U.S. Natural Gas – A Decade of Change and the Emergence of the Gas-Centric Future

Francis O' Sullivan

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Natural gas – The new “unconventional” paradigm

The past decade has been a period of huge change for natural gas in the United States – Perspectives on supply and price have been fundamentally altered and a much more gas-centric future is being envisaged by many

Comparison of spot natural gas price with historical oil-to-gas ratios
$/MMBtu of gas

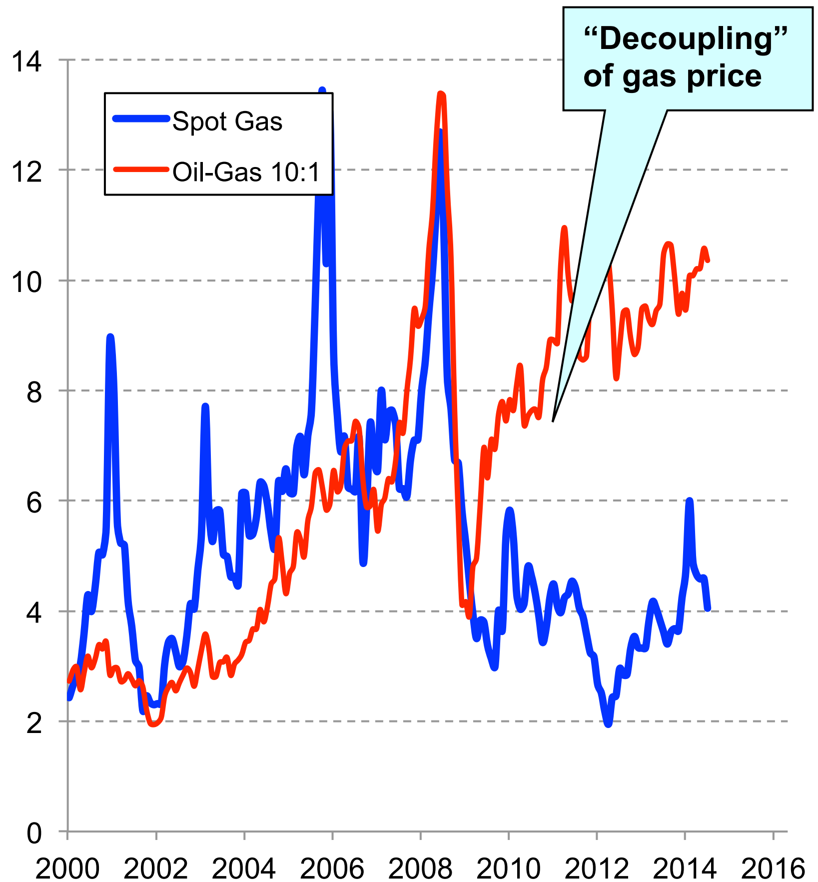
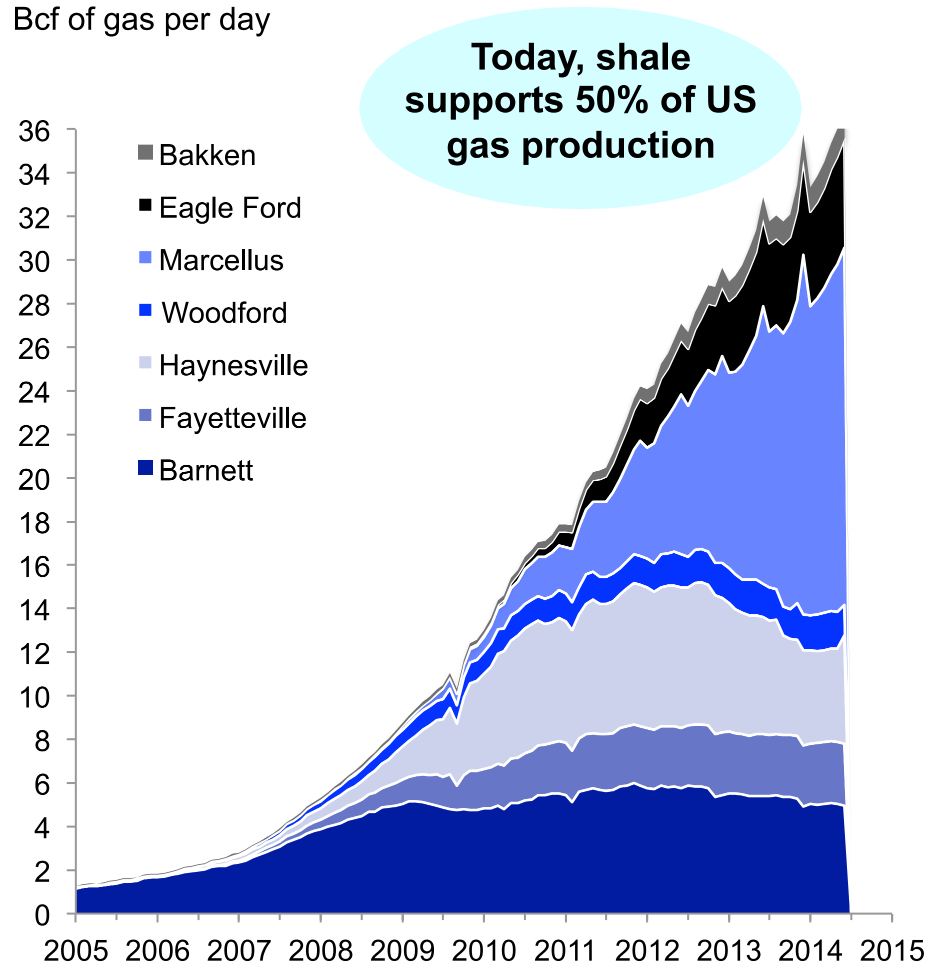


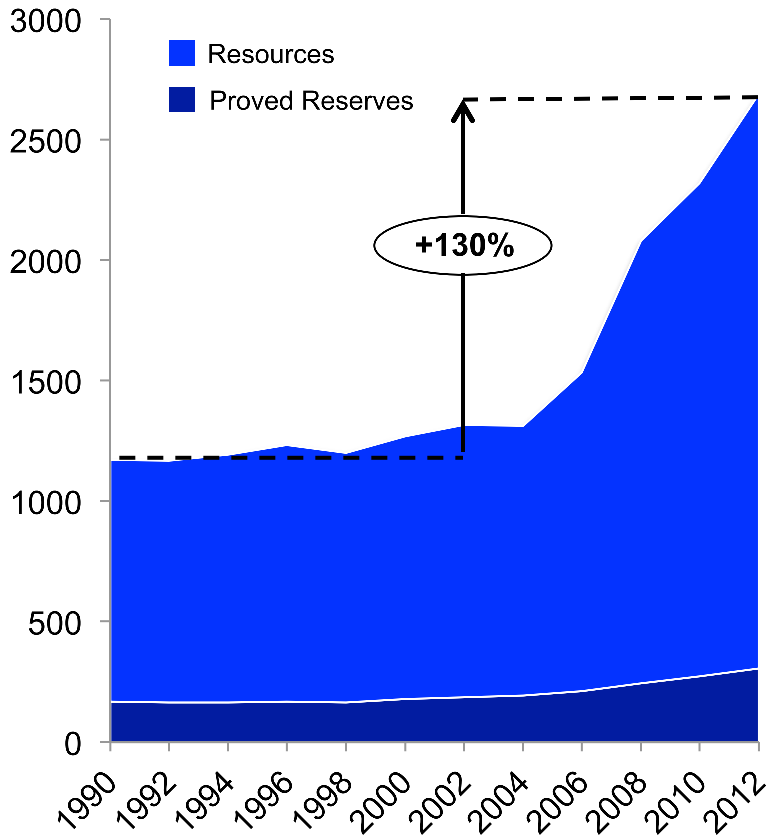
Illustration of gas production growth from the main U.S. shale plays since 2005
Bcf of gas per day



Source: F. O'Sullivan, United States Energy Information Administration, HPDI Production Database

However, the fact that shale gas production is still in its infancy means that large uncertainties surround resource estimates – As more well data becomes available the uncertainty envelope will likely narrow

Illustration of growth in US natural gas proved reserve and resource estimates from ’90 to ‘10
Tcf of gas



Breakdown of the PGC 2012 shale gas resource estimates by major U.S. shale play*
Tcf of Gas

	Min	Most Likely	Max
Fort Worth Basin: Barnett Shale	11	48	83
Arkoma Basin: Fayetteville & Woodford	75	104	137
E. TX & LA Basin: Haynesville & Bossier	76	149	293
TX Gulf Coast Basin: Eagle Ford & Pearsall	29	59	105
Appalachian Basin: Marcellus, Ohio & Utica	220	563	1242
Uinta Basin: Mancos & Manning Canyon	37	60	129
Other Basins:	34	90	234
Total Mean Estimate:	482**	**1073**	2223**

1. EIA 2010 assessment based on 2008 PGC assessment with updated estimates of technically recoverable shale gas volumes

Source: F. O’Sullivan, NPC data, PGC data, EIA data

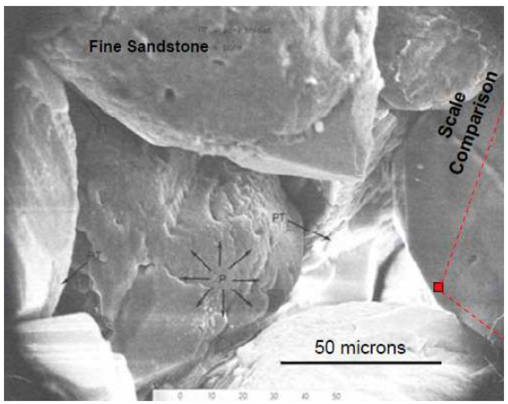
The shale formations supporting the recent production growth are essentially source rocks – The physics underlying production from a shale setting is very different to that of conventional gas reservoir

Darcy's Law – A fundamental relationship in petroleum engineering

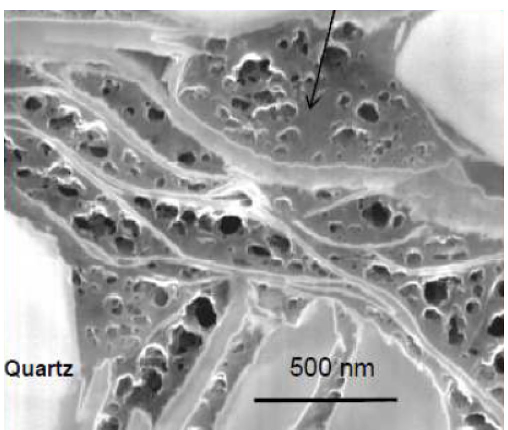
$$q = -\frac{k}{\mu}\nabla P$$

$q =$ Fluid flux
$k =$ Permeability
$\mu =$ Viscosity
$\nabla P =$ Pressure gradient

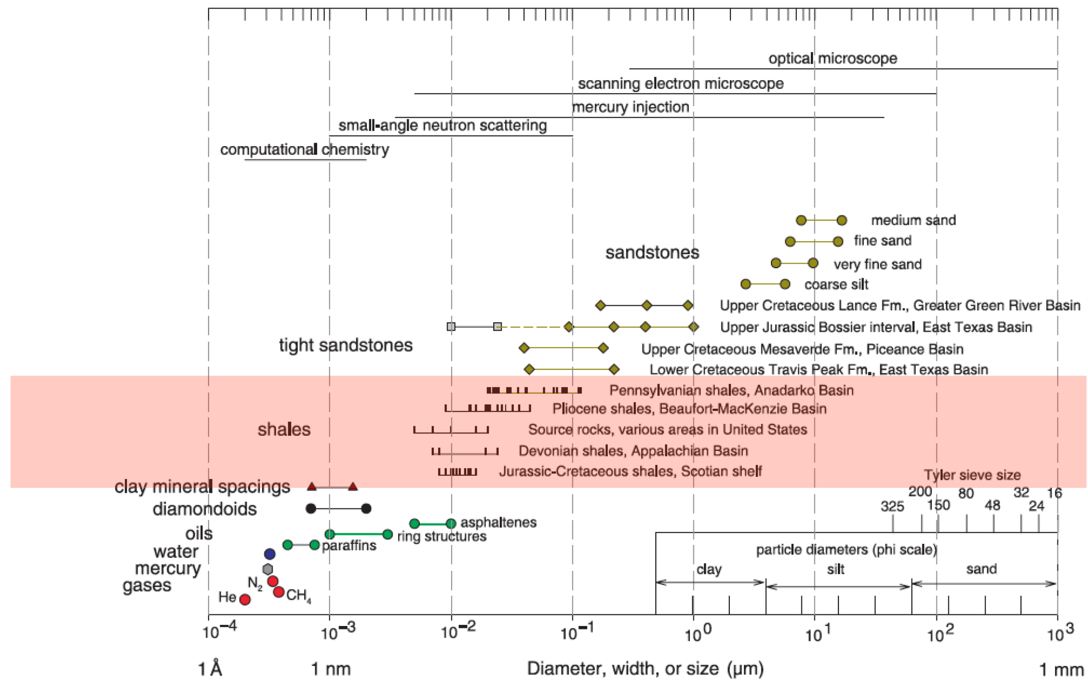
Fine sandstone



Shale



Pore throat size spectrum

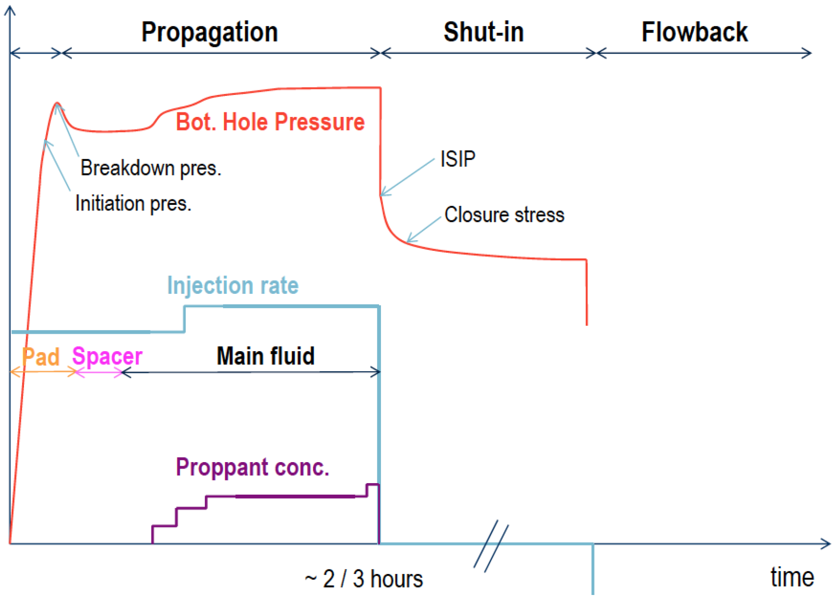


$k_{Sandstone}$ 10-100's mD k_{Shale} 10-100's nD

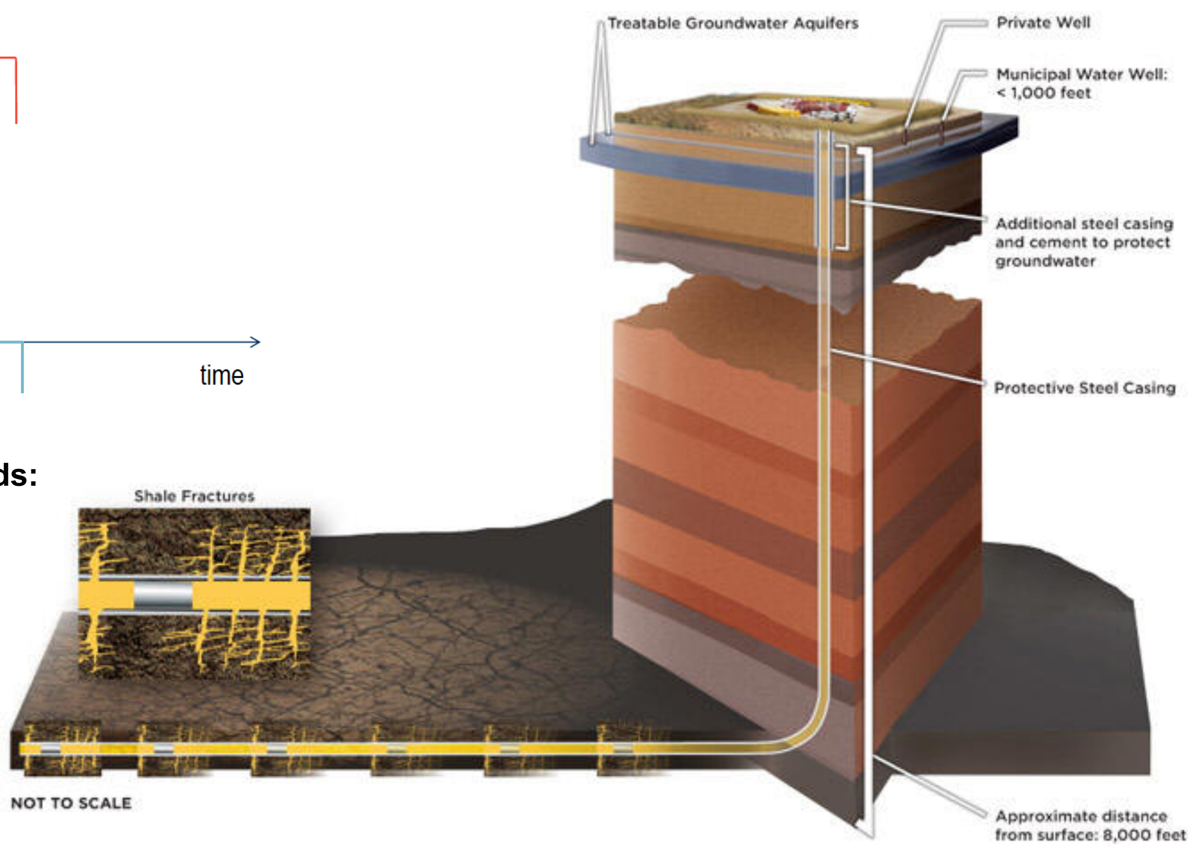
Source: P. Nelson, Pore-throat sizes in sandstones, tight sandstones, and shales, AAPG Bulletin, v. 93, no. 3 (March 2009), pp. 329–340

The combination of horizontal drilling and hydraulic fracturing is required to achieve an acceptable flow rate from a shale formation – Stimulation is not new but the scale of today's treatments are an order of magnitude larger

A fracturing stage pumping and pressure profile



A contemporary unconventional well layout



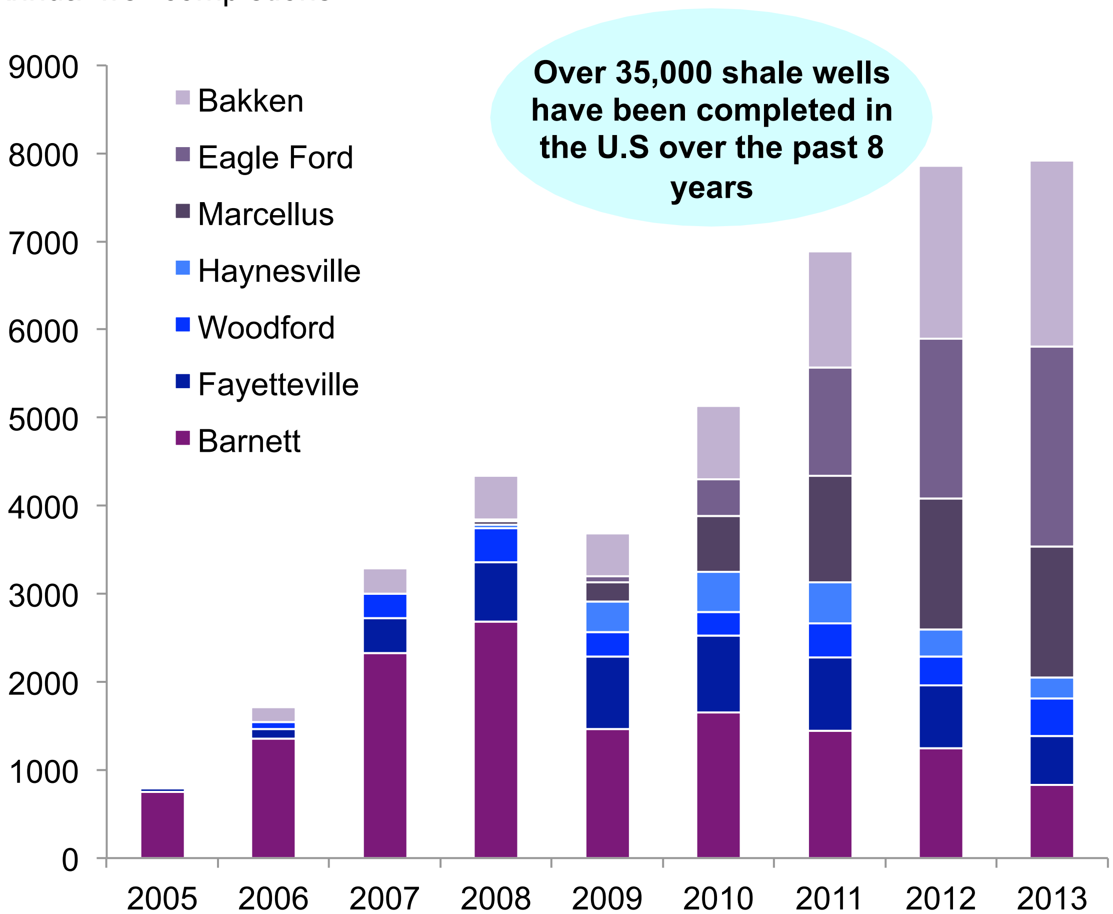
Hydraulic fracturing a single well demands:

- Horse power – 20-30,000 HP
- Pressures – 4-8,000 psi
- Water – 4-6 M gallons
- Sand – 1-2,000 Tons

Source: F. O'Sullivan, Brice Lecampion

The rise of U.S. shale oil and gas production has led to a large increase in the number of hydraulic fracture treatments – With this has come an increased focus on the array of complex environmental issues associated with the process

Horizontal wells completed in major U.S. shale plays
Annual well completions



Some of the environmental issues associated with hydraulic fracturing

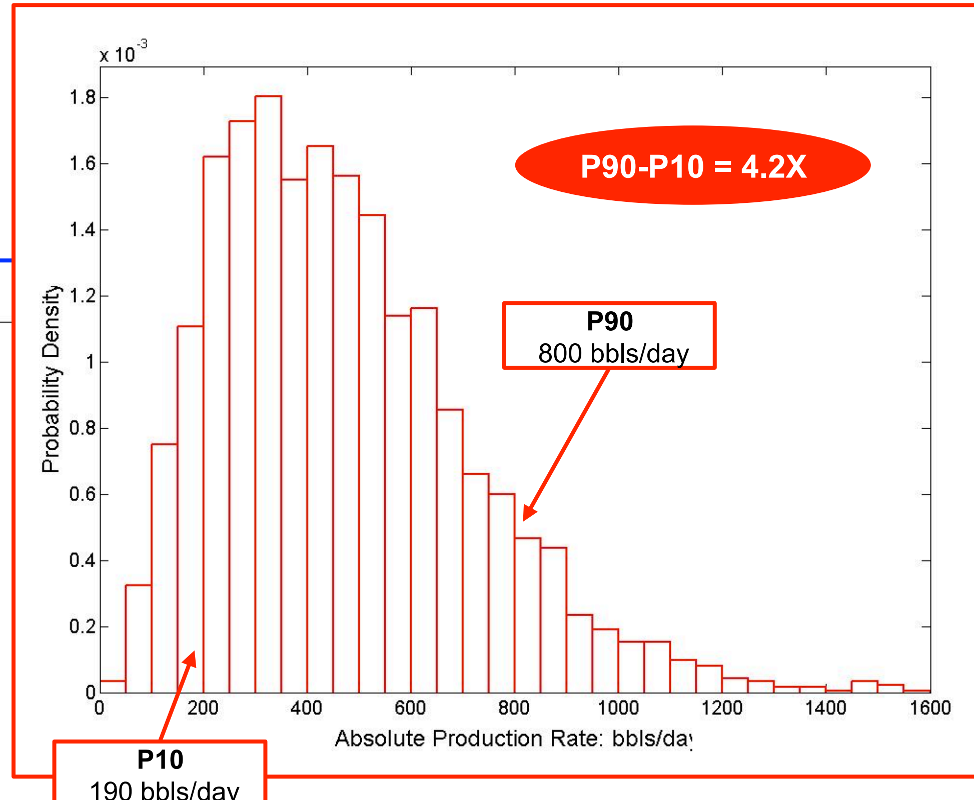
- **Water impacts**
  - Ground water and surface water contamination
  - Very large and impulsive demand on limited local resources
- **Air impacts**
  - Fugitive methane leakage
  - VOC emissions and other local air quality impacts
- **Community impacts**
  - Heavy traffic and surface disturbance
  - Ecosystem fragmentation
  - Induced seismicity

Source: F. O'Sullivan, HPDI Production Database

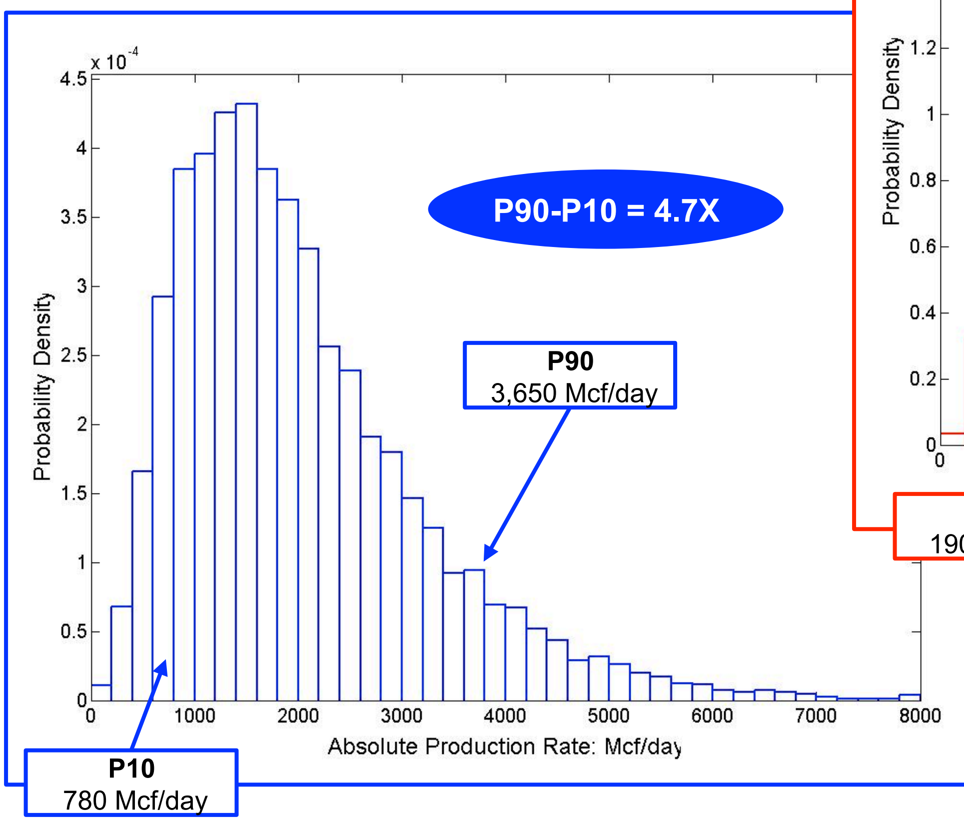
Understanding the shale resource – Productivity and economics

Reviewing early-life well performance across the major shale plays reveals some interesting features – Well productivity distributions tend to be broad and all display positive skew.

Distribution of absolute peak month well productivity[1]
Bakken H wells drilled between 2010 and 2012



Distribution of absolute peak month well productivity[1]
Barnett H wells drilled between 2005 and 2012



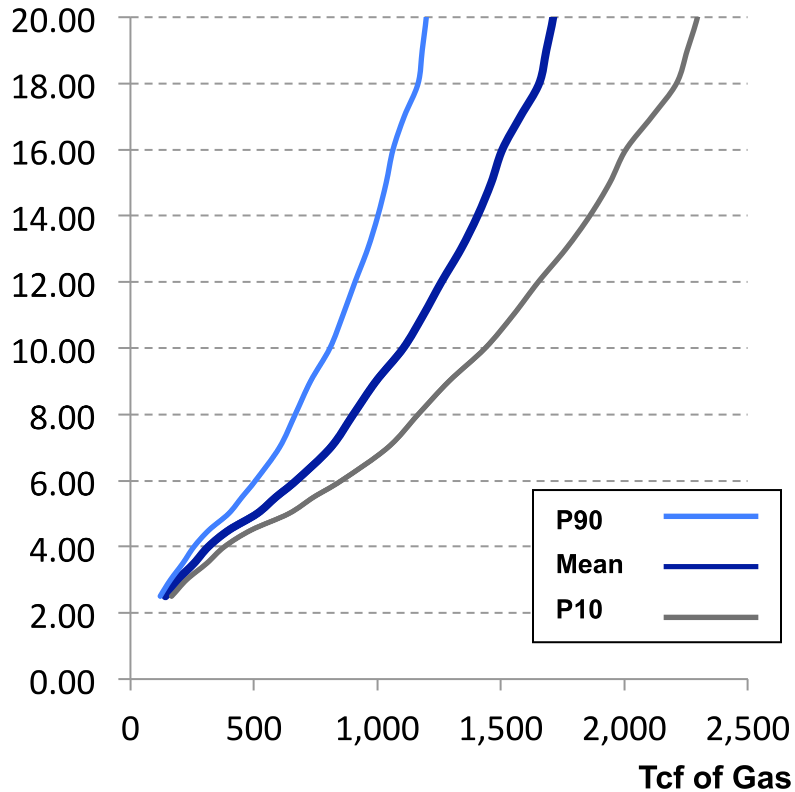
Identifying the drivers of performance variability is exceptionally difficult

- Impact of geological variation
- Impact of well completion design
- Temporal impact of a creaming process
- Etc.

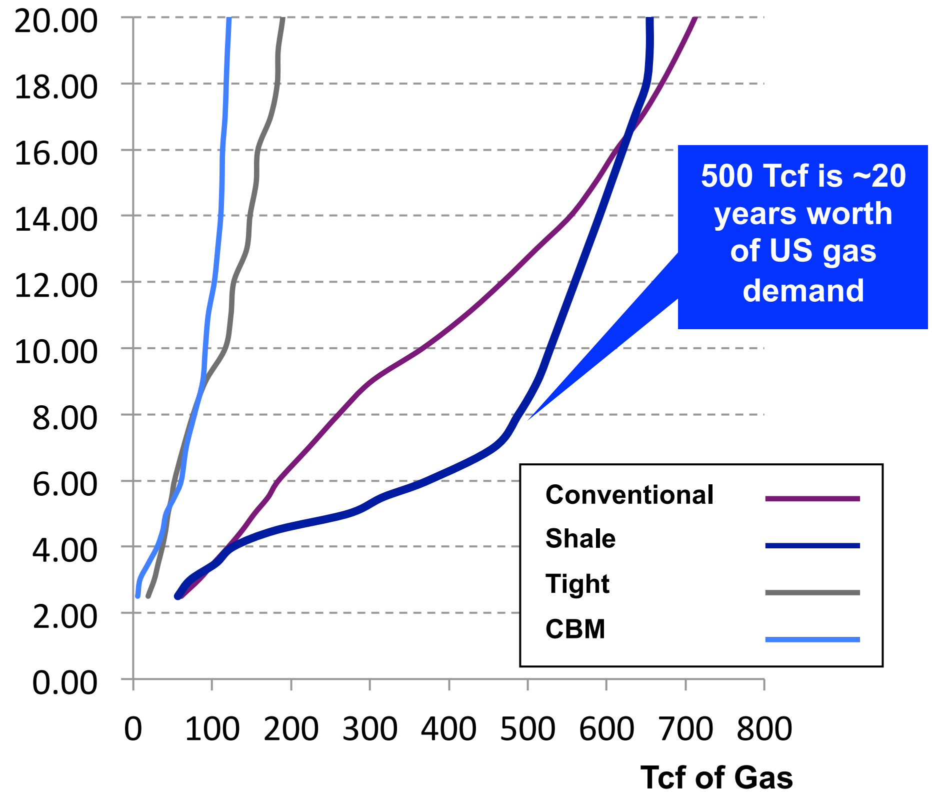
1. Peak month production rate reported in units of Mcf/day and bbls/day
Source: F. O'Sullivan, HPDI database

Shale has provided the U.S. with an abundance of moderate cost gas, with 500 Tcf or more available at or below $6.00/MMBtu – Although often suggested as such, shale gas is not cheap

Aggregate United States natural gas supply curve
$/MMBtu breakeven gas price*



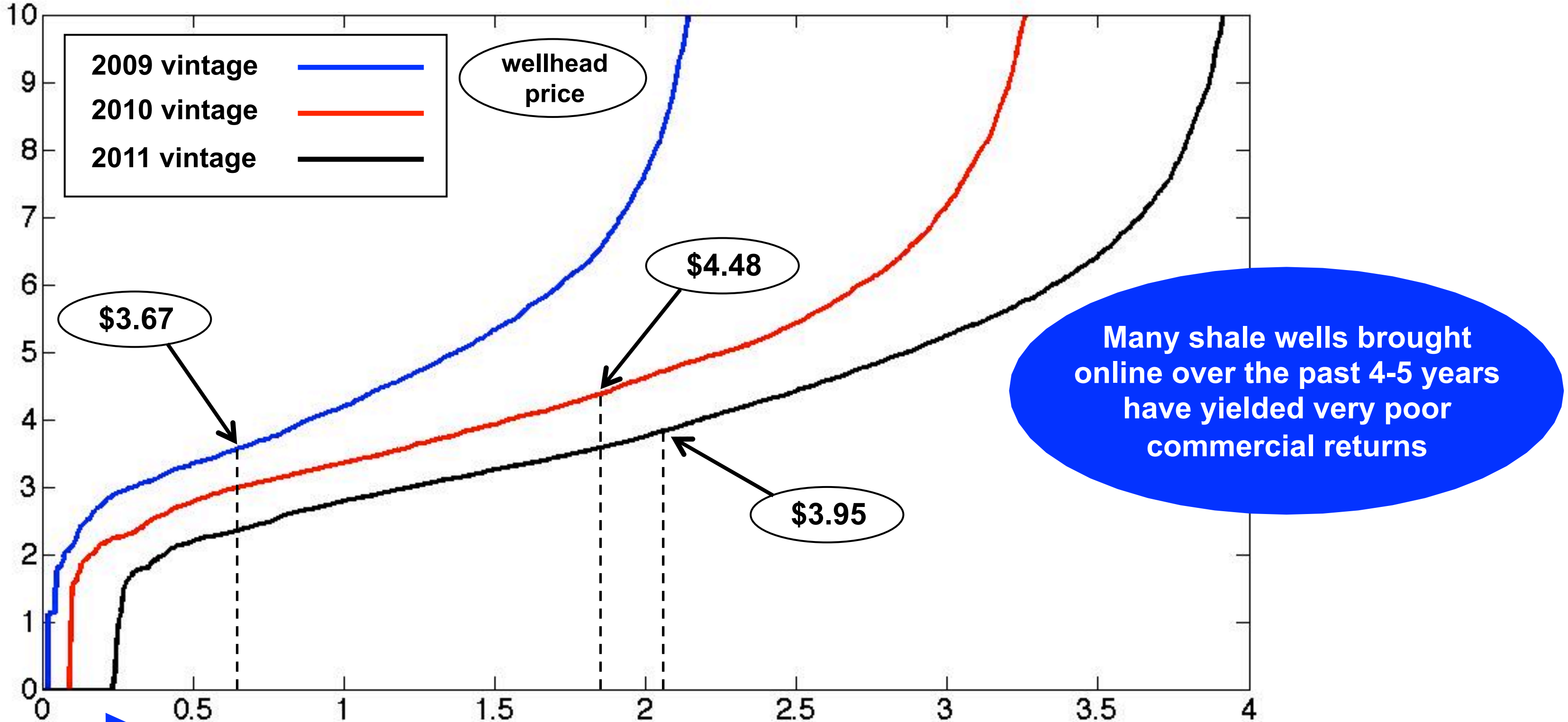
Breakdown of United States natural gas supply curves by resource type
$/MMBtu breakeven gas price*



* Cost curves calculated using 2007 cost bases. U.S. costs represent wellhead breakeven costs. Cost curves calculated assuming 10% real discount rate
Source: F. O'Sullivan, MIT Gas Supply Team analysis, ICF Hydrocarbon Supply Model, Data strictly for illustrative purposes only

Naturally, the variability in well productivity has major implications for the economics of the shale resource – Extensive drilling has pushed supply up and prices down, but much of this gas has been produced below cost

Retrospective U.S. shale gas curves for the '09, '10 and '11 well vintages
$/MMBtu breakeven gas price[1]



First 12 month gas production from shale well vintage
Tcf of Gas

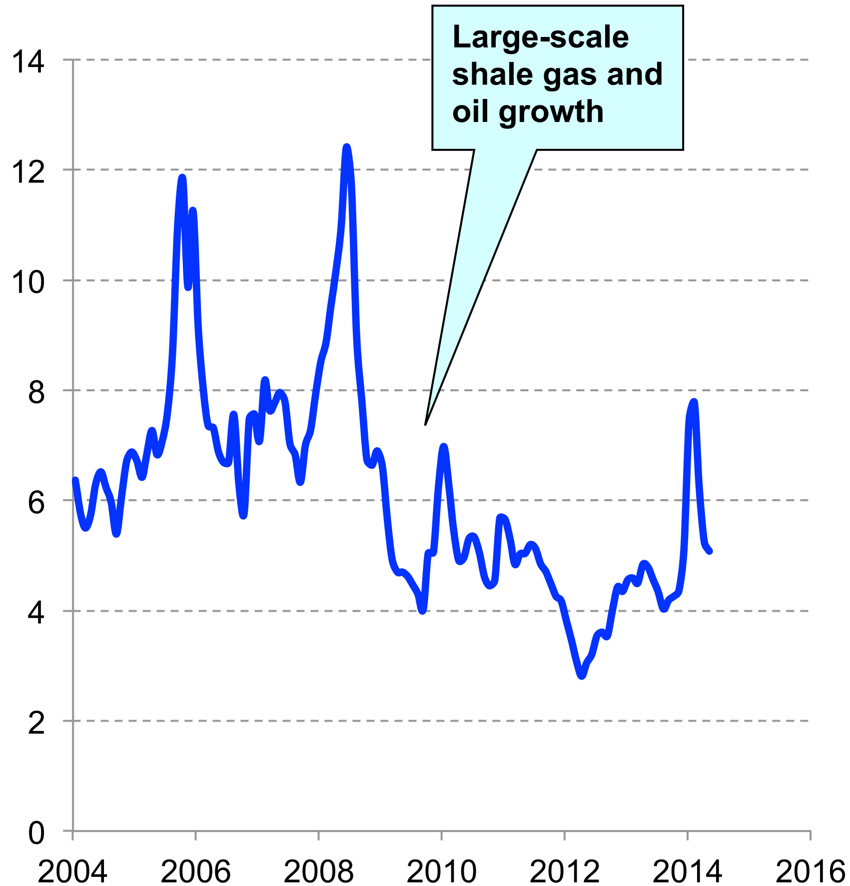
Liquids targeted drilling is increasingly delivering ultra low-cost gas to the system

1. Supply curves include: Bakken, Barnett, Eagle Ford, Fayetteville, Haynesville, Marcellus and Woodford plays, and represent only gas produced by horizontal wells
Source: F. O'Sullivan

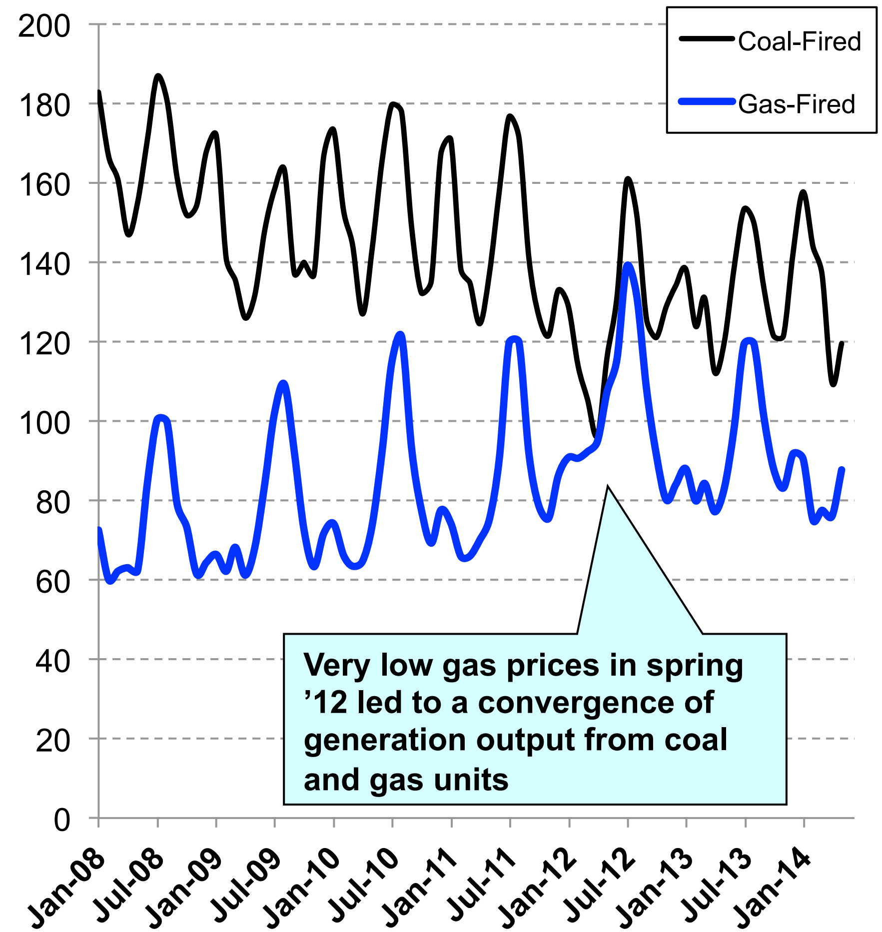
Domestic and international market evolution – The changing role for U.S. gas

Over the past several years falling gas prices have led to gas increasingly displacing coal-fired generation – More gas use for power generation going forward is certain

Evolution of natural gas prices for power generation from 2004 in the United States
$/MMBtu of gas



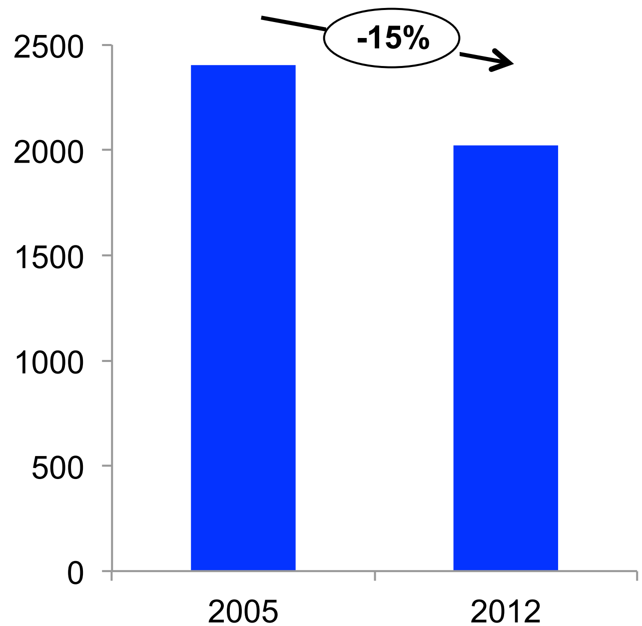
Comparison of coal and gas-fired power generation levels in the U.S. since January 2008
TWhrs



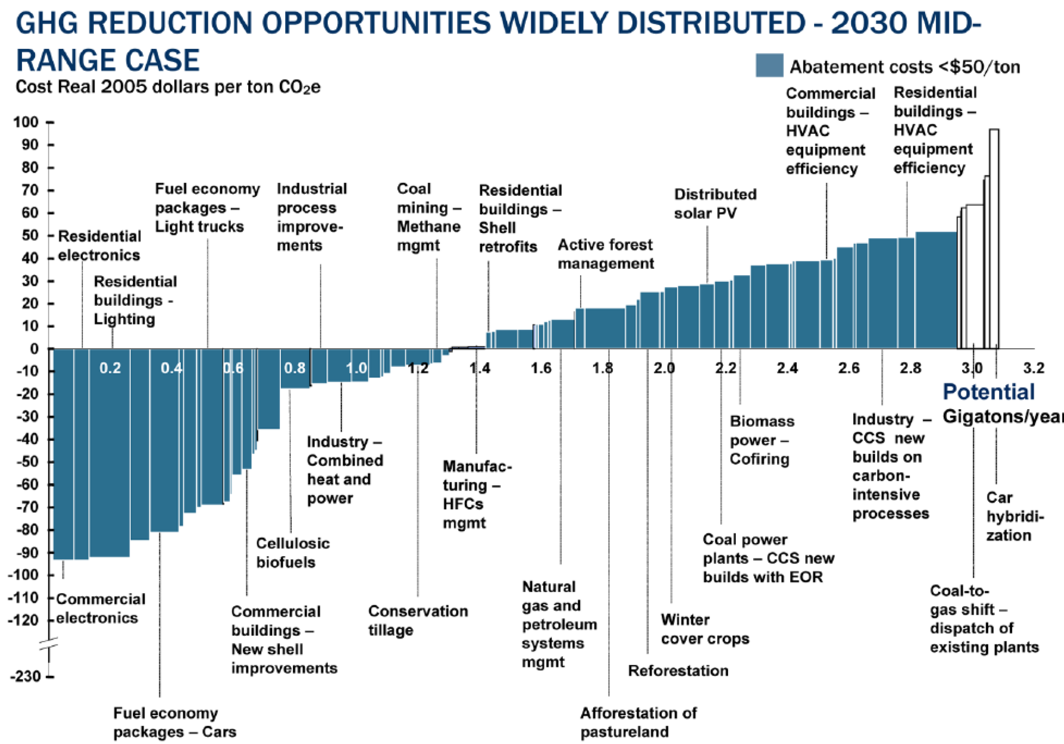
Source: F. O'Sullivan, United States Energy Information Administration

CO_2 emissions from U.S. power generation have fallen by 15% since 2005 due largely to coal-to-gas switching – The emission reductions have had negative costs, but how sustainability these reductions will be is unclear

US CO_2 emissions from electric power generation in 2005 and 2012
Tg of CO_2



The McKinsey abatement curve - 2007

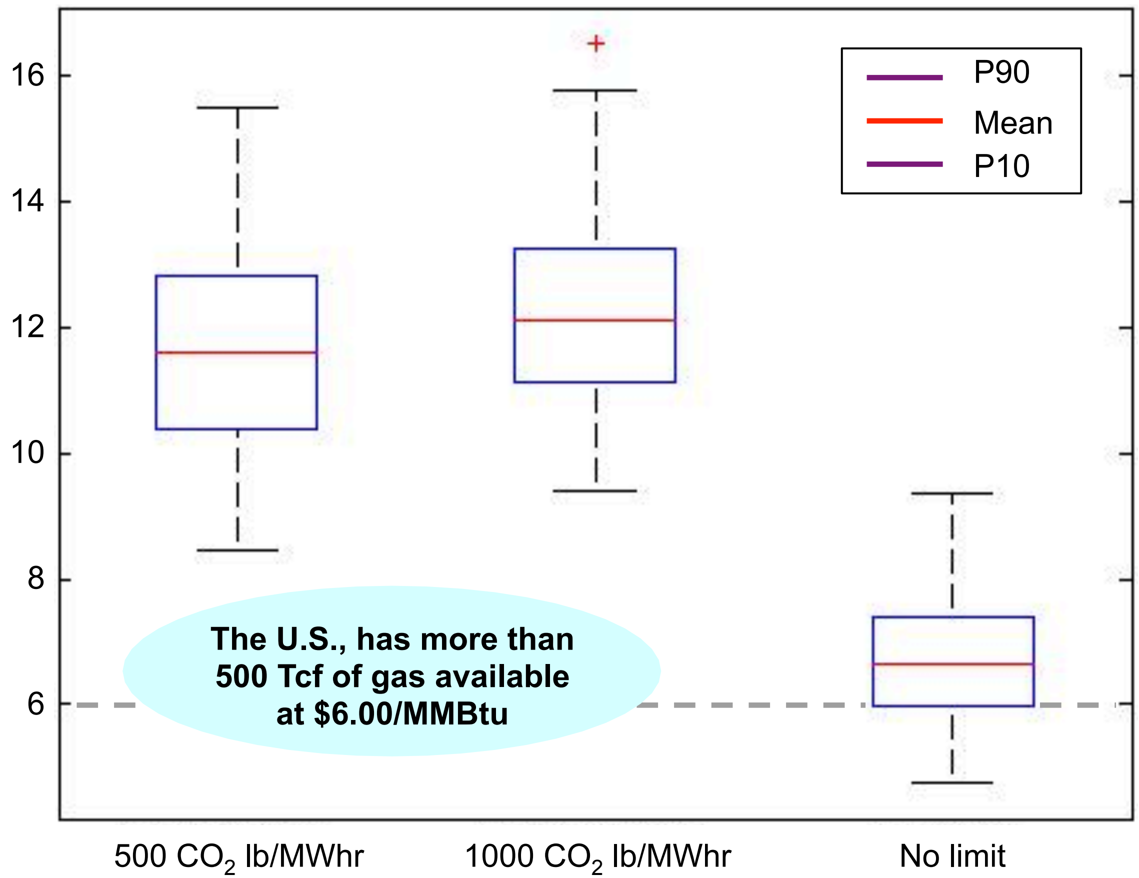


- **In 2007, McKinsey estimated that coal-to-gas switching would yield 80MT of CO_2 abatement at at cost of >$50/ton**
- **Compared to 2005 levels, lower cost gas from shale has resulted in >350MT of annual CO_2 abatement, at zero to negative cost**

Source: McKinsey & Company. United States Environmental Protection Agency

Going forward, the abundance of moderate-cost gas in the U.S. points to gas-fired generation dominating new build – This conclusion cannot be drawn for other regions where gas markets are oil-linked

Gas price needed for new build coal selection ahead of NGCC assuming various carbon emissions limits and no EOR[1]
$/MMBtu



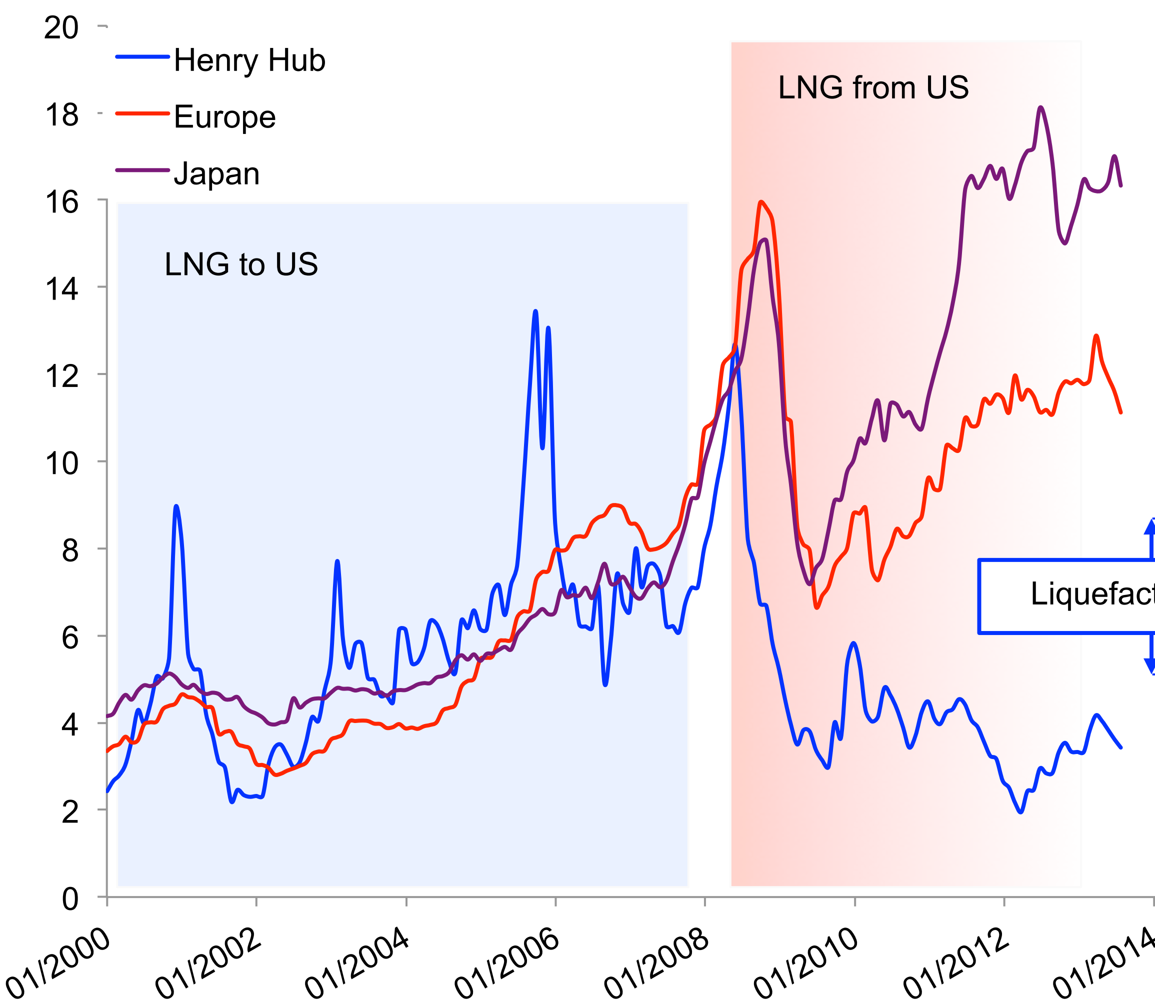
- **The structure of global gas markets means that dynamics in the U.S. are not necessarily relevant elsewhere**
- **U.S. gas-on-gas market will likely continue to ensure gas is the most attractive new build option**
- **Liquids-linked pricing outside North America means coal-fired plants are less disadvantaged**
- **The breaking of oil-linked gas pricing in East Asia over the coming years is a major uncertainty**

1. N=10,000. Heat rate, Capital cost and O&M costs scale linearly. CO2 emissions are function of emission standard, heat rate and unabated emissions. Costs based on NETL (2011) for PC, EIA (2011) and IEA (2011) for NGCC. Costs for NGCC are interpolated from reported costs on 0% and 90% capture. Natural gas price constant over lifetime of plant. Capacity factor: 75% with 5% standard deviation. Transport and storage cost: $15/ton CO2 captured. Capital charge: 15%. Coal price: $2.1/MMBtu. Capital cost uncertainty: if capture, standard deviation $100/kW, if no capture, standard deviation $25/kW.

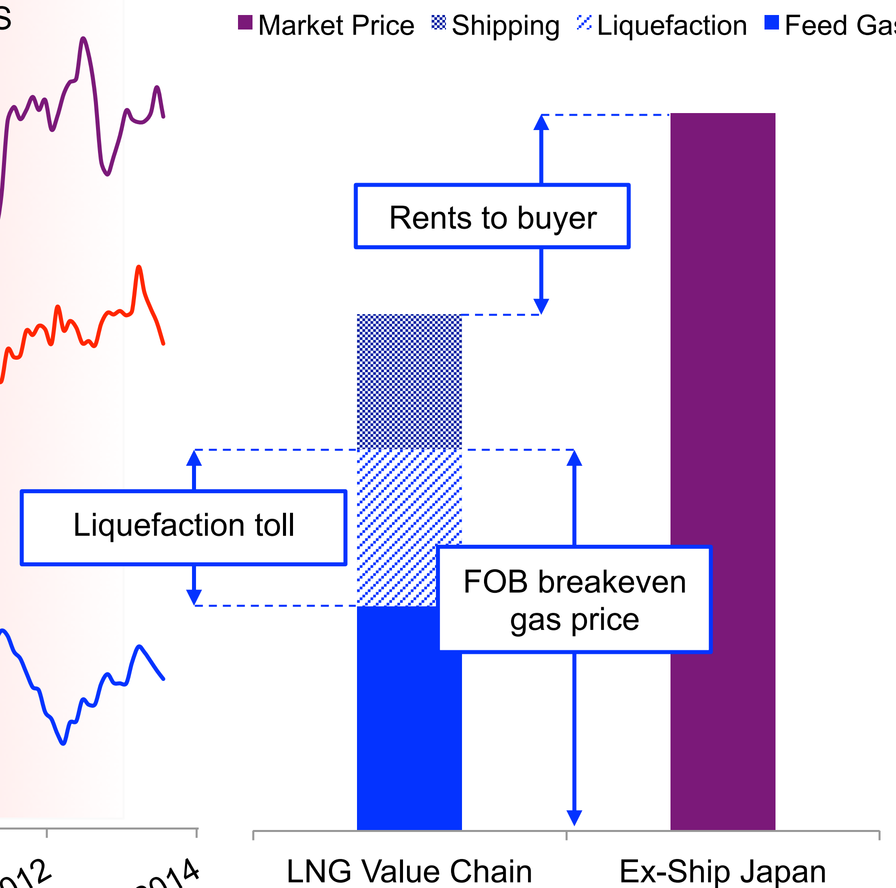
Source: Analysis by J. Eide & H. Herzog, MIT, F. O'Sullivan

The global gas price differentials that exist today makes U.S. shale exports (to Asia) look very attractive – The U.S.-Japan differential will likely narrow over the coming years but shale gas supply will likely remain in-the-money

Variation in natural gas spot pricing in major global markets since 2000
$/MMBtu



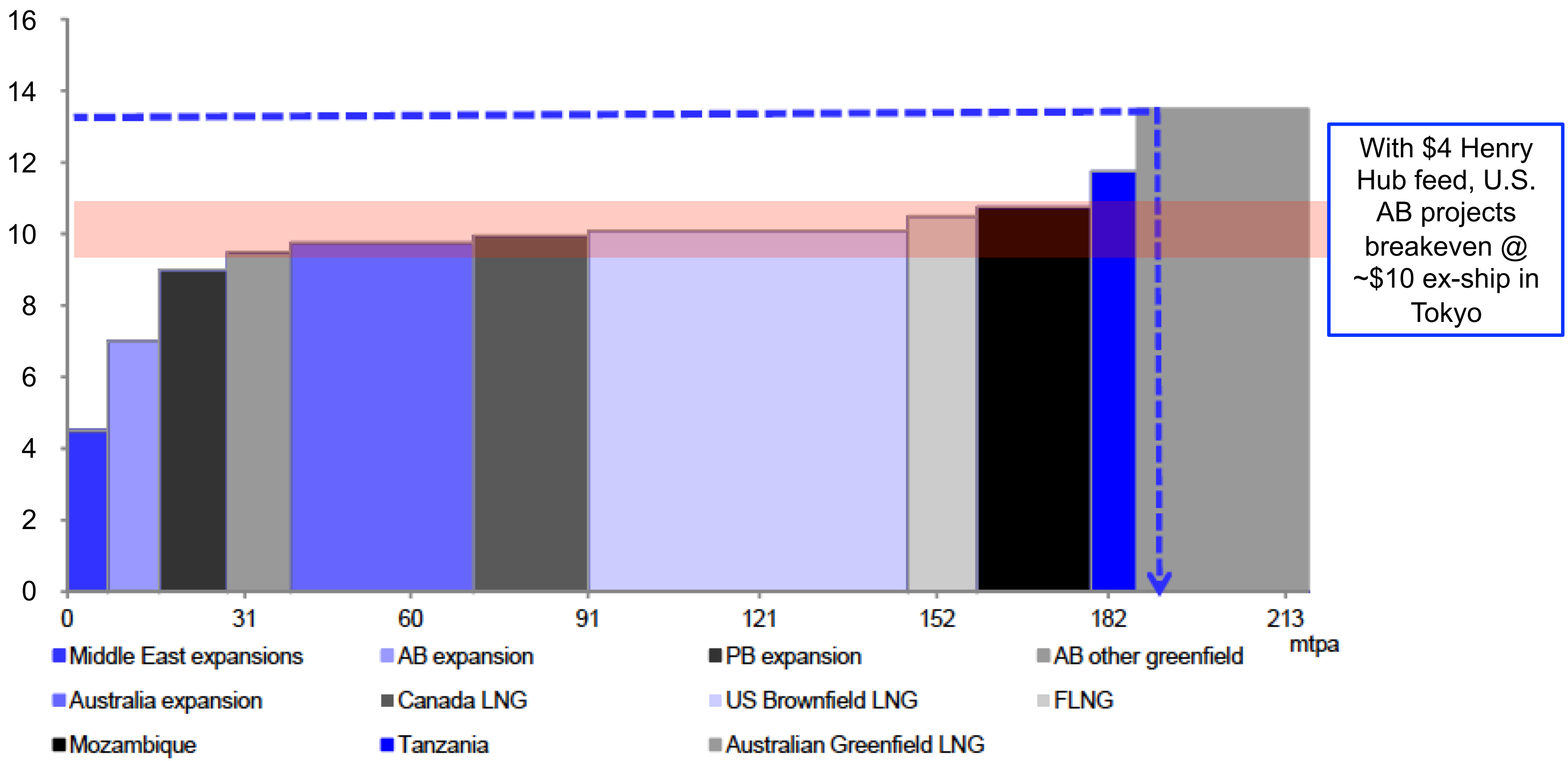
Conceptual U.S. shale-based LNG value chain



Source: F. O'Sullivan, EIA, Bloomberg

Considering the medium term supply stack, U.S. export projects will be quite competitive in supplying Asia – The real risk lies in the feed gas price, though most U.S. projects are passing this through and running as tolling operations

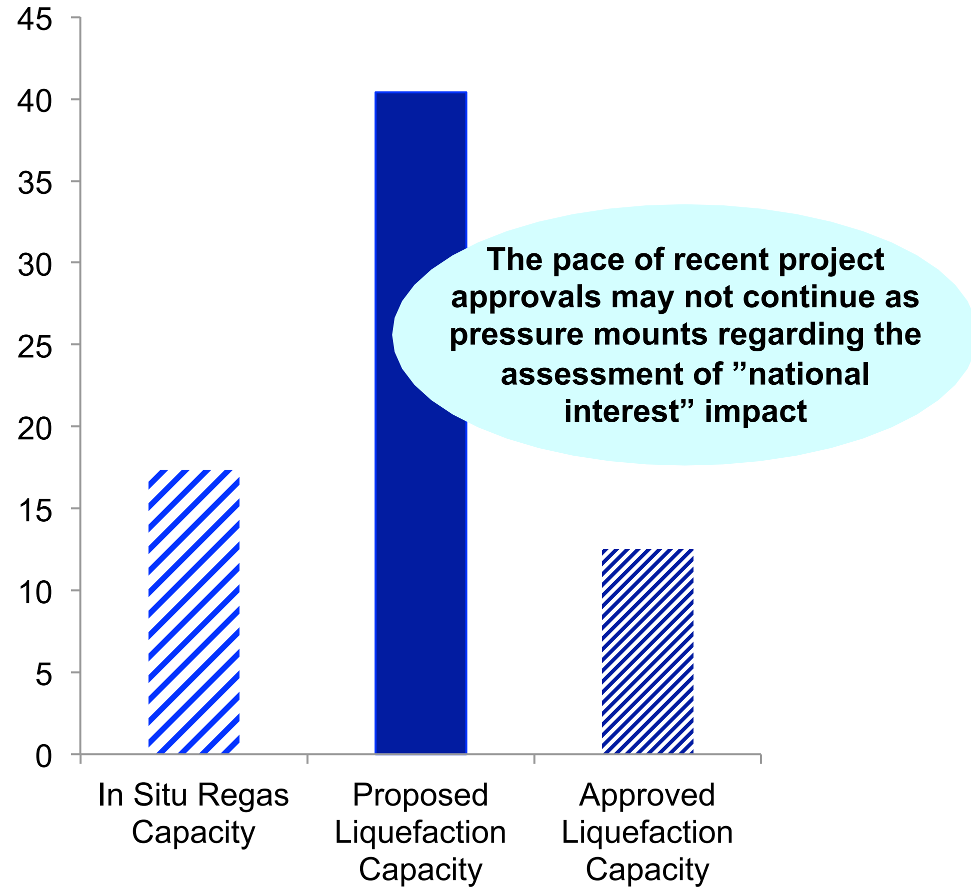
Estimation of new LNG supply curve to 2025 based upon project with high probability of completion
Ex-ship Tokyo breakeven price - $/MMBtu



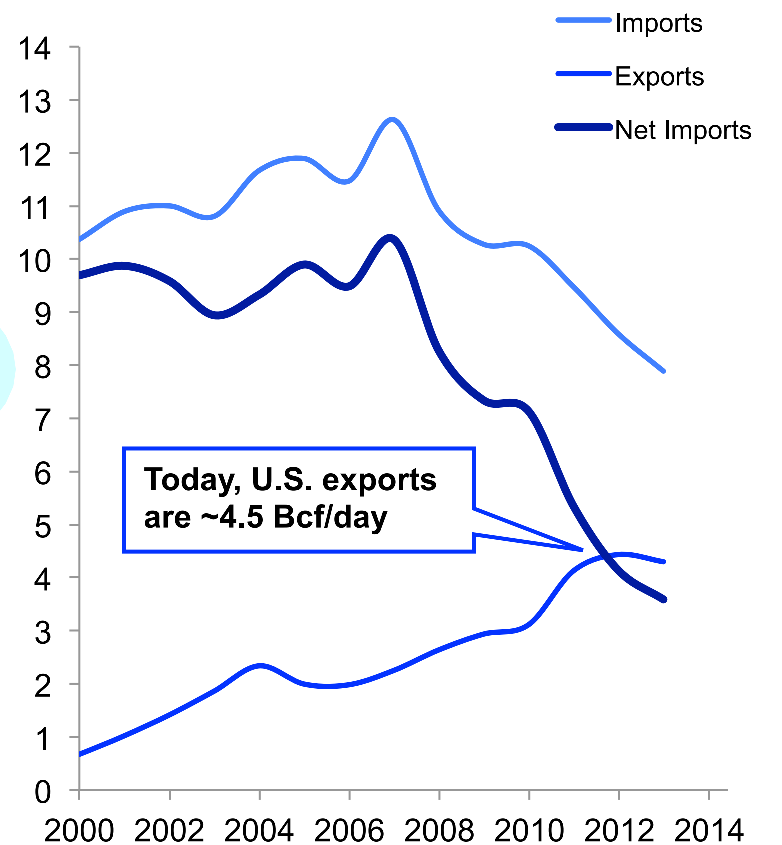
Source: F. O'Sullivan, IGU, Deutsche Bank

The capacity seeking LNG export approval is enormous but the realized levels will be more modest – At full capacity, current licenses for NFT LNG export would more than double U.S. gas exports

Snapshot of U.S. LNG import and export capacity as of September 2013
Bcf/day



Variation in U.S. natural gas imports and exports from 2000 and 2013
Bcf/day



Source: United States Energy Information Administration, United States Department of Energy, CRS