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The Future of Natural Gas

An Interdisciplinary MIT Study

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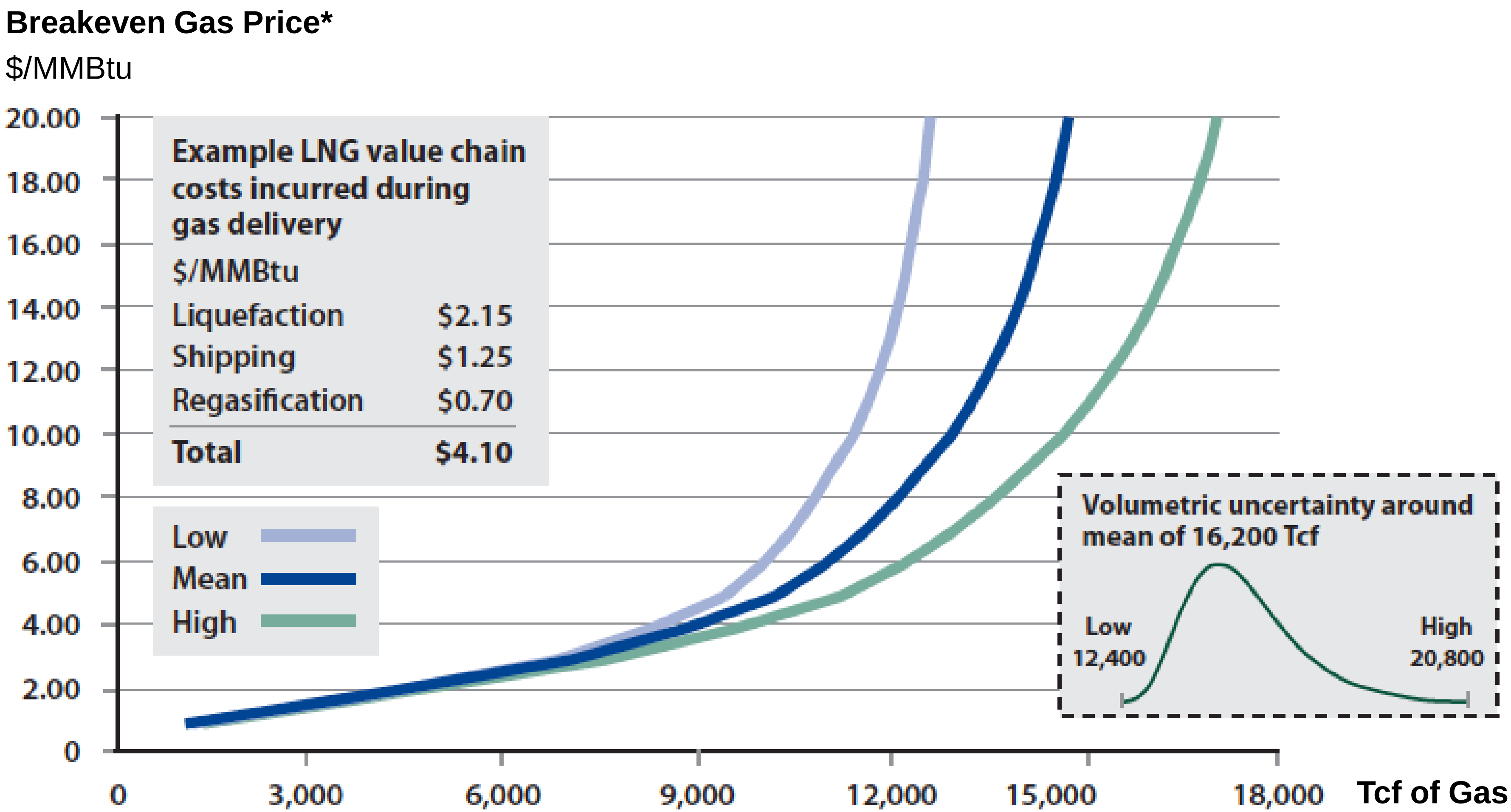
Global Gas Supply Cost Curve
(Excludes unconventional gas outside North America)



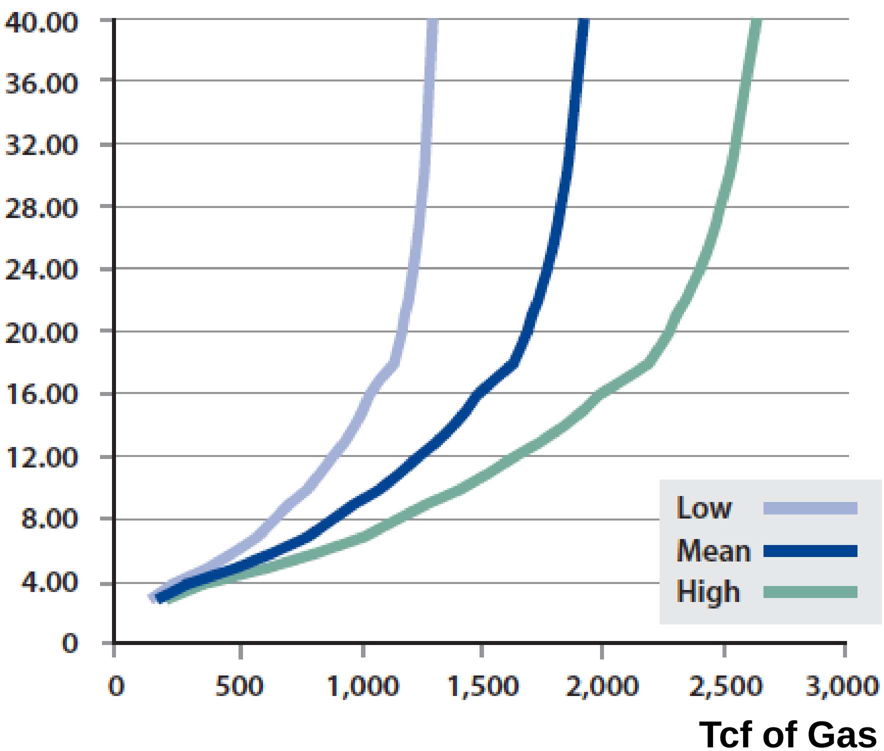
* Cost curves based on 2007 cost bases. North America cost represent wellhead breakeven costs. All curves for regions outside North America represent breakeven costs at export point. Cost curves calculated using 10% real discount rate and ICF Supply Models

** Assumes two 4MMT LNG trains with ~6,000 mile one-way delivery run, Jensen and Associates

U.S. Gas Supply Cost Curve

Breakeven Gas Price*

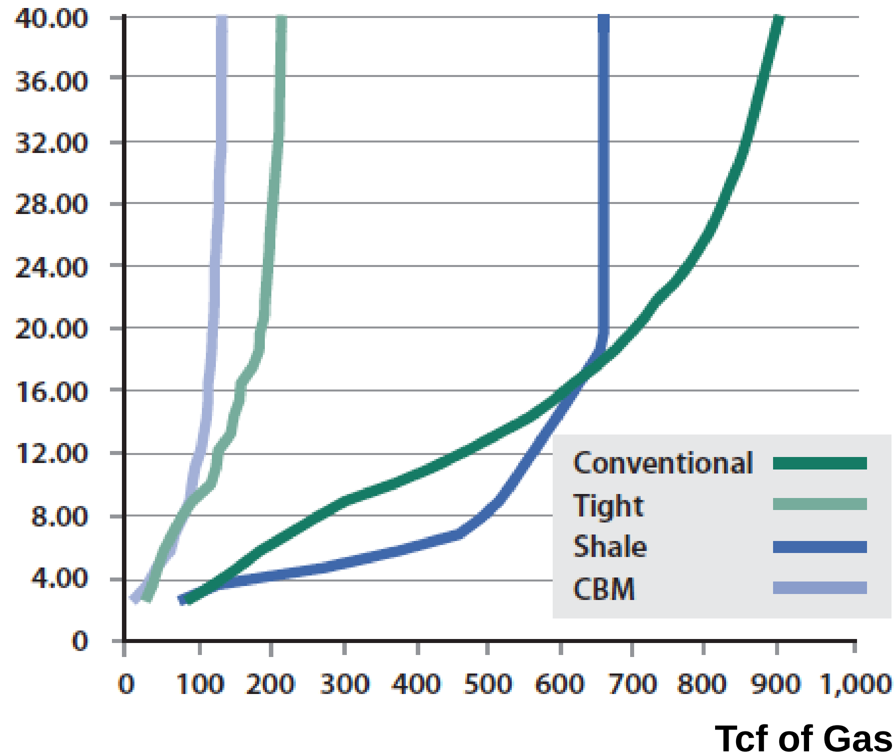
$/MMBtu



Breakdown of Mean U.S. Supply Curve by Gas Type

Breakeven Gas Price*

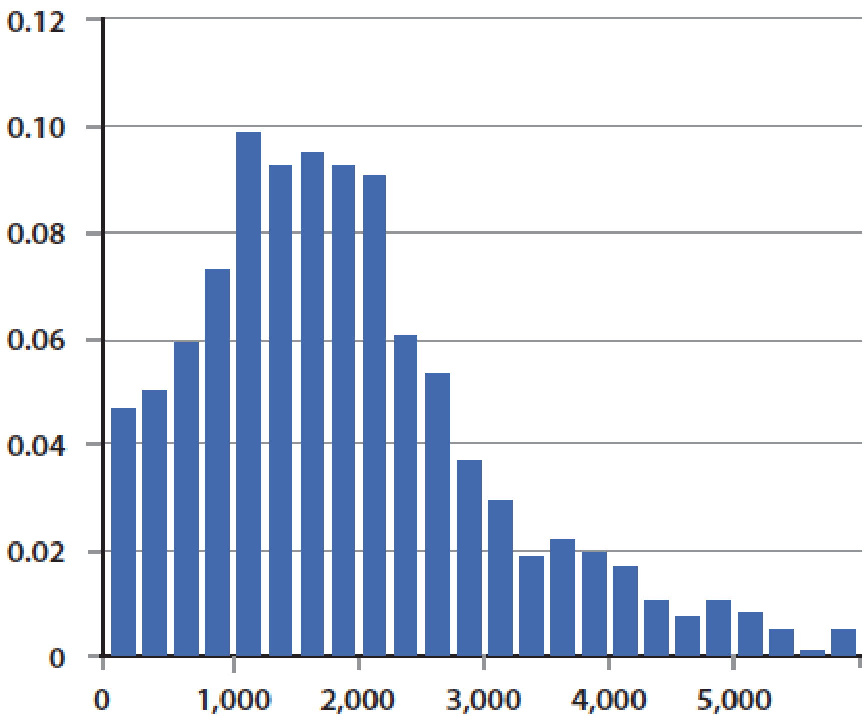
$/MMBtu



* Cost curves calculated using 2007 cost bases. U.S. costs represent wellhead breakeven costs. Cost curves calculated assuming 10% real discount rate and ICF Supply Models

Variation in Shale Well Performance and Per-Well Economics

IP Rate Probability
(Barnett 2009 Well Vintage)



IP Rate: Mcf/day
(30-day avg.)

Impact of IP Rate Variability on Breakeven Price (BEP)*
(2009 Well Vintages)

		P20	P50	P80
Barnett	**IP** Mcf/d	2,700	1,610	860
	BEP $/Mcf	$4.27	$6.53	$11.46
Fayetteville	**IP** Mcf/d	3,090	1,960	1,140
	BEP $/Mcf	$3.85	$5.53	$8.87
Haynesville	**IP** Mcf/d	12,630	7,730	2,600
	BEP $/Mcf	$3.49	$5.12	$13.42
Marcellus**	**IP** Mcf/d	5,500	3,500	2,000
	BEP $/Mcf	$2.88	$4.02	$6.31
Woodford	**IP** Mcf/d	3,920	2,340	790
	BEP $/Mcf	$4.12	$6.34	$17.04

* Breakeven price calculations carried out using 10% real discount rate
** Marcellus IP rates estimated based on industry announcements and available regulatory data

Source: MIT, HPDI production database and various industry sources

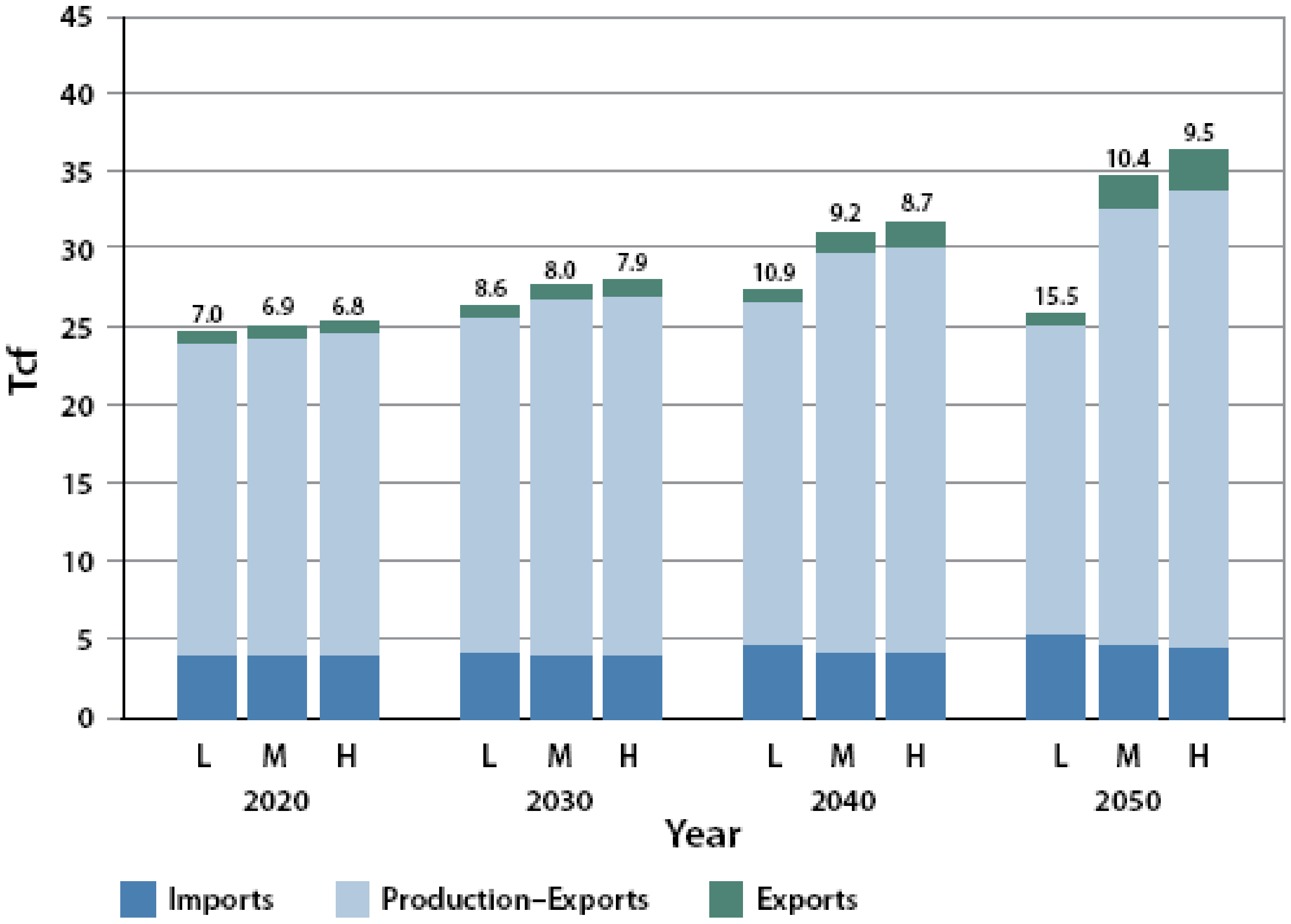
System Studies of Gas Futures

- Emissions Prediction and Policy Analysis Model
  - Strength: explore market interactions
  - Limitation: some industry details beneath the level of market aggregation

- Influences on U.S. Gas Futures
  - Size of resource base, and cost
  - Evolution of international gas markets
  - Development of technology over time
  - Greenhouse gas mitigation policy (?)

U.S. Gas Use, Production, Imports and Exports

No New Climate Policy



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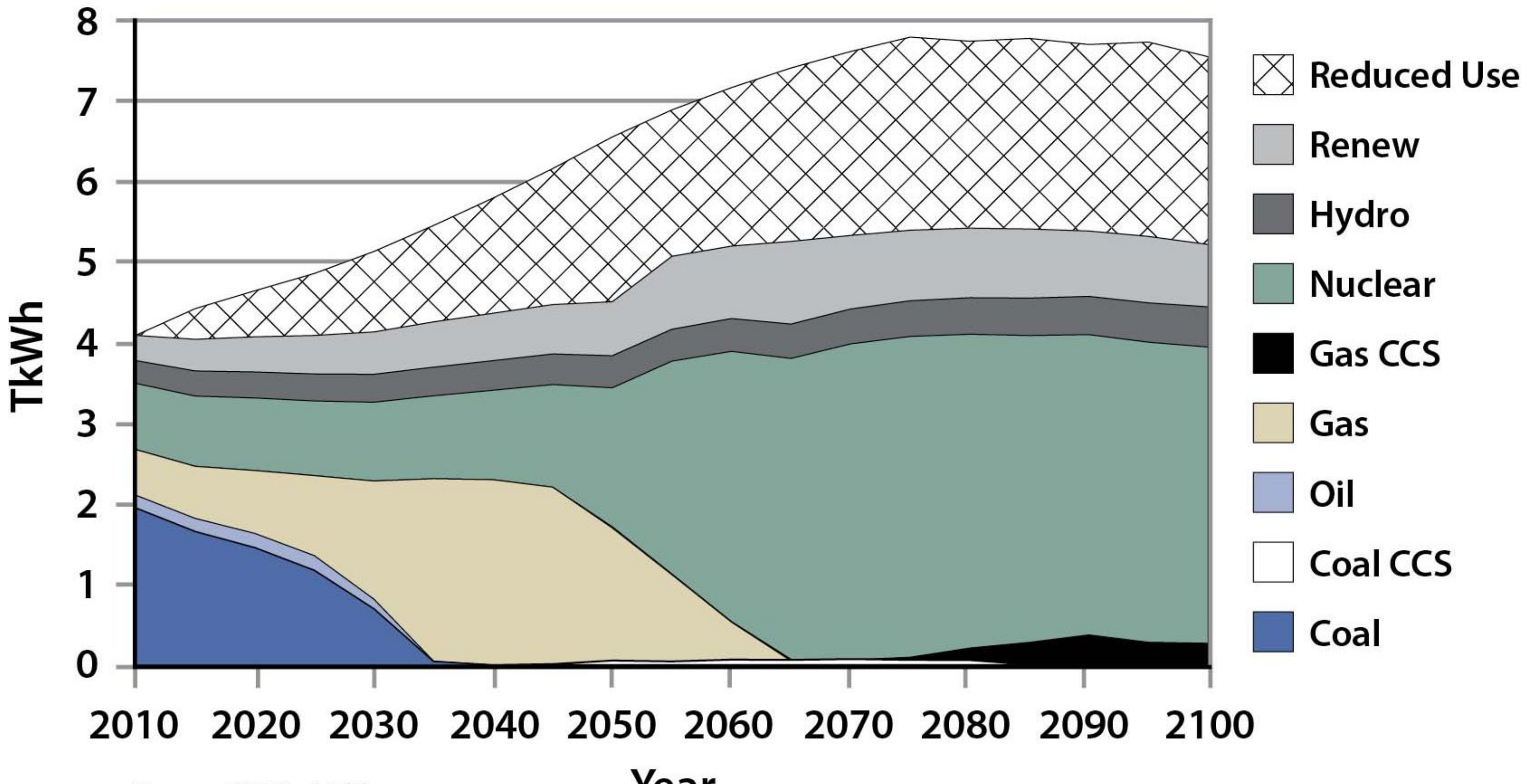
Energy Mix in Electric Generation Under a Price-Based Climate Policy

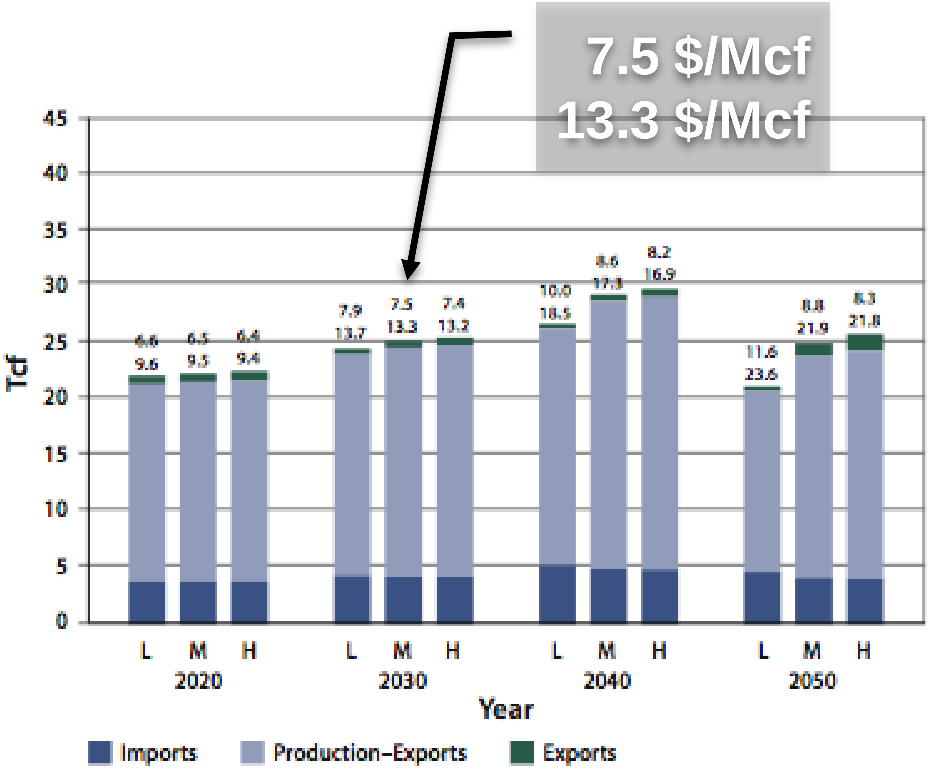
Mean Natural Gas Resources and Regional Natural Gas Markets (TkWh)

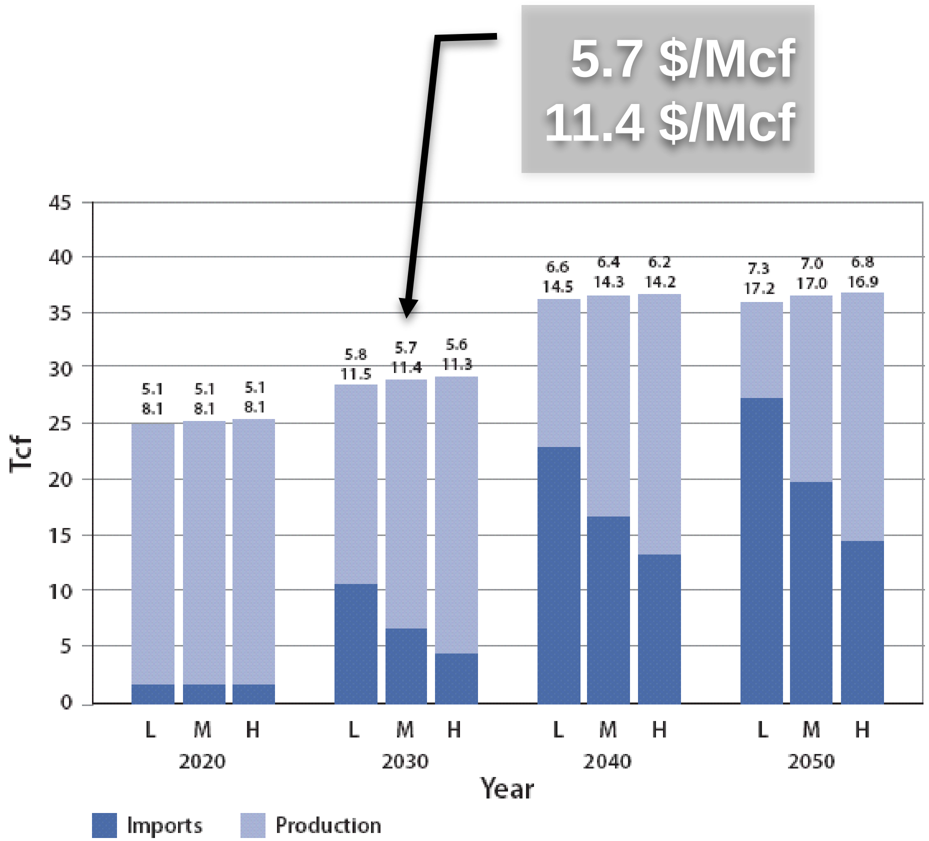


Source: EPPA, MIT

International Market Evolution

With C-constraints





Regional Markets

Global Market

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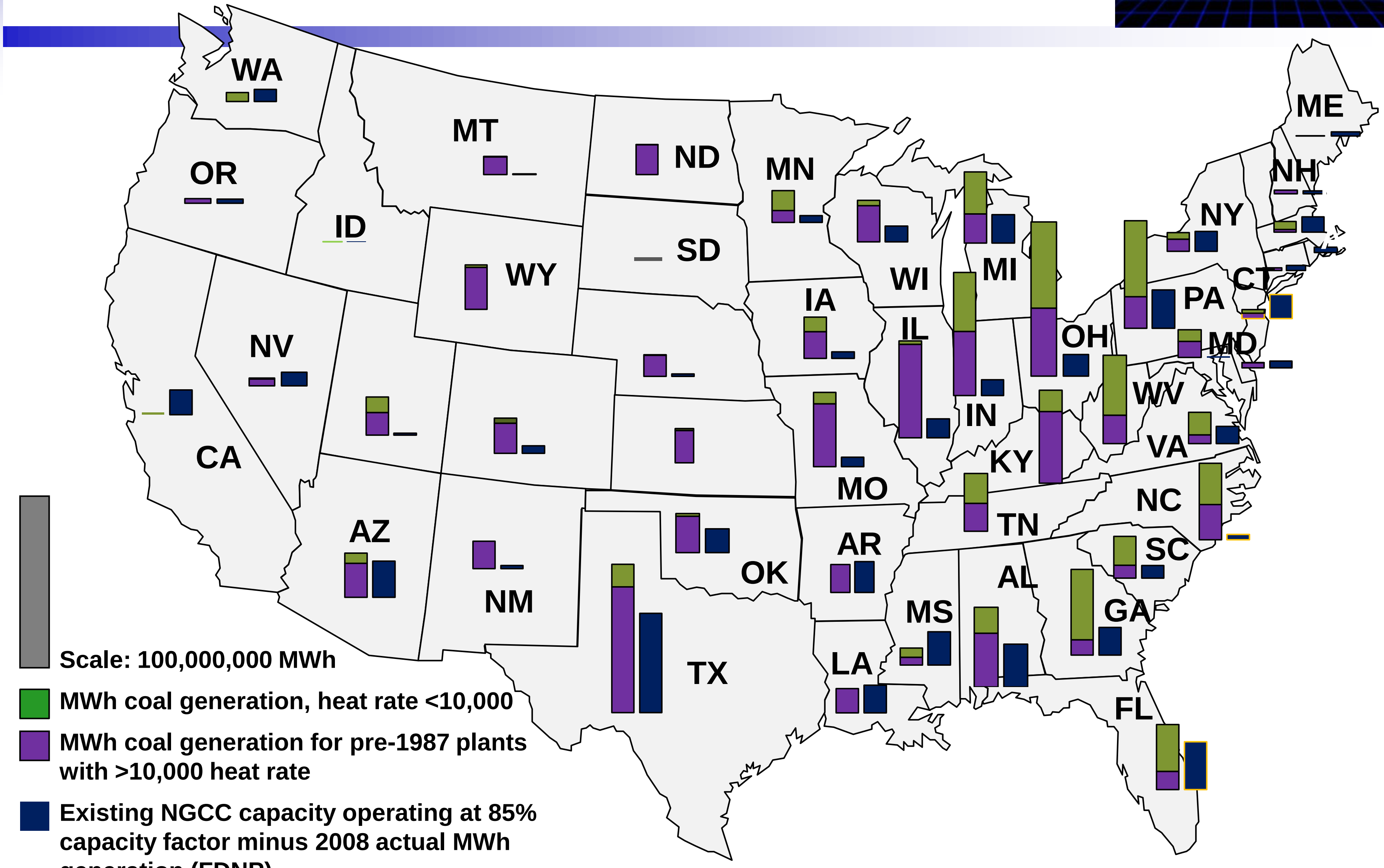
“The U.S. natural gas supply situation has enhanced the substitution possibilities for natural gas in the electricity, industry, buildings, and transportation sectors.”

Scale and Location of Fully-Dispatched NGCC Potential and Coal Generation (MWh, 2008)



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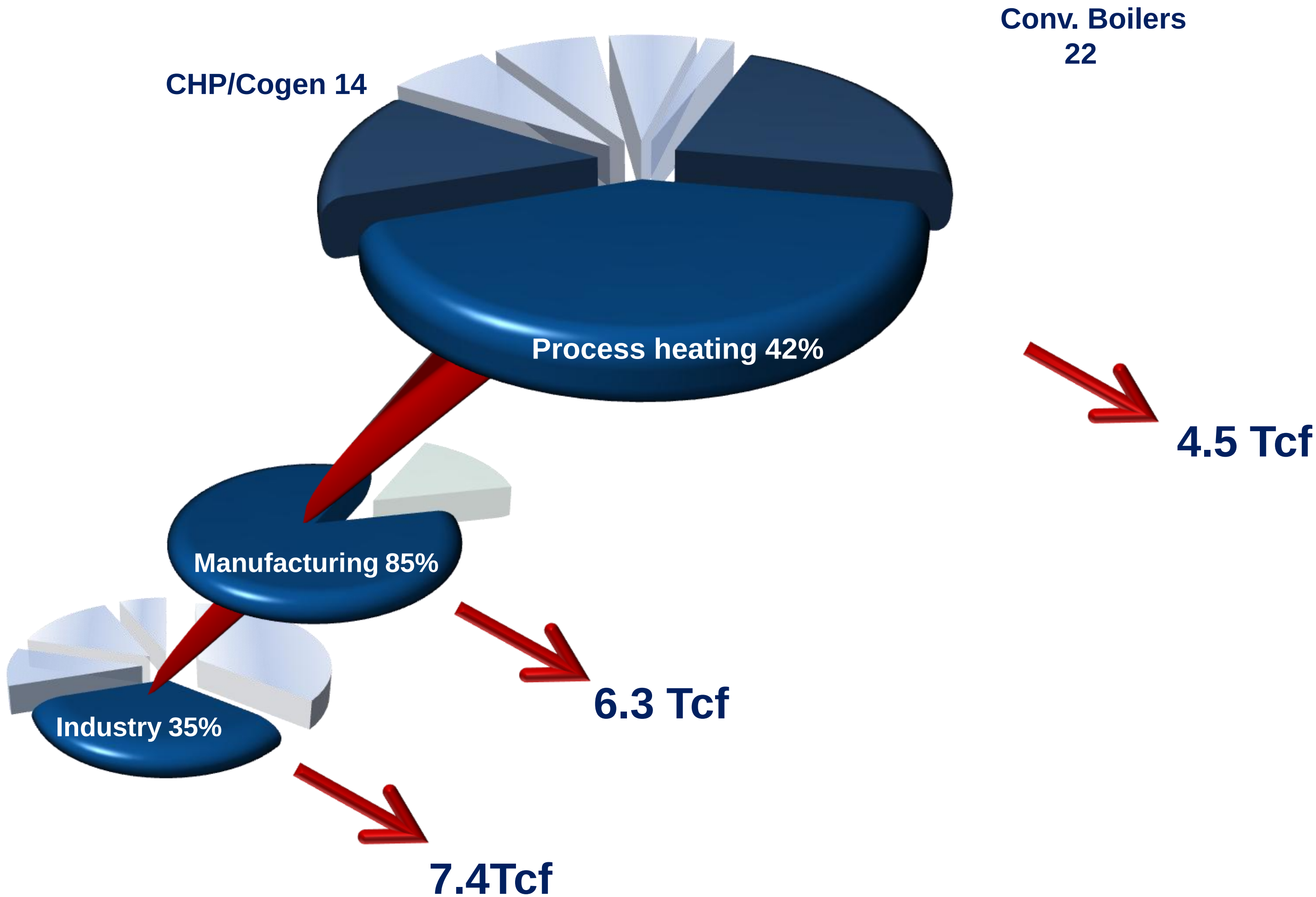
Nationwide, Coal Generation Displacement With Surplus NGCC Would:

- Reduce CO_2 emissions from power generation by 20%
- Reduce CO_2 emissions nationwide by 8%
- Reduce mercury emissions by 33%
- Reduce NO_X emissions by 32%
- Cost roughly $16 per ton/$CO_2$

The displacement of coal generation with NGCC generation should be pursued as the only practical option for near term, large scale CO_2 emissions reductions

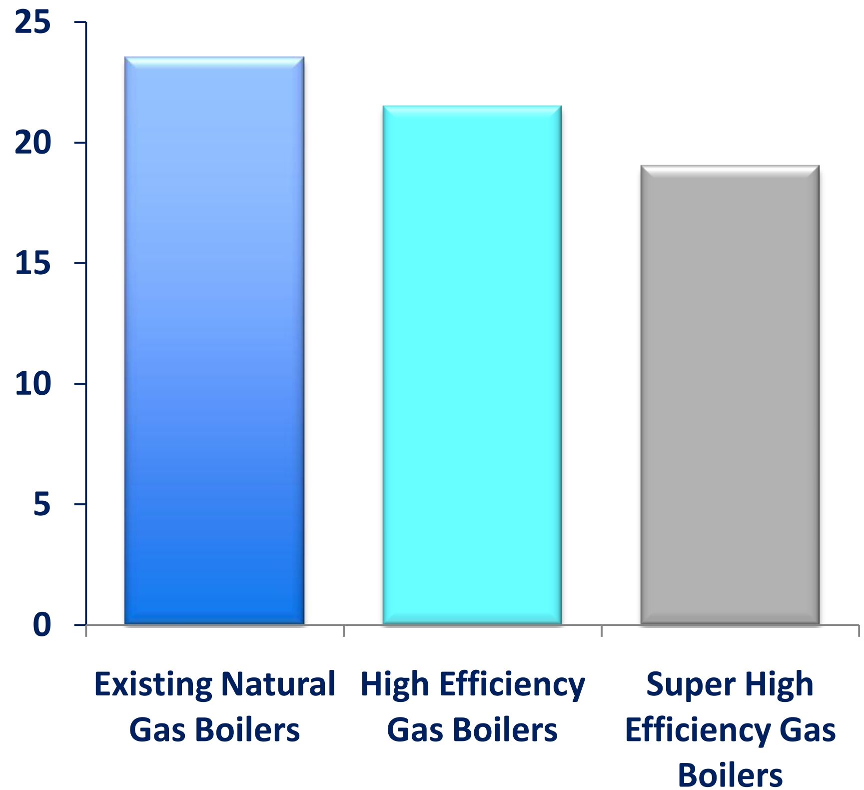
Industrial Gas Demand

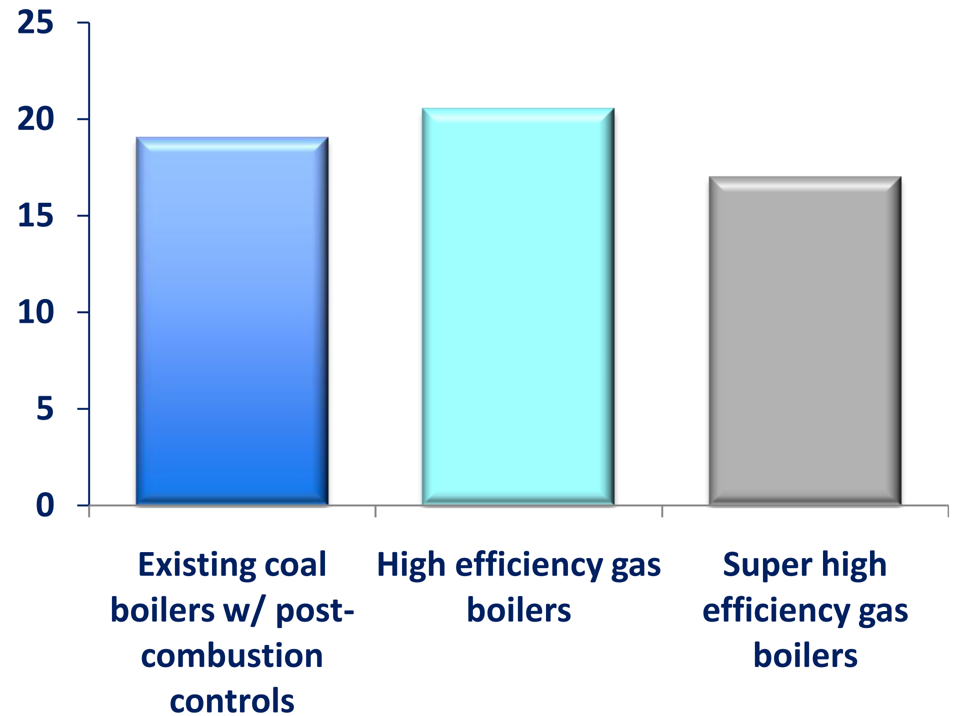


Industrial Boiler Replacement Costs

Net Present Value Costs (millions $)

Replacement of existing NG boilers





NG vs. coal boilers with MACT standards

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For buildings, a move to full fuel cycle efficiency (site vs. source) metrics will improve how consumers, builders, policy makers choose among energy options (especially natural gas and electricity).

Efficiency metrics need to be tailored to regional variations in climate and the electricity supply mix.

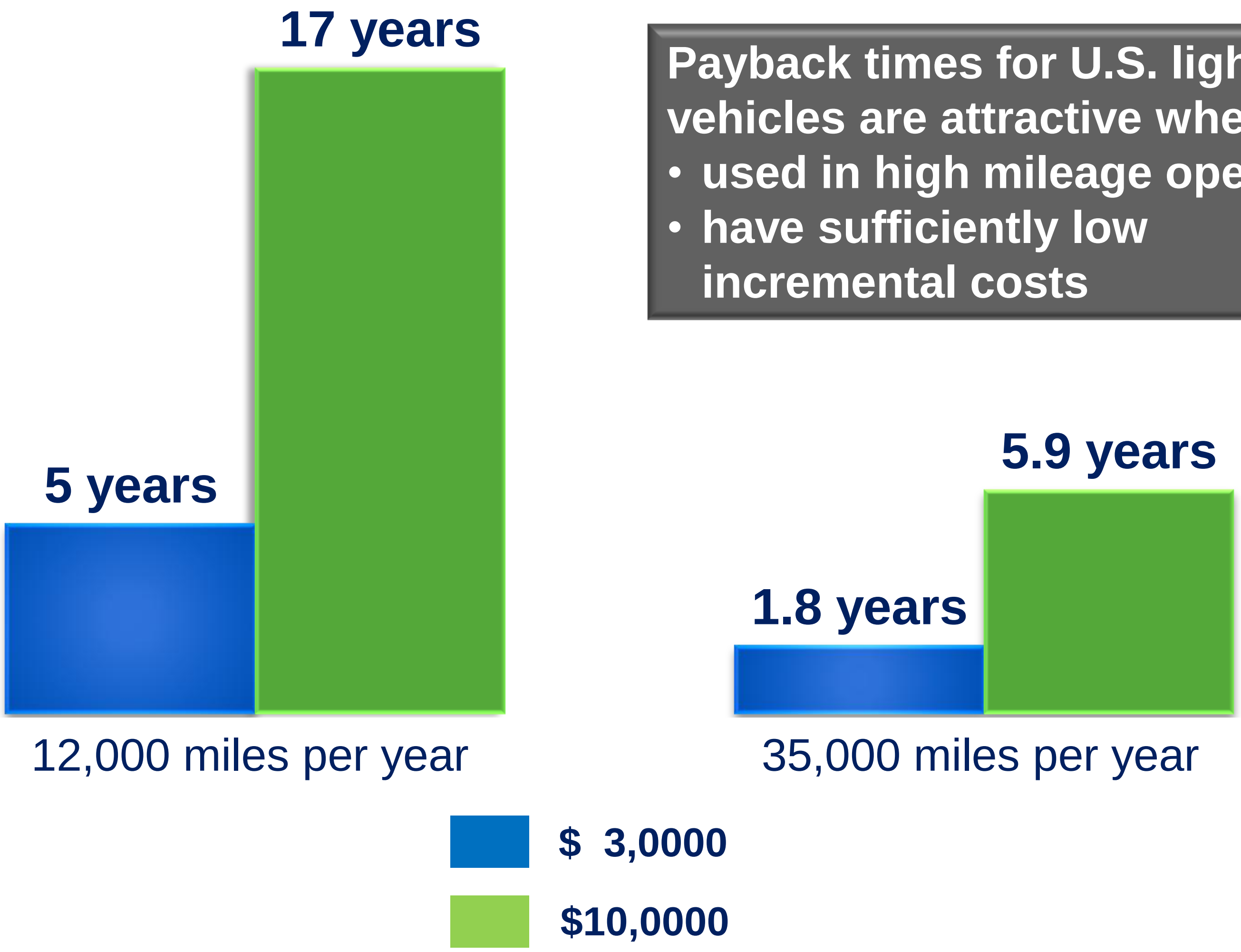
Gas-Oil Price Differential

If the current trend of large oil-gas price ratios continues, it could have significant implications for the use of natural gas in transportation.

Tradeoffs between fuel cost, vehicle cost, fuel infrastructure needs, operational implications?

Years Payback for CNG Light Duty Vehicles

($1.50 gallon of gasoline equivalent spread)

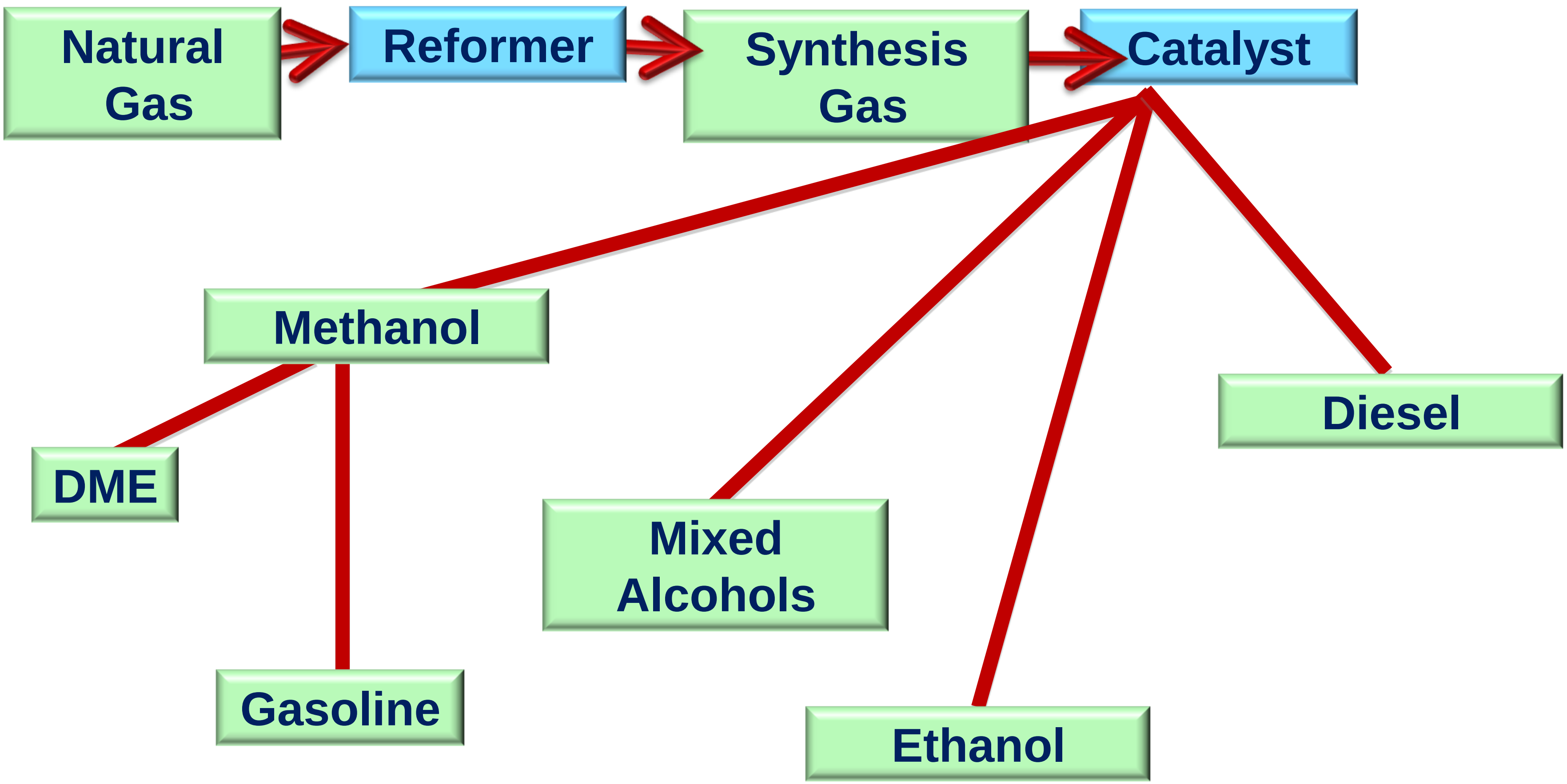


Payback times for U.S. light duty vehicles are attractive when—
- **used in high mileage operations**
- **have sufficiently low incremental costs**

LNG Long Haul Truck Limitations

- Low temp onboard fuel storage
- Fueling infrastructure with competitive pricing
- High incremental cost and lower resale value
- Mitigation in hub-to-hub

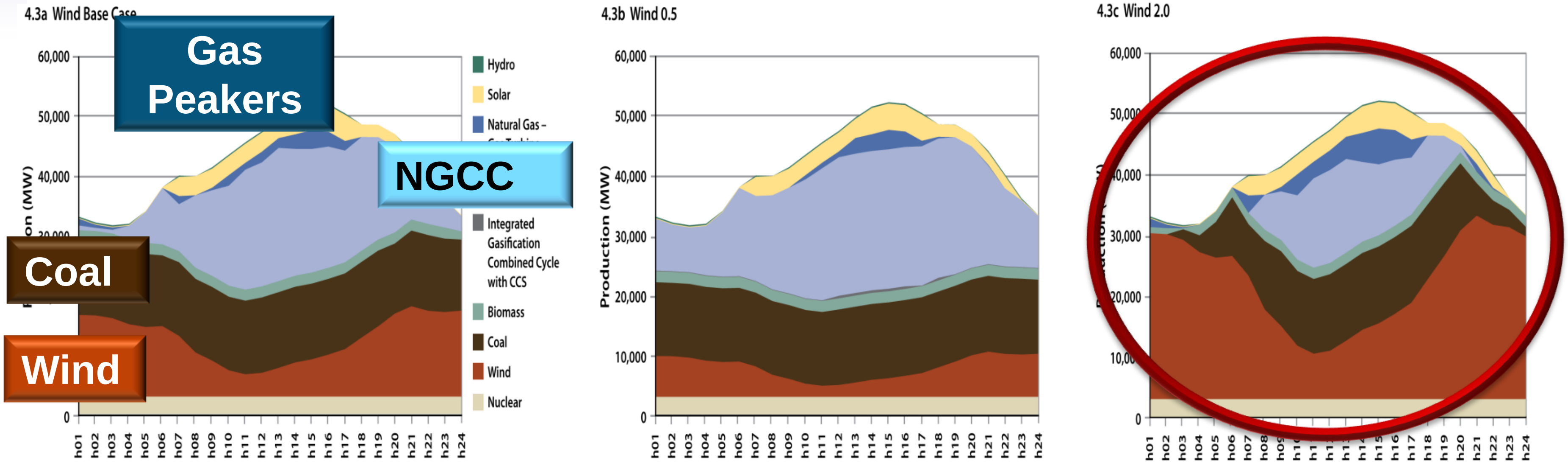
Conversion of Natural Gas to Liquid Fuels



The potential for gas to reduce oil dependence could be increased by its conversion…into liquid fuels…methanol is the only one that has been produced from natural gas for a long period at large industrial scale.

The U.S. government should implement an open fuel standard, requiring tri-flex-fuel capability for light-duty vehicles.

Large Scale Penetration of Intermittent Wind in Short Term for ERCOT



The principal impacts of increased deployment of intermittent renewable energy sources in the short term are –

- **the displacement of NGCC generation**
- **increased utilization of operating reserves**
- **more frequent cycling of mid-range or even base load plants.**

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To view a full copy of this report, please visit

www.web.mit.edu/mitei/research/studies/natural-gas-2011.shtml

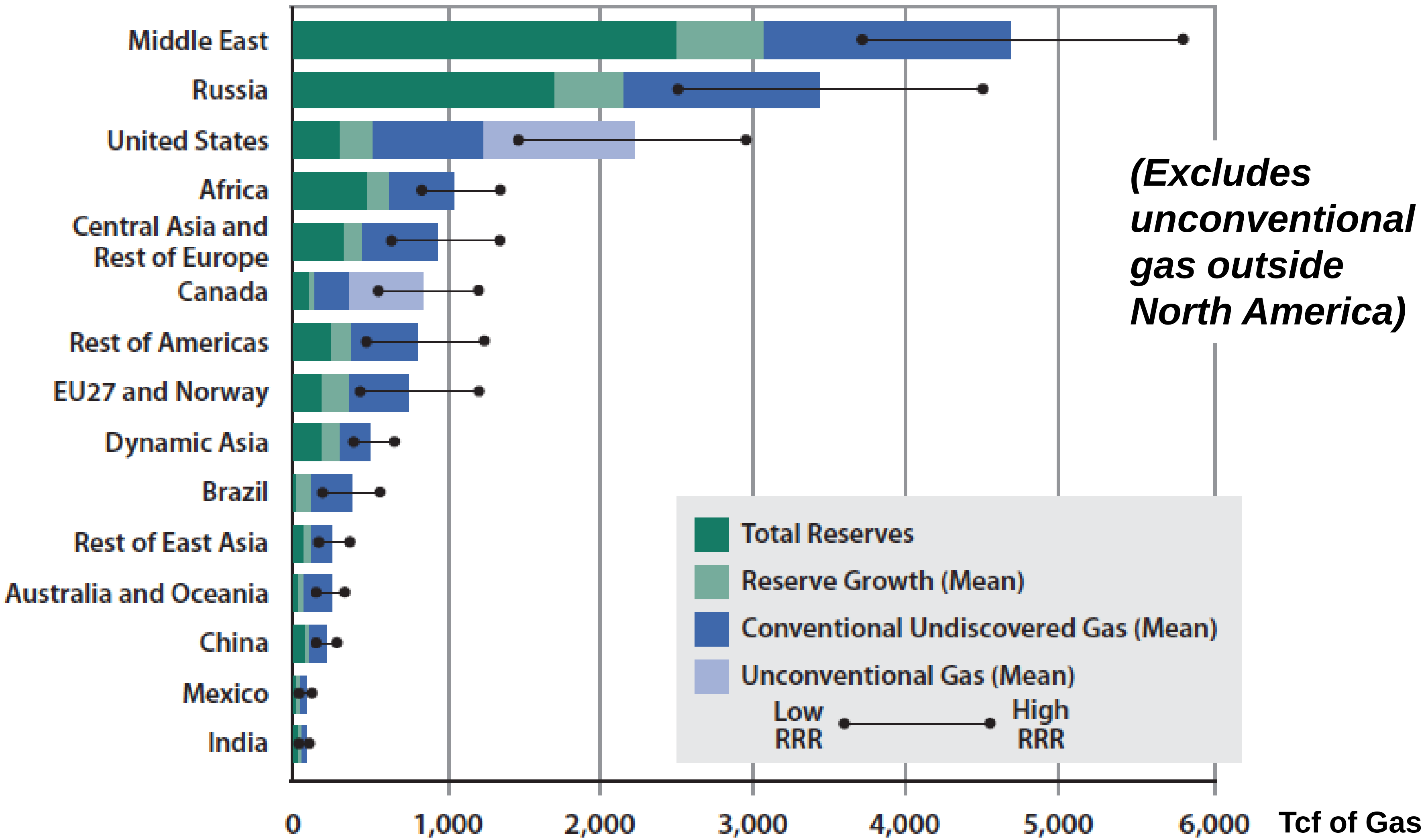
For hard copy, email or business card

Supplementary papers only on website

(Future of Fuel Cycle study also)

Backup

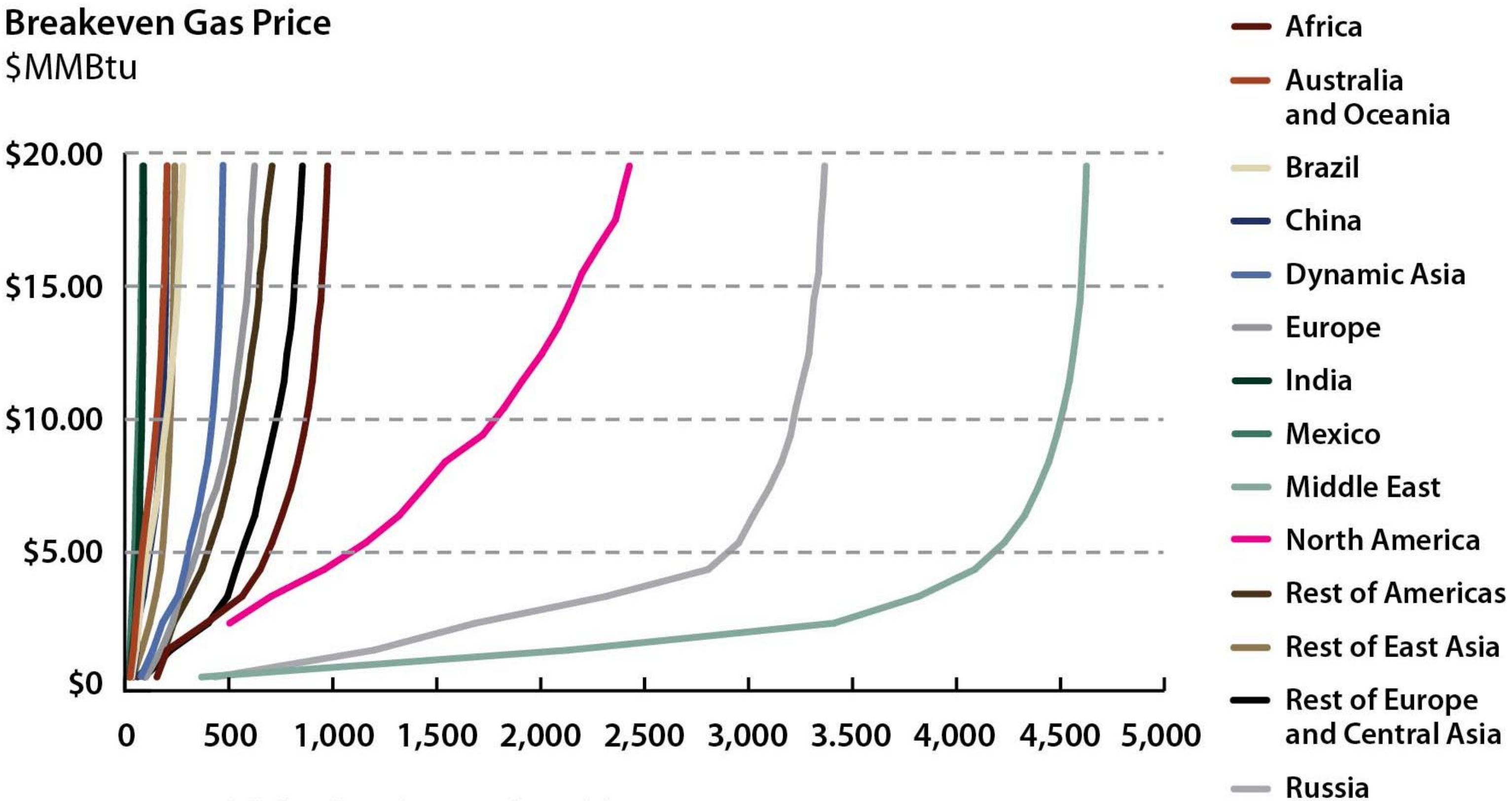
Remaining Recoverable Natural Gas Resources



(Excludes unconventional gas outside North America)

Global Gas Supply Cost Curve by EPPA Region

2007 Cost Base



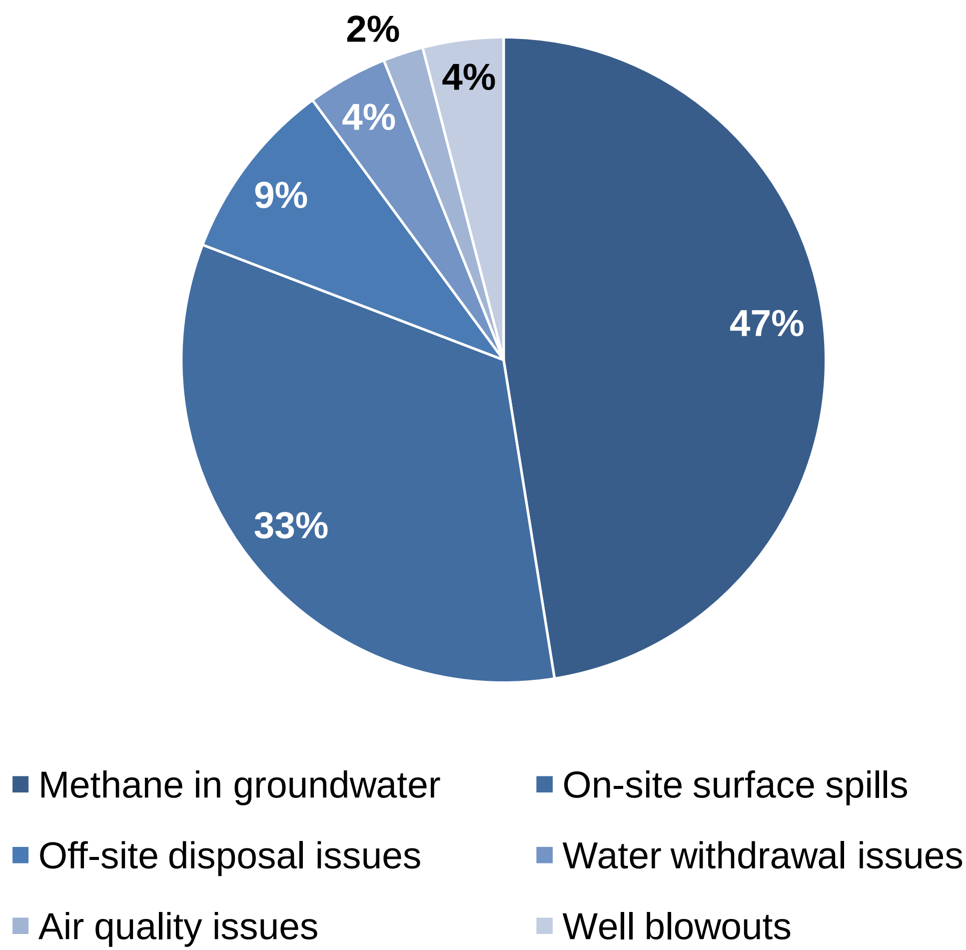
Source: MIT; ICF Global Hydrocarbon Supply Model

Key Environmental Issues Associated with Shale Gas Development

Primary environmental risks associated with shale gas development

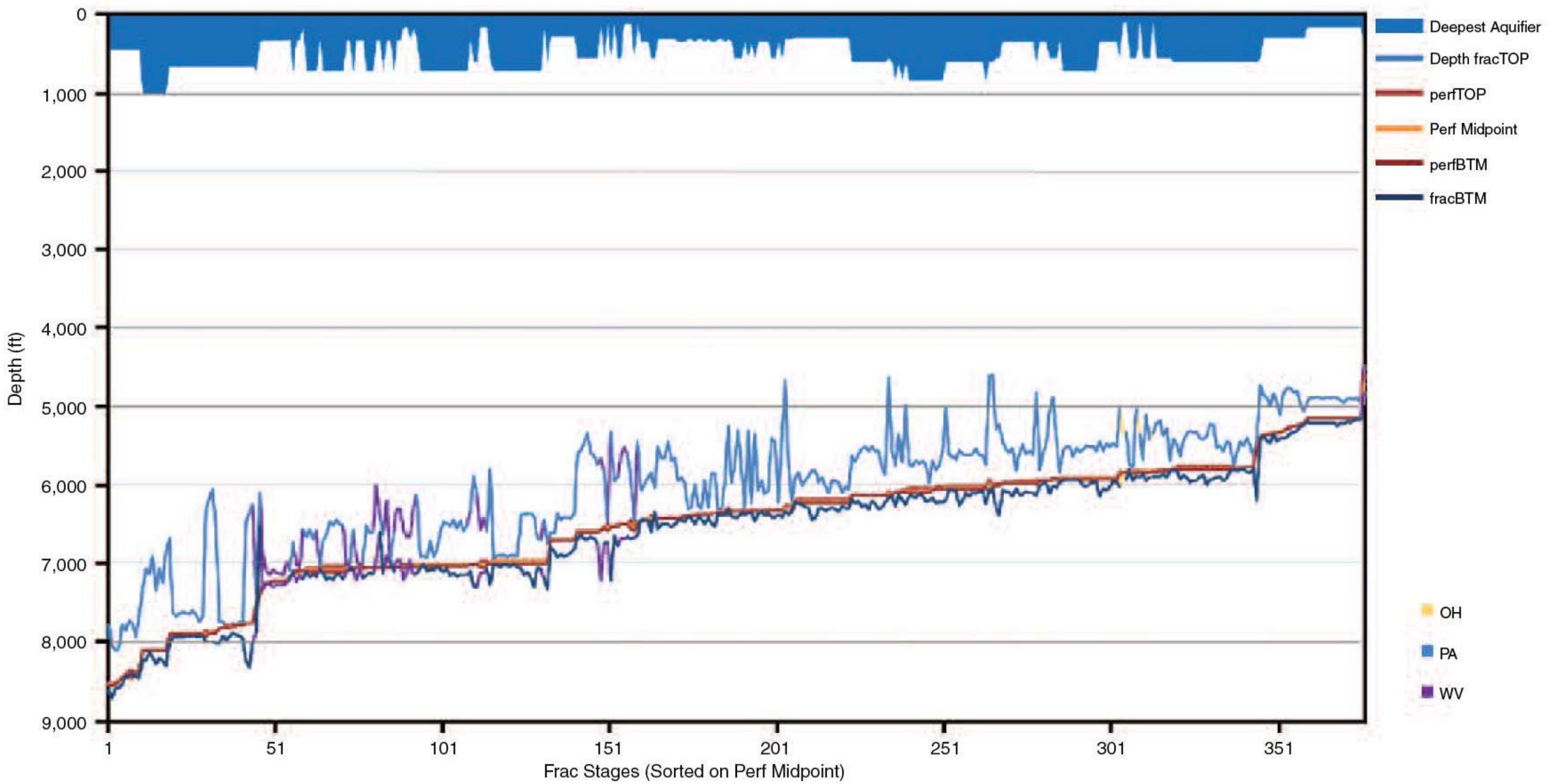
1. Contamination of groundwater aquifers with drilling fluids or natural gas
2. On-site surface spills of drilling fluids, fracture fluids and wastewater
3. Contamination as the result of inappropriate off-site wastewater disposal
4. Excessive water withdrawals for use in high-volume fracturing operations
5. Excessive road traffic and degraded air quality

Breakdown of Widely-Reported Environmental Incidents Involving Gas Drilling; 2005-2009



Fracture Growth in the Marcellus

Marcellus Shale Mapped Fracture Treatments (TVD)



Source: Pinnacle Halliburton Service, Kevin Fisher, Data Confirm Safety of Well Fracturing from July 2010

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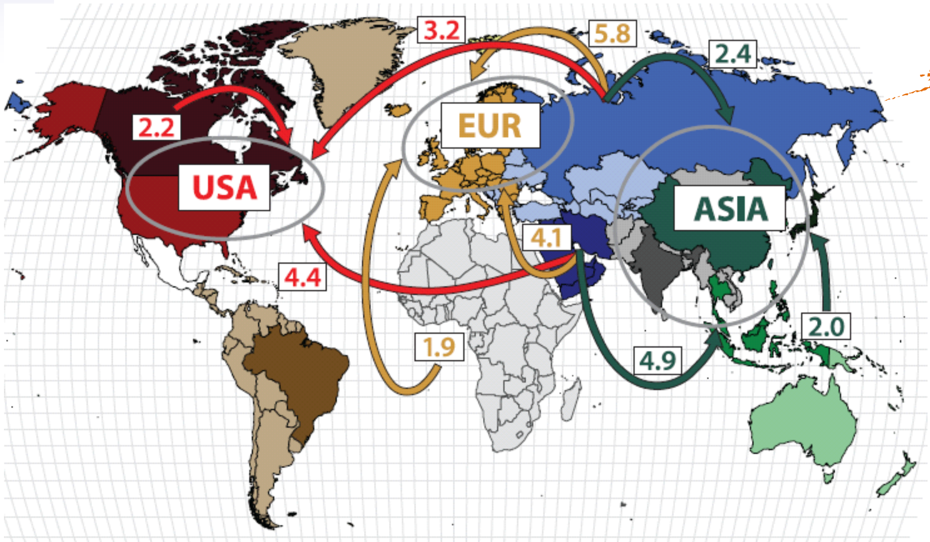
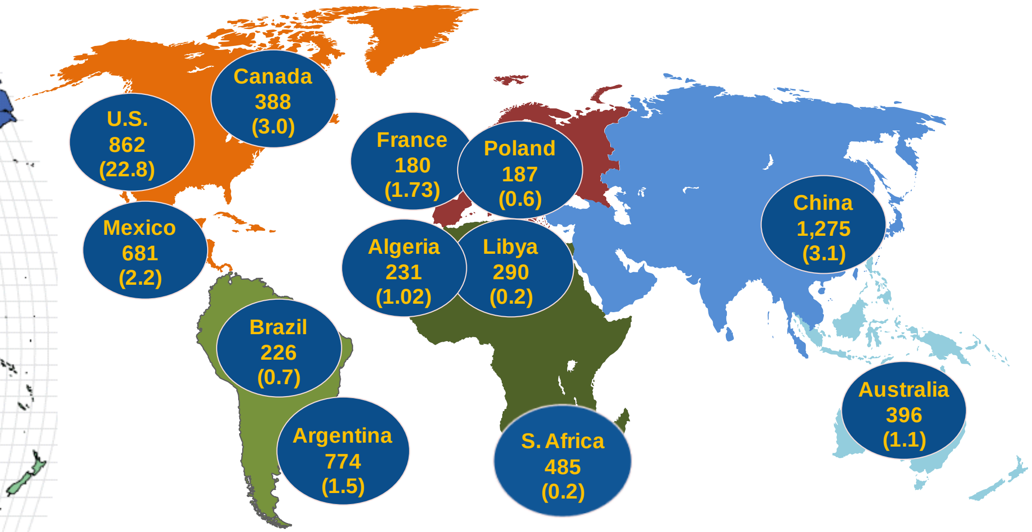
Recommendations

- **For optimum long-term development, need to improve understanding of shale gas science and technology**
  - Government-funded fundamental research
  - Industry/gov't. collaboration on applied research
  - Should also cover environmental research
- **Determine and mandate best practice for gas well design and construction**
- **Create transparency around gas development**
  - Mandatory disclosure of frac fluid components
  - Integrated water usage and disposal plans

Global Gas Market and Geopolitics

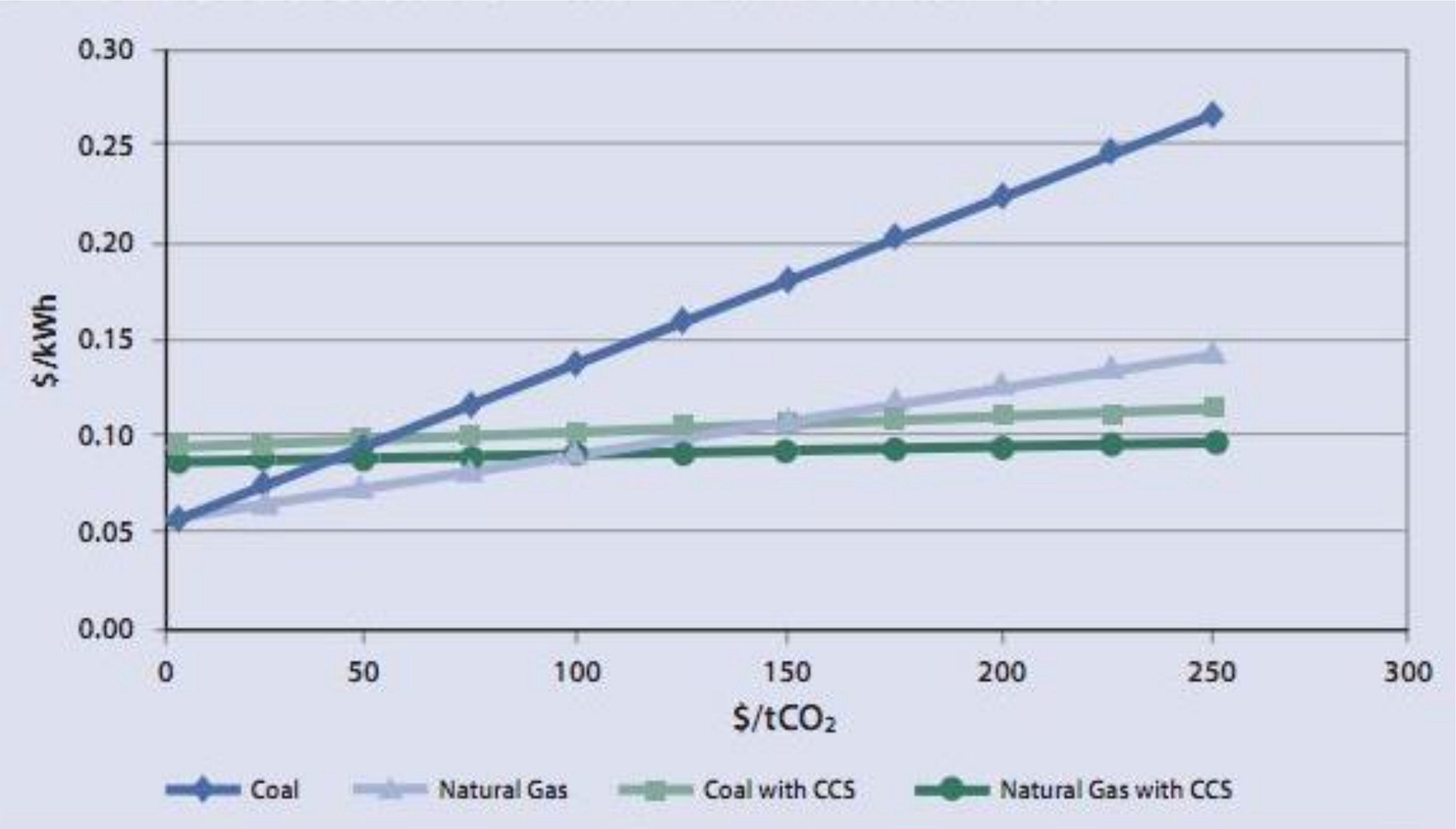




Global Gas Market in 2030 | Recoverable Shale (2009 use)

- More liquid, integrated global markets
  - In U.S. economic interest
  - Reduce security concerns
- Recommendations
  - Support market integration, supply diversity
  - Aid transfer of shale technology

Levelized Cost of Electricity at Different Carbon Prices



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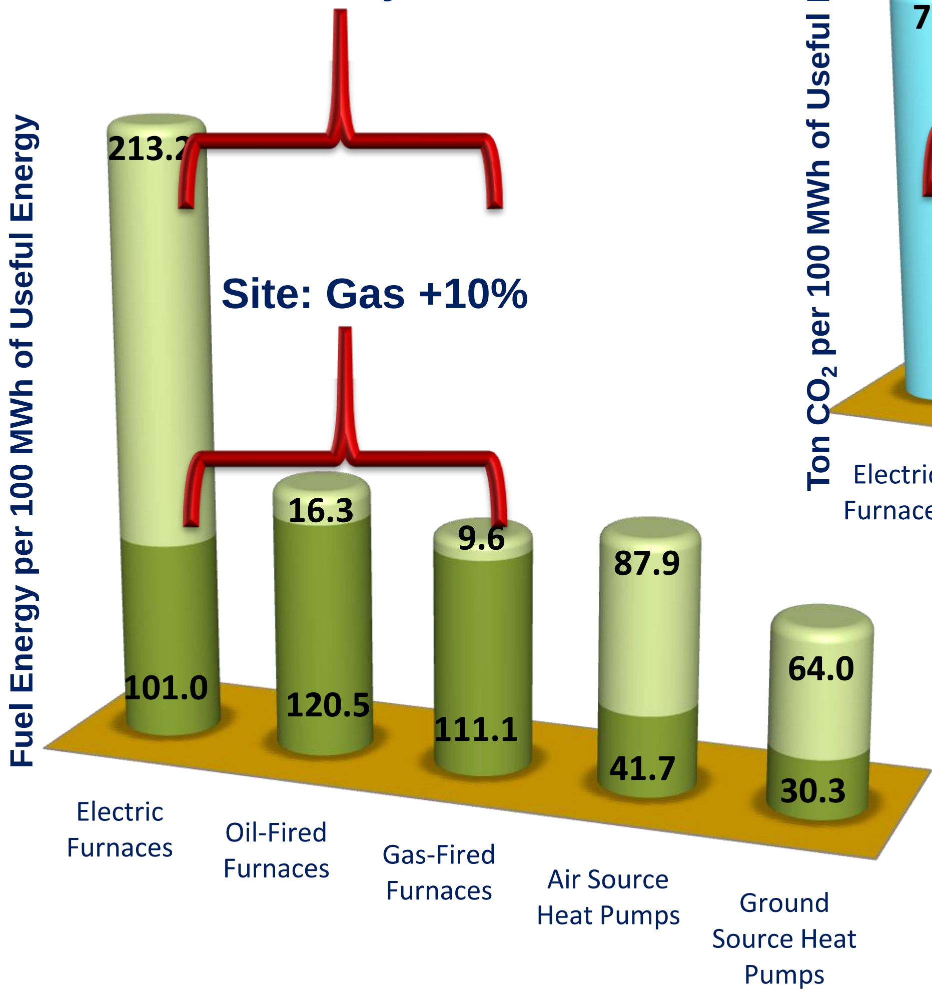
Buildings: Full Fuel Cycle Energy/CO_2

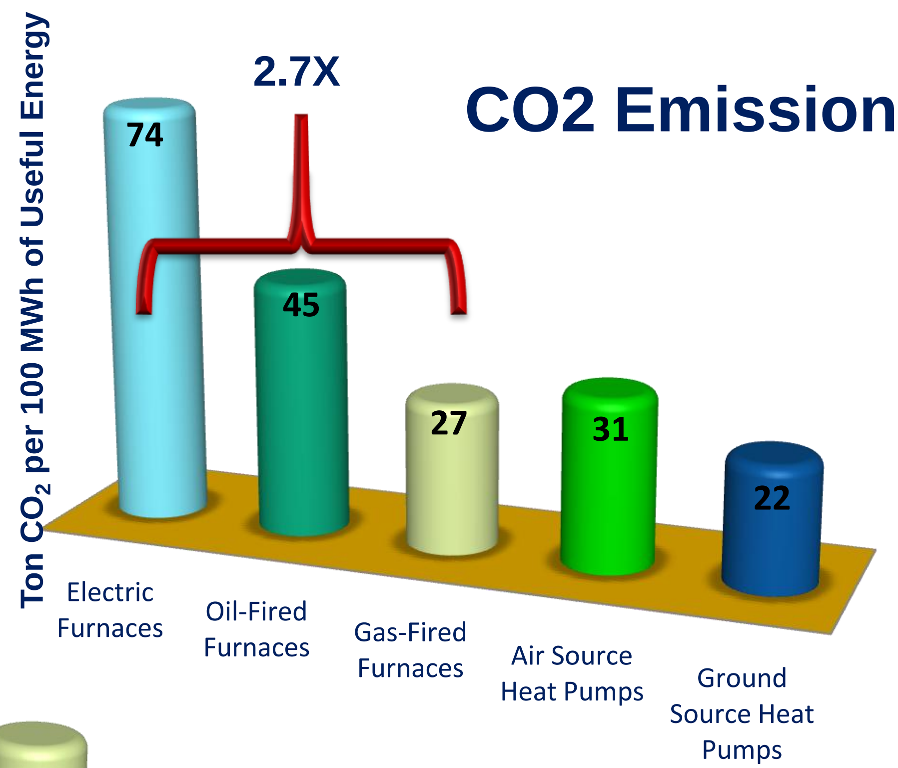
Energy Consumption



+ = Source Energy

Site Energy

CO2 Emissions



Price Benchmarks Vs. Observed Prices 1991–2010

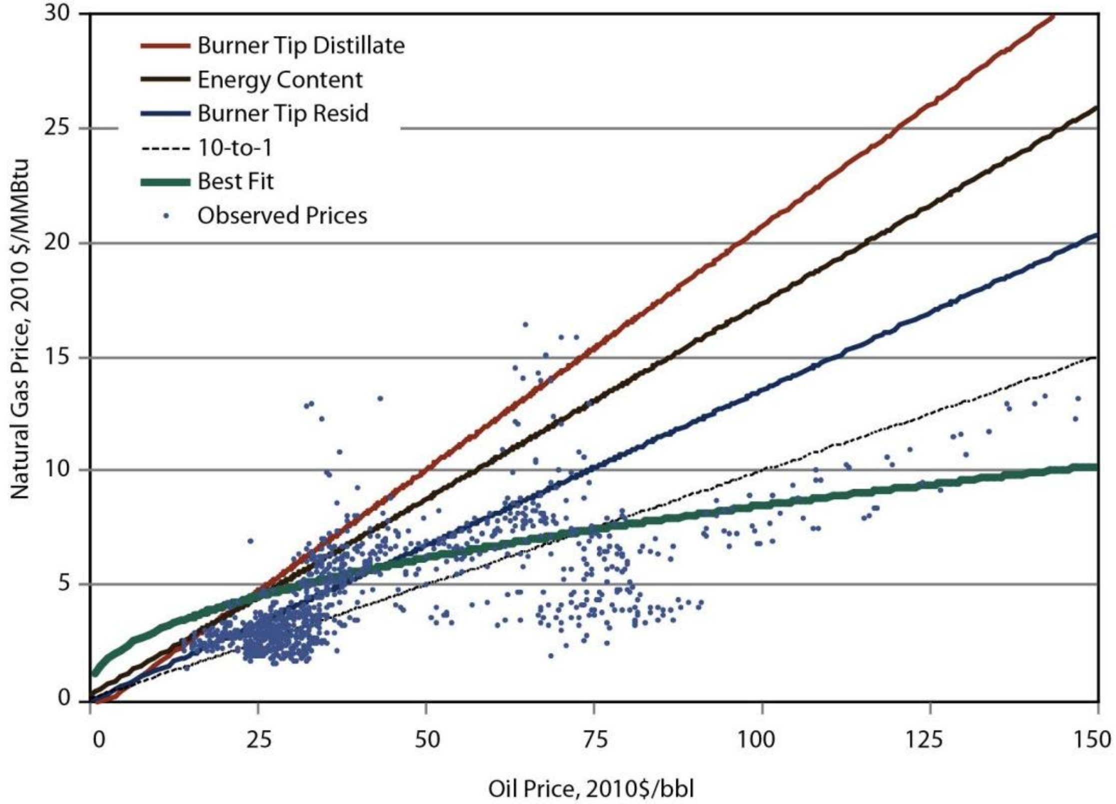
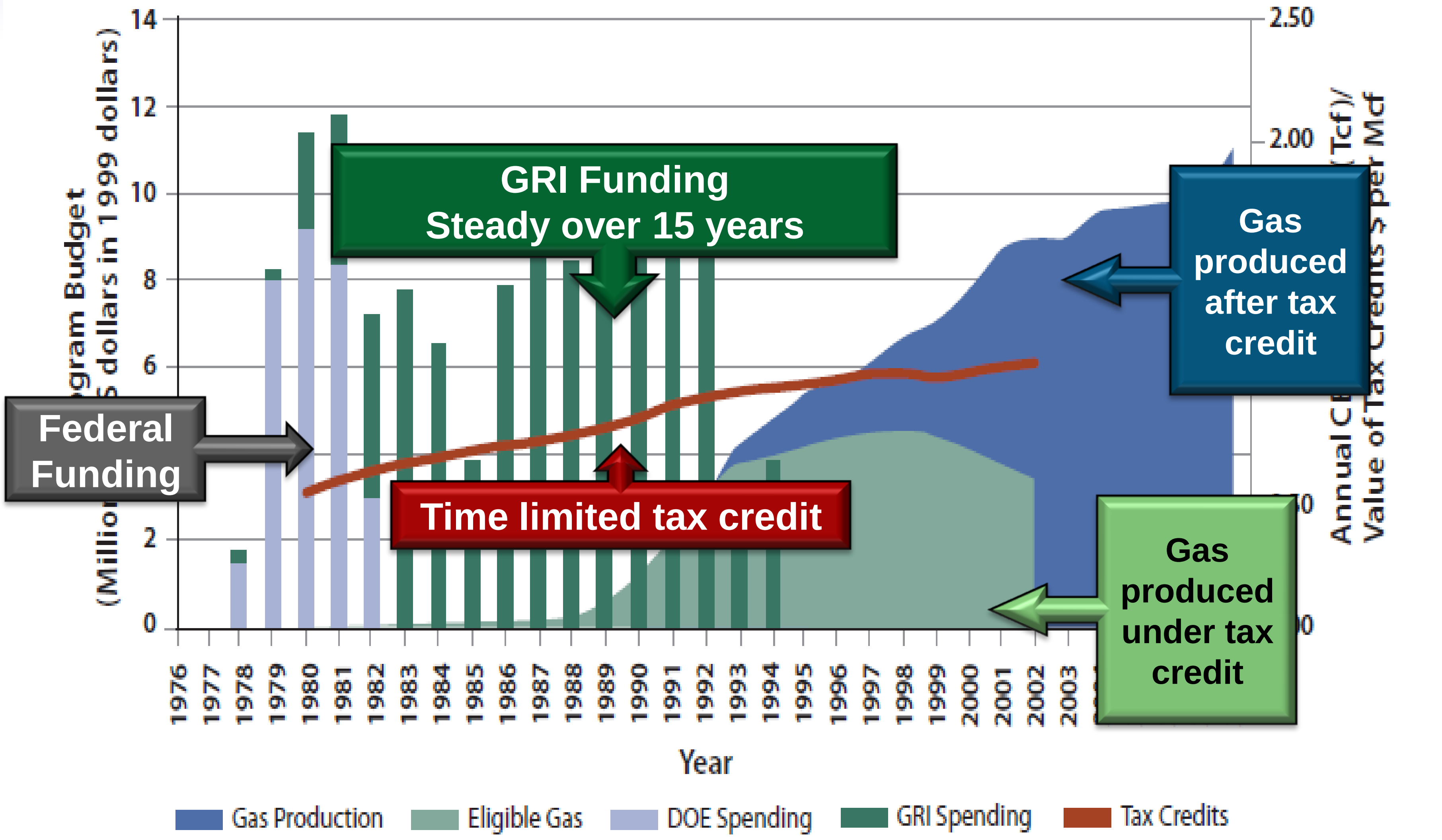


Figure 7.2 charts natural gas prices as a function of oil prices. The four straight lines show the four pricing rules-of-thumb. Using the ordering of the lines at the right of the figure, the top line is the burner-tip parity rule based on natural gas competing with distillate fuel oil, the second line is the energy-content equivalence rule, the third line is the burner-tip parity rule based on natural gas competing with residual fuel oil, and the fourth line is the 10-to-1 rule. The slightly curved line is the best-fit line calculated from a statistical analysis incorporating a number of additional variables and dynamics. The scatterplot of data points are the actual price combinations observed over the 1991 to 2010 period. All observed prices are quoted in real terms in 2010 dollars.

RD&D Spending



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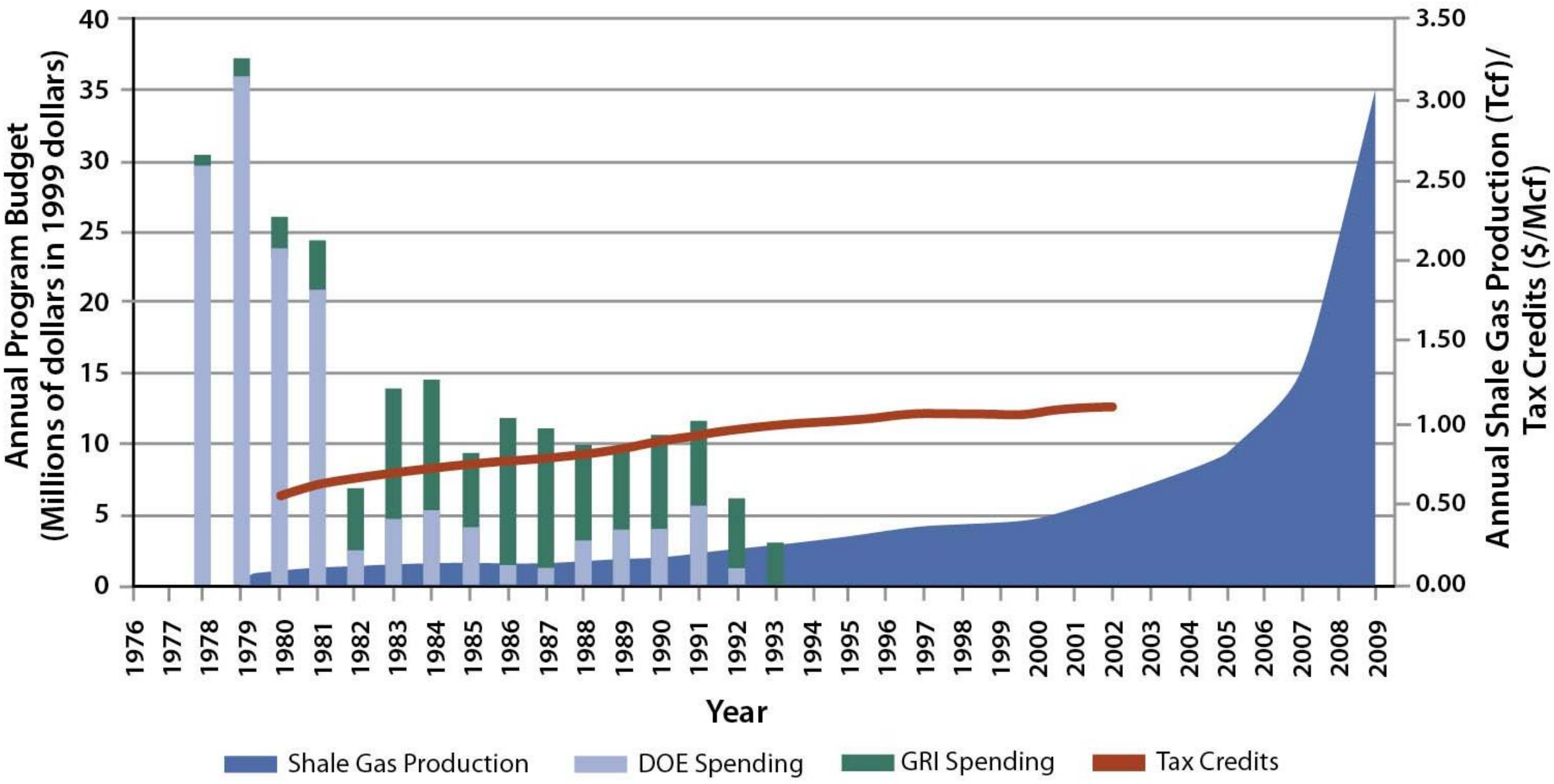
Shale Gas RD&D Spending and Supporting Policy Mechanisms



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