Enhanced Gas Recovery and CO$_2$ Sequestration

Overview of Geological Storage Options
1. Depleted oil and gas reservoirs
2. Use of CO$_2$ in enhanced oil and gas recovery
3. Deep saline formations — (a) offshore (b) onshore
4. Use of CO$_2$ in enhanced coal bed methane recovery

Enhanced Gas Shale Recovery and CCS
Enhanced Coalbed Methane and CCS

IPCC (2005)
Utilization of CO$_2$ for Enhanced CBM Production

![Graph showing sorption of different gases (CO$_2$, CH$_4$/CO$_2$, CH$_4$/CO$_2$, and N$_2$) as a function of pressure (psi)].

- **Butt cleat**
- **Face cleat**
- **Coal matrix**
- **Darcy flow**
- **Desorption/adsorption and diffusion**

*Getting from Here to There*
Fluid Flow Simulation
CO$_2$ Sequestration and ECBM

5-spot, 80-acre well spacing using the simulator GEM.

1. **Primary production 5 years:**
   - 4 production wells

2. **Followed by Enhanced Recovery with CO$_2$:**
   - One injector and 4 producers
   - Injector BHP constraint of 4 MPa (~600 psi).

3. **Hydraulic fracture case:**
   - Hydraulic fracture placed at base of injection well

Ross, Hagin and Zoback (2009)
## History-Matching to Constrain Model Parameters

### Geostatistics

<table>
<thead>
<tr>
<th>Property</th>
<th>Minimum and Maximum Value</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal face cleat permeability</td>
<td>100-500 mD</td>
<td>300 mD</td>
</tr>
<tr>
<td>Horizontal butt cleat permeability</td>
<td>10-160 mD</td>
<td>100 mD</td>
</tr>
<tr>
<td>Vertical face cleat permeability</td>
<td>10-160 mD</td>
<td>100 mD</td>
</tr>
<tr>
<td>Matrix permeability</td>
<td>0.04-0.7 mD</td>
<td>0.5 mD</td>
</tr>
<tr>
<td>Matrix porosity</td>
<td>0.011-0.1</td>
<td>0.05</td>
</tr>
</tbody>
</table>

### History-matching water production

<table>
<thead>
<tr>
<th>Production Wells</th>
<th>Average Water Production per Month (bbl/month) (WOGCC, 2006)</th>
<th>History-matched Average Water Production per Month (bbl/month)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well 1</td>
<td>1768</td>
<td>1762</td>
</tr>
<tr>
<td>Well 2</td>
<td>2844</td>
<td>2854</td>
</tr>
<tr>
<td>Well 3</td>
<td>1696</td>
<td>1695</td>
</tr>
<tr>
<td>Well 4</td>
<td>3153</td>
<td>3151</td>
</tr>
<tr>
<td>Well 5</td>
<td>937</td>
<td>930</td>
</tr>
</tbody>
</table>
Gas Migration in the Cleats
After 13 Years of Injection

Are Shrinkage and Swelling Being Modeled Correctly?
Total Volumes of CO$_2$ Injected and CH$_4$ Produced after 13 Years of Injection

- Sequester ~99% of total CO$_2$ injected.

- With ECBM, CH$_4$ production increased by ~5-8 fold.

- Roughly, at 9 kt/y of CO$_2$/well, 7000 injection wells will be needed for all CO$_2$ emissions in Wyoming (63 million tons/y)

Ross, Hagin and Zoback (2009)
CO$_2$/CH$_4$ Adsorption in Appalachian Devonian Shales

- Only one study on shale adsorption for both CO$_2$ and CH$_4$
- ~5x greater adsorption of CO$_2$
- Linear relation between TOC and adsorption capacity
Sequestration and Enhanced Recovery in Gas Shales?

CCS is Attractive and Timely Because
• Increase in Production Has Not Yet Occurred
• Operational Procedures are Geometrically Ideal
Current Drilling and Stimulation Schemes

Multi-lateral completions

Microseisms from various hydro-frac stages
Opportunity to Develop Shale Gas with CCS for Enhanced Production and Carbon Sequestration

Getting from Here to There

CH₄ Production

CO₂ Injection

Multi-lateral completions

Microseisms from various hydro-frac stages
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Many Fundamental Questions About Gas Shale Reservoirs

Optimization of Unconventional Gas Resources

- How do these rocks respond mechanically during slick-water fracturing?
- How do the mechanical properties evolve during production and gas adsorption/desorption?
- What are the controls on permeability and surface area development during fracturing?
Many Fundamental Questions About Gas Shale Reservoirs

- How do these rocks respond mechanically during slick-water fracturing?
- How do the mechanical properties evolve during production and gas adsorption/desorption?
- What are the controls on permeability and surface area development during fracturing?

Enhanced Recovery and Carbon Sequestration

- Is there the potential for significant adsorption of CO$_2$ and desorption of CH$_4$ at the pore scale?
Complications…

- Clay content and type
- Kerogen maturity and type
- Shale fabric and microstructure
- Adsorbed and free gas content
- Water saturation
- Depth and temperature effects
- CO₂ phase
- Geochemistry
- Permeability and diffusion times
- Stress- and adsorption-dependent permeability
- Natural and enhanced fracture networks
- Stress state
- Constitutive models
- Injection rate
- Production design
An Unconventional Gas Primer
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- Tight Gas

Adequate Unconventional Gas Resources

Carbon Sequestration in Coal and Shale Gas

Opportunities of Enhanced Methane Recovery

Some Outstanding Technical Questions

Unconventional Gas Production is Going to Happen
Unconventional Gas Development Will Increase as Demand/Price Rise

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<th>Volume TCF</th>
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<td><strong>649 TCF</strong></td>
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DOE (2009)
So if It’s Going to Happen, Let’s Do It Right

CO₂ Injection

Multi-lateral completions

Microseisms from various hydro-fracture stages

CH₄ Production

Getting from Here to There
Acknowledgements

- John Vermylen
- Paul Hagin
- Rob Heller
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- Owen Hurd
- Yi Yang
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- Indrajit Das
- Tony Kovscek, ERE
- Wenjuan Lin, ERE
- Brad Copithorne
- Financial Support from GCEP, SRB Consortium, ConocoPhillips, Chevron, BP
Can This be Applied Globally?

ExxonMobil (2009)
## Global CBM Resource Base (Top 8)  
(various sources)

<table>
<thead>
<tr>
<th>Country</th>
<th>Estimated CBM Resource Base (Trillion Cubic Feet/ TCF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canada</td>
<td>600-3250</td>
</tr>
<tr>
<td>Russia</td>
<td>600-2800</td>
</tr>
<tr>
<td>China</td>
<td>1060-1235</td>
</tr>
<tr>
<td>Australia</td>
<td>282-494</td>
</tr>
<tr>
<td>US</td>
<td>141-388</td>
</tr>
<tr>
<td>Ukraine</td>
<td>71-424</td>
</tr>
<tr>
<td>India</td>
<td>30-140</td>
</tr>
<tr>
<td>Germany</td>
<td>106</td>
</tr>
</tbody>
</table>
Nuclear Power Scenario (EPRI)

*Achieving all targets is very aggressive, but potentially feasible.*

EIA Base Case 2007

<table>
<thead>
<tr>
<th>Technology</th>
<th>EIA 2007 Reference</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>Load Growth ~ +1.5%/yr</td>
<td>Load Growth ~ +1.1%/yr</td>
</tr>
<tr>
<td>Renewables</td>
<td>30 GWe by 2030</td>
<td>70 GWe by 2030</td>
</tr>
<tr>
<td>Nuclear Generation</td>
<td>12.5 GWe by 2030</td>
<td>64 GWe by 2030</td>
</tr>
<tr>
<td>Advanced Coal Generation</td>
<td>No Existing Plant Upgrades</td>
<td>150 GWe Plant Upgrades</td>
</tr>
<tr>
<td></td>
<td>40% New Plant Efficiency by 2020–2030</td>
<td>46% New Plant Efficiency by 2020; 49% in 2030</td>
</tr>
<tr>
<td>CCS</td>
<td>None</td>
<td>Widely Deployed After 2020</td>
</tr>
<tr>
<td>PHEV</td>
<td>None</td>
<td>10% of New Vehicle Sales by 2017; +2%/yr Thereafter</td>
</tr>
<tr>
<td>DER</td>
<td>&lt; 0.1% of Base Load in 2030</td>
<td>5% of Base Load in 2030</td>
</tr>
</tbody>
</table>