RICE UNIVERSITY

The Rice World Gas Trade Model

CEC Workshop Presentation

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Acknowledgment:
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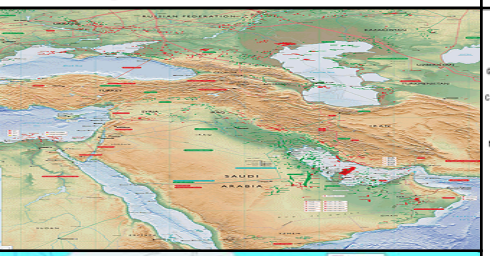

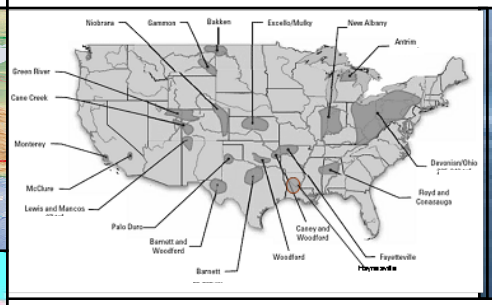

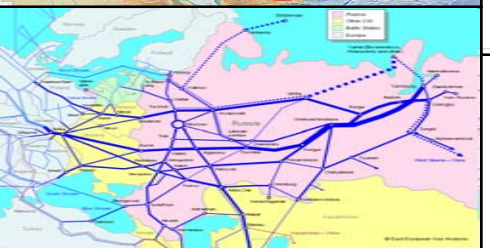

June 16, 2009

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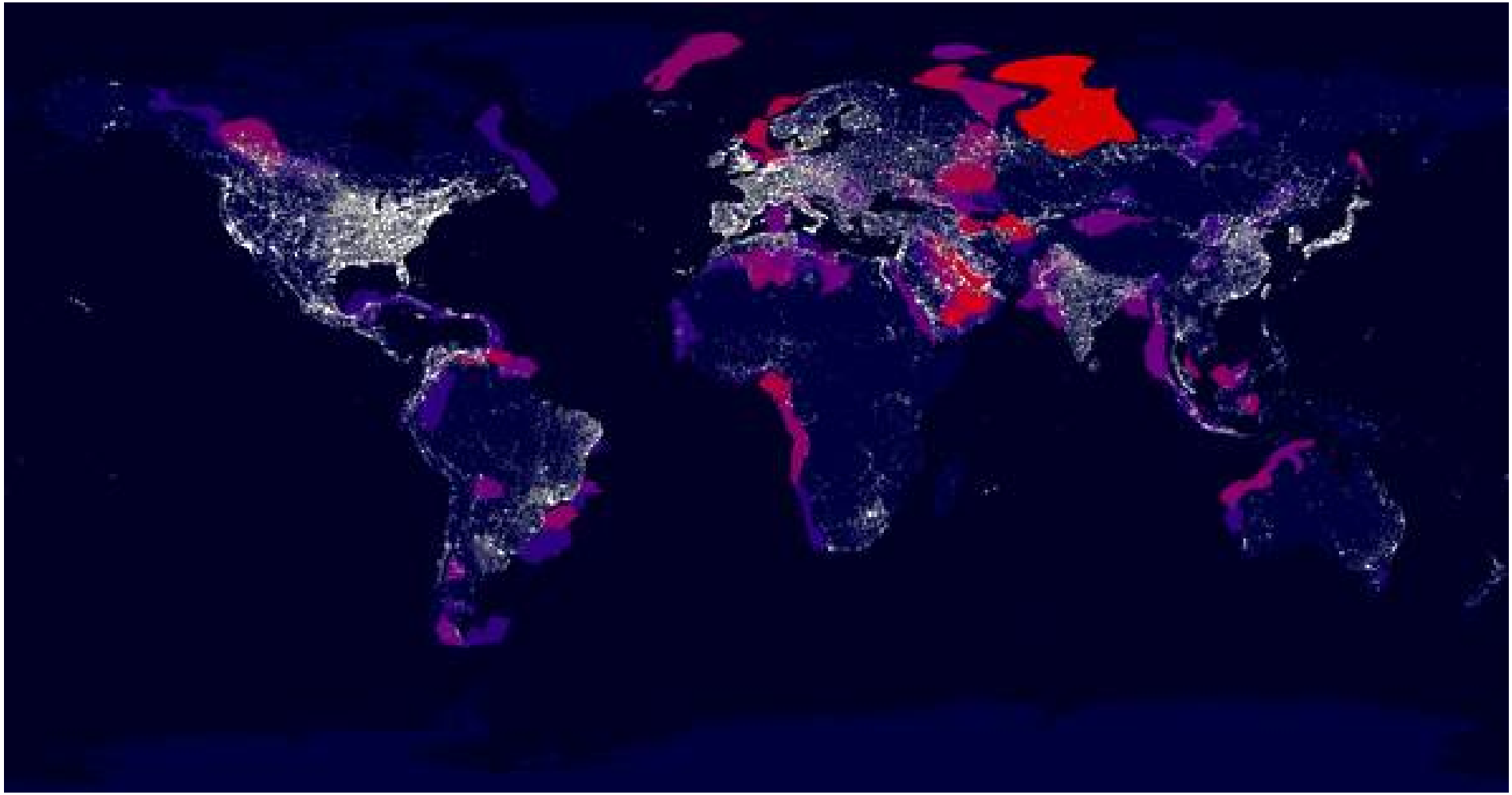
According to the USGS, global natural gas supply potential is large, but…



… supplying markets will require substantial infrastructure investment.

Modeling a Global Gas Market: The RWGTM

- The Rice World Gas Trade Model (RWGTM) has been developed to examine potential futures for global natural gas, and to quantify the impacts of geopolitical influences on the development of a global natural gas market.
- The model predicts regional prices, regional supplies and demands and inter-regional flows.
- Regions are defined at the country and sub-country level, with extensive representation of transportation infrastructure
- The model is non-stochastic, but it allows analysis of many different scenarios. Geopolitical influences can alter otherwise economic outcomes
- The model is constructed using the *MarketBuilder* software from Altos
  - Dynamic spatial general equilibrium linked through time by Hotelling-type optimization of resource extraction
  - Capacity expansion is determined by current *and* future prices along with capital costs of expansion, operating and maintenance costs of new and existing capacity, and revenues resulting from future outputs and prices.

Projections when Uncertainty Abounds

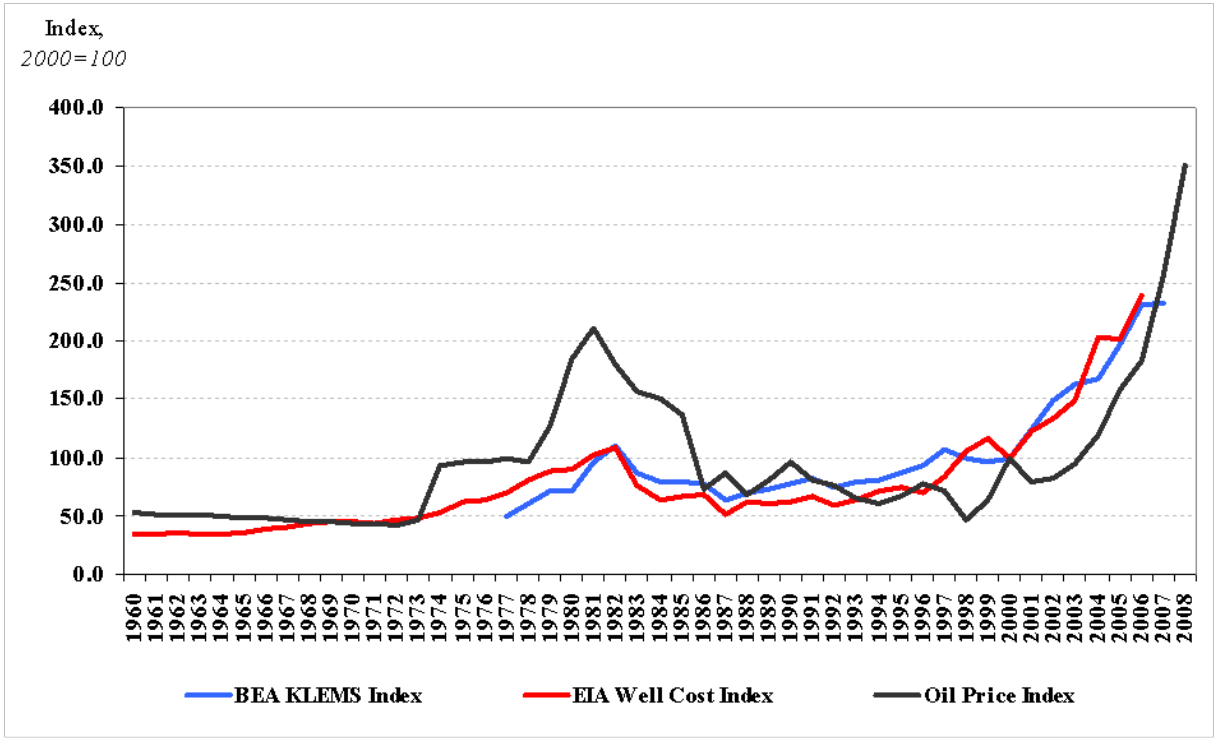
- The RWGTM has many variable inputs each with a different range of uncertainty.
- As such, probabilities are not easily attached to any projected outcome.
- Nevertheless, the model allows analysis of many different scenarios.
- The primary value of forecasting is not in the point estimate. Rather, the benefit of the exercise is, in many ways, the exercise itself. Understanding the influence of variables on a predicted outcome is important when
  - (a) forming policy
  - (b) planning long term capital investments
- Furthermore, understanding the sources of uncertainty is extremely valuable. It helps to explain the path traveled, which helps to guide public and corporate decision-makers when navigating potential futures.
- Long run forecasts are most heavily influenced by supply-side and technology assumptions, and accounting for economic growth.
  - Resource assessments and costs determine prices and patterns of trade.
  - Appropriate accounting of economic growth allows for “emerging nations”.
- Short run forecasts are most heavily influenced by demand-side factors.
  - Capital is deployed, so near term production is largely determined.
  - Assumptions about economic activity.

RWGTM: Supply

- Over 140 regions globally
- Natural gas resources are represented as…
  - associated and unassociated natural gas resources,
  - Conventional, CBM and shale deposits in North America and Australia, and
  - conventional gas deposits in the rest of the world
- … in three categories
  - proved reserves (updated 2006 Oil & Gas Journal estimates)
  - growth in known reserves (P-50 USGS estimates and NPC estimates)
  - undiscovered resource (P-50 USGS estimates and NPC estimates)
- North American cost-of-supply estimates are econometrically related to play-level geologic characteristics and applied globally to generate costs for all regions of the world.
  - Long run costs increase with depletion.
  - Short run adjustment costs limit the “rush to drill” phenomenon.
  - We allow technological change to reduce mining costs longer term.
- Costs are benchmarked against an index tied to hydrocarbon prices.

RWGTM: Supply (cont.)

- Development costs tend to move with hydrocarbon prices. Thus, long term *a priori* views should be tested in order to understand the effect of changes.



- Implication: A project in 1998 was roughly 2.5 times more expensive in 2007, even though nothing else about the project changed.

RWGTM: Supply (cont.)

- Supply is distributed by major basin throughout the world.
- An example, supply regions in North America…

RWGTM Supply Regions

United States (56 regions)

Appalachian Basin – Kentucky, New York, Pennsylvania, Ohio, Virginia, West Virginia
Gulf Coast Onshore – Alabama, Mississippi, Florida, Louisiana (North, South), Texas (Railroad Districts 1-6)
Gulf of Mexico Offshore – Texas, Louisiana, Alabama
Michigan Basin – Michigan
Midcontinent – Arkansas, Oklahoma, Texas (Railroad Districts 7B, 9, 10)
Permian Basin – New Mexico, Texas (Railroad Commission Districts 8, 8A, 7C)
Rocky Mountains – Colorado (Piceance, Denver, Raton), Wyoming (Powder River, Southwestern, Green River, Wind River), Utah (Uinta, Eastern Great Basin), Montana, North Dakota
San Juan Basin – Colorado, New Mexico

Canada (6 regions)

Western Canadian Sedimentary Basin – Alberta, British Columbia, Saskatchewan
Arctic Canada
Eastern Canada – Ontario, Eastern Canada Offshore

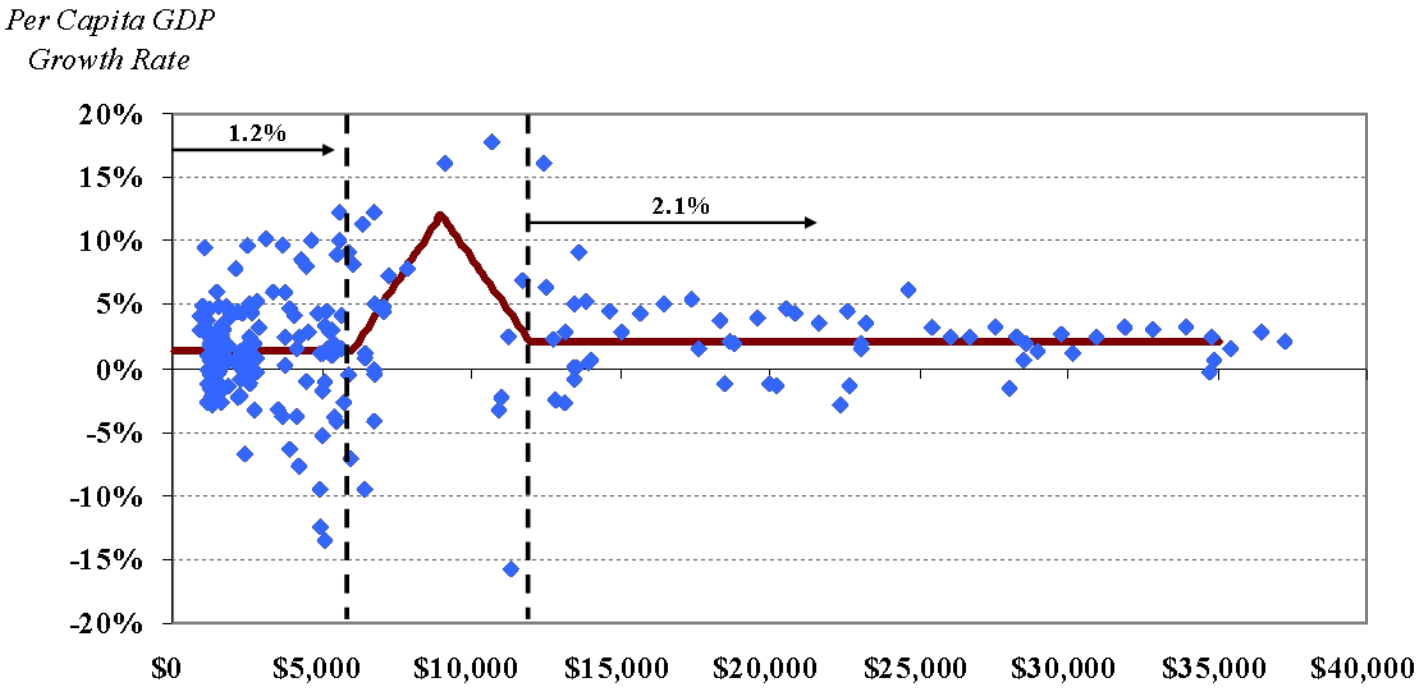
Mexico (2 regions)

RWGTM: Demand

- US demand is modeled by sector
  - Power demand determined by own price, cross price, total electricity demand, installed capacity, weather and hydro generation
  - Residential and Commercial demand determined by population, income, own price, cross price and weather
  - Industrial demand determined by industrial production, own price, and cross price
- RoW demand is determined by a system in which
  - … economic growth is based on conditional convergence to historical US growth rates at various levels of per capita income.
  - … energy intensity declines as income rises.
  - … the natural gas share of total energy increases with income, but declines with relative price increases.
  - Demand is modeled as 2 sectors (direct use and power) where data is available.
- Demand can be lost to IGCC from 2010 and other new technologies from 2020
  - Demand lost to coal gasification is concentrated in large coal producing countries and is limited to electricity generation
  - After 2020, the proportion of demand vulnerable to a backstop above $7/MMBtu increases until in 2055 all reference case demand could be satisfied at a price of $10

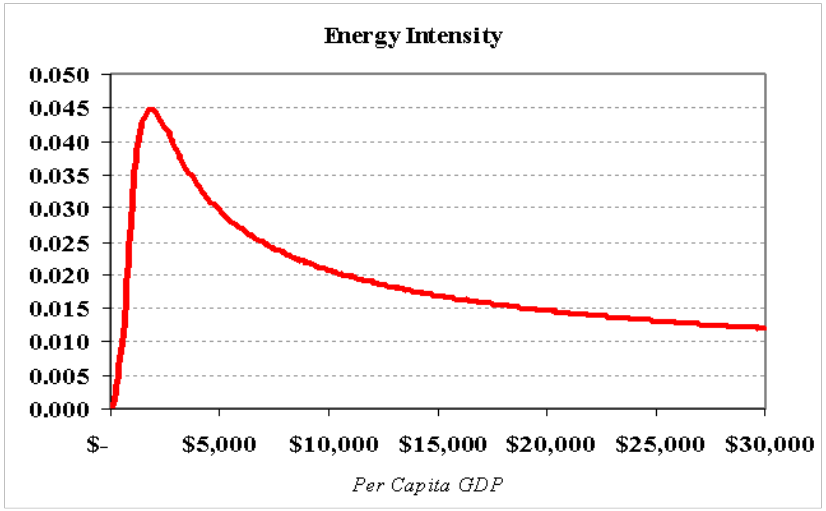
RWGTM: Demand (cont.)

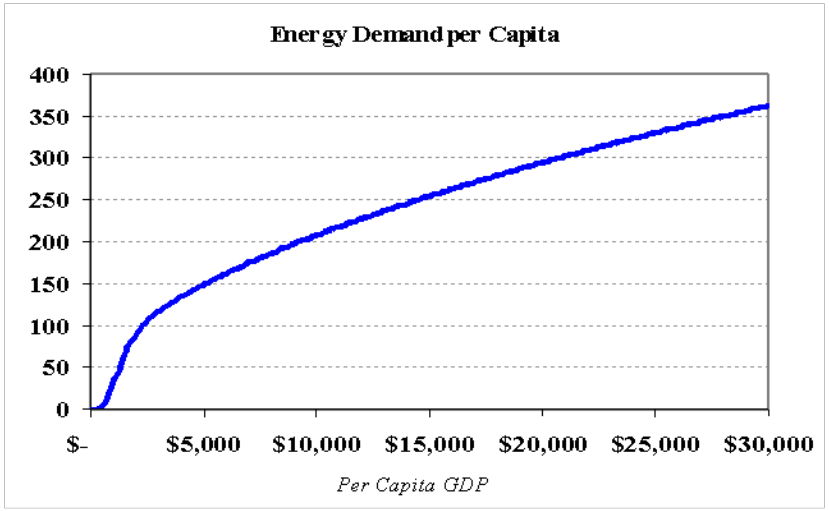
- Economic growth is based on conditional convergence to historical US growth rates at various levels of per capita income. The reference path is estimated using a piecewise linear spline knot regression. Various knots were tested, and 3 knots were ultimately used



RWGTM: Demand (cont.)

- Energy intensity falls as income rises (see Medlock and Soligo, *EJ* 2001)
  - Estimated using dynamic panel regression (70 countries)
    - $\ln(E/Y)_{t,i} = a_{0,i} + a_1 * \ln(Y/POP)_{t,i} + a_2 * \ln(P)_{t,i} + a_3 * \ln(E/Y)_{t-1,i}$





- The natural gas share of total energy is bound between 0 and 1.
  - Dynamic panel regression (29 countries).
  - Share is positively influenced by increased development, reflecting natural gas as a premium fuel and trends toward electrification.
  - Share is negatively influenced by relative price increases, but price elasticity falls as natural gas share rises reflecting rigidities of installed capital.

RWGTM: Demand (cont.)

- Over 300 regions
- Demand is modeled as "direct use" and "gas for power" where data is available. In the US, demand is modeled as residential, commercial, industrial and power.
- Regions are defined at the country and sub-country level. A snapshot of the regional detail in the current version of the RWGTM is provided in the table to the right.

RWGTM Demand Regions

Africa (11 regions)
- 1 demand region – Algeria*, Egypt*, Libya, Morocco, Tunisia, Angola, Nigeria, East Africa (Sudan/Ethiopia/Somalia/Kenya/Uganda/Tanzania), Southern Africa (South Africa/Namibia/Mozambique/Botswana), West Central Coast Africa (Cameroon/Equatorial Guinea/Gabon/Congo), Northwest Africa (Other Africa)

Asia (18 regions)
- 1 demand region – Vietnam/Laos/Cambodia, Afghanistan, Bangladesh, Myanmar, Pakistan*, Thailand*
- 4 demand regions – India*
- 8 demand regions – China*

Asia-Pacific (20 regions)
- 1 demand region – Brunei, Philippines*, Singapore, Taiwan
- 2 demand regions – South Korea*, Malaysia*
- 5 demand regions – Indonesia*
- 7 demand regions – Japan*

Australasia (13 regions)
- 1 demand region – New Zealand*, Papua New Guinea
- 11 demand regions – Australia*

Europe (57 regions)
- 1 demand region – Balkans, Bulgaria, Czech Republic*, Denmark*, Finland*, Greece*, Hungary*, Ireland*, Luxembourg, Norway*, Portugal*, Romania, Slovakia*, Sweden*, Switzerland*
- 2 demand regions – Netherlands*, Poland*
- 3 demand regions – Austria*
- 4 demand regions – United Kingdom*
- 5 demand regions – Belgium*, Italy*
- 6 demand regions – France*
- 7 demand regions – Spain*
- 8 demand regions – Germany*

FSU (11 regions)
- 1 demand region – Armenia, Azerbaijan, Belarus, Estonia, Latvia, Lithuania, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Tajikistan, Turkmenistan, Uzbekistan
- 3 demand regions – Ukraine
- 7 demand regions – Russia

Middle East (17 regions)
- 1 demand region – Bahrain, Iraq, Israel*, Jordan, Kuwait, Oman, Qatar, Syria*, UAE, Yemen
- 2 demand regions – Iran, Saudi Arabia*
- 3 demand regions – Turkey*

North America (116 regions)
- 8 demand regions – Canada*, Mexico*
- 100 demand regions – United States**

South and Central America (19 regions)
- 1 demand region – Central America, Other Caribbean, Suriname/Guyana/French Guiana, Cuba, Bolivia*, Colombia*, Ecuador, Paraguay, Peru*, Trinidad & Tobago*, Uruguay*, Venezuela*
- 2 demand regions – Brazil*, Chile*
- 3 demand regions – Argentina*

* - natural gas demand modeled as direct use and power generation
** - natural gas demand modeled as residential, commercial, industrial and power generation

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RWGTM: Pipelines

- To facilitate calculations of optimal capacity expansions
  - Supplies and demands are aggregated into discrete "nodes"
  - Existing parallel pipes are aggregated into a single link
    - The US pipeline architecture is based on EIA data and data provided for the NPC study released in 2003
    - The European pipeline architecture was based on data provided by *Gas Strategies*
  - We allow for many *potential* pipelines
    - Routes discussed in the press or trade publications
    - Routes that appear profitable at prices calculated in initial iterations
- Pipeline costs are split into fixed and variable costs
  - Fixed costs are based on a regression analysis of EIA cost data (annual cost per unit of capacity) for over 100 pipeline projects from 2002-2005
    - Determinants are pipeline length, pipeline capacity, and whether routes cross mountains, water or populous areas
  - Variable costs – FERC filed rates in the US and a calculated tariff based on a rate of return recovery almost everywhere else, unless specific rate information is available.

RWGTM: LNG

- We represent LNG routes primarily by "hubs and spokes"
  - Process vetted via industry review
  - This allows for many potential trading partners while keeping the number of alternative routes under control
  - Shipping distances were obtained from a publication of the National Imagery and Mapping Agency
  - Contracts can be modeled, but we typically do not
- LNG costs were based on various industry sources
  - Shipping costs are represented as lease rates per unit distance
  - Liquefaction costs are represented as fixed costs plus variable costs
  - Regasification costs are represented as fixed costs (which vary by location primarily due to land cost) and variable costs
  - Allow technological change to reduce LNG costs at rates based on a statistical fit to the IEA *World Energy Investment Outlook*

The RWGTM (cont.)

- Required return on investment varies by region and type of project (using ICRG and World Bank data). This changes with the level of economic development reflecting a declining risk premium.
- Detailed transportation network
- For all capital investments in both the upstream and midstream, we allow for existing and potential pipeline links, then "let the model decide" optimal current and future capacity utilization.
- Typically compare a constrained outcome to the "reference case" in order to quantify the effect of the constraint (which is typically geopolitical).
  - Our reference case is not necessarily our "view" of the world.
  - Any single forecast must consider various constraints in global gas market.
- More information is available in Peter Hartley and Kenneth B Medlock III, "The Baker Institute World Gas Trade Model" in *The Geopolitics of Natural Gas*, ed. Jaffe, Amy, David Victor and Mark Hayes, Cambridge University Press (2006).

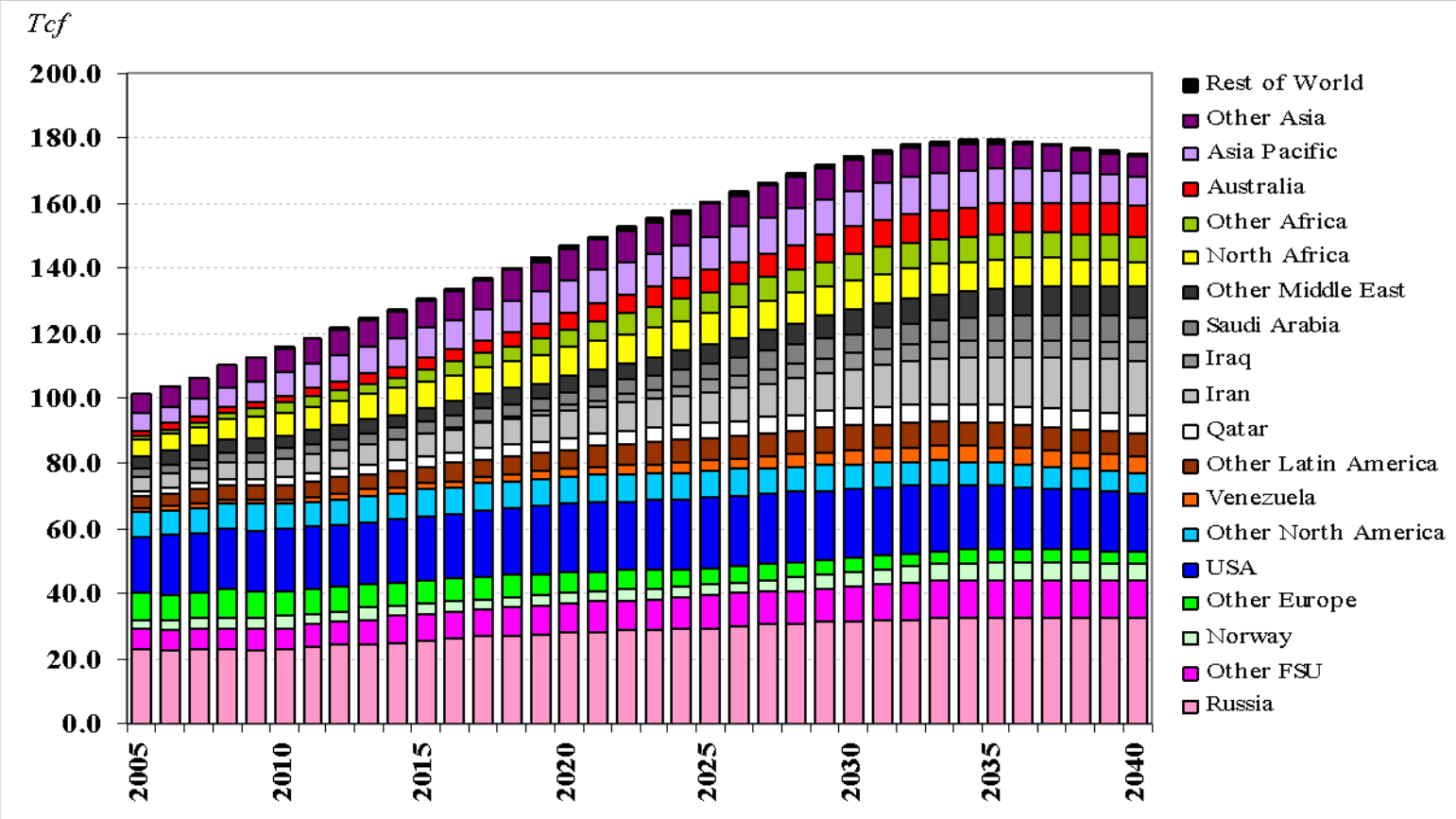
Some Examples of BIPP Studies involving the RWGTM

- Drilling Access restrictions
  - Relaxation renders Alaska PL uneconomic for an additional 10 years.
  - Relaxation pushes need for substantial LNG increases out 10 years.
- Options for Russian gas
  - Most significant source of long term competition for European market is Iraq. Location of resource and size of domestic market are key drivers.
  - Short term rents are offset by longer term losses in market share.
  - Substantial growth opportunity to Asia
- Turkey as an international gas hub
  - Remains a demand sink until 2020s. Iraqi gas development is key.
- Energy Modeling Forum Study 23
  - Study looks at various constraints on global market development to understand the manner in which markets may evolve. Special Issue of the *Energy Journal* released earlier this year.
- Effect of Carbon Constraints
  - Positive carbon prices tends to favor increased gas demand.
  - Biggest global winner in a gas-favored outcome is Iran.

Select Reference Case Results

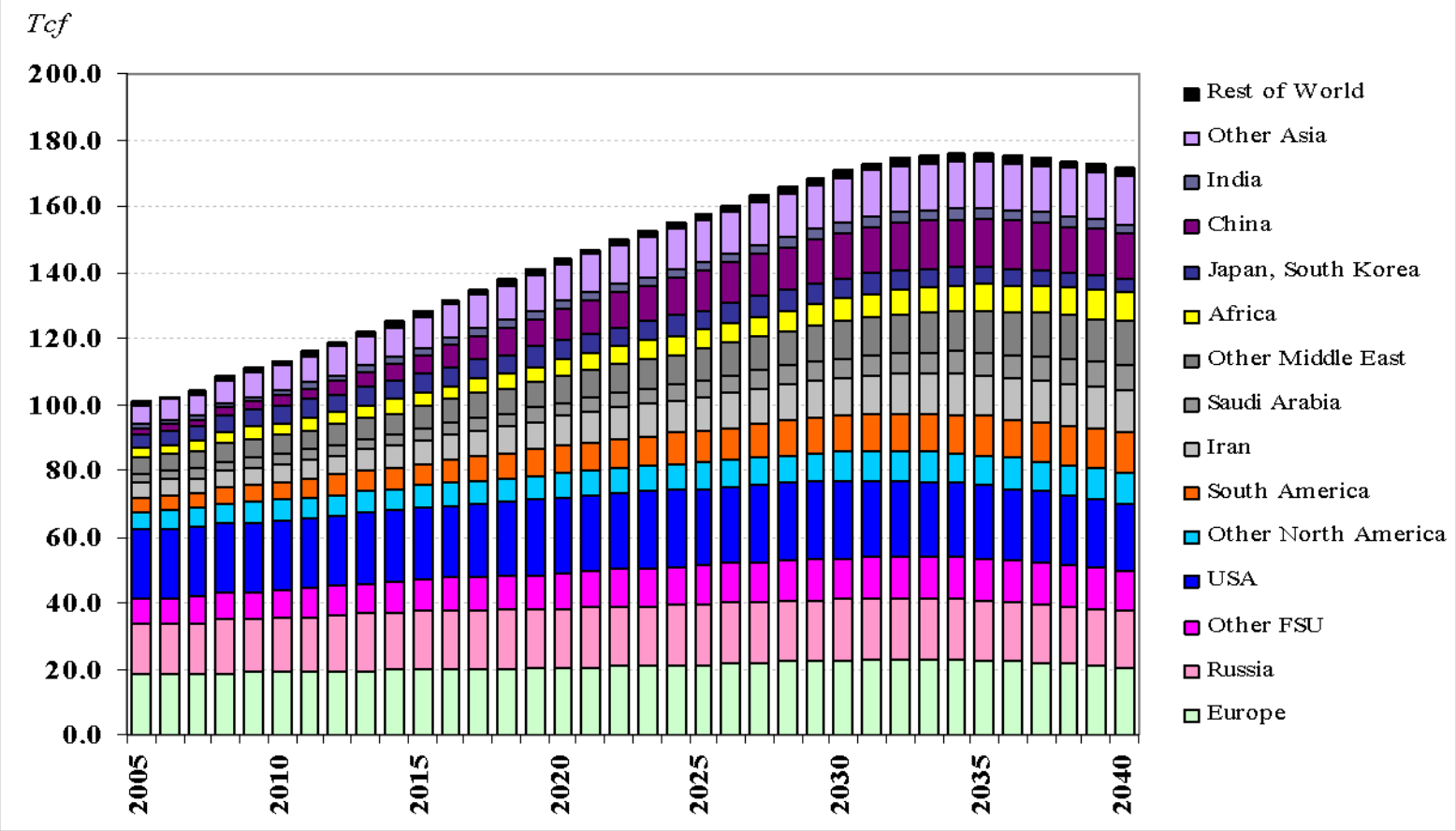
Reference Case

- The Reference Case allows commercial considerations to dominate outcomes.
- Supply
  - Substantial growth from the Middle East and the FSU
  - Declines in Europe and near term growth in US driven by shale



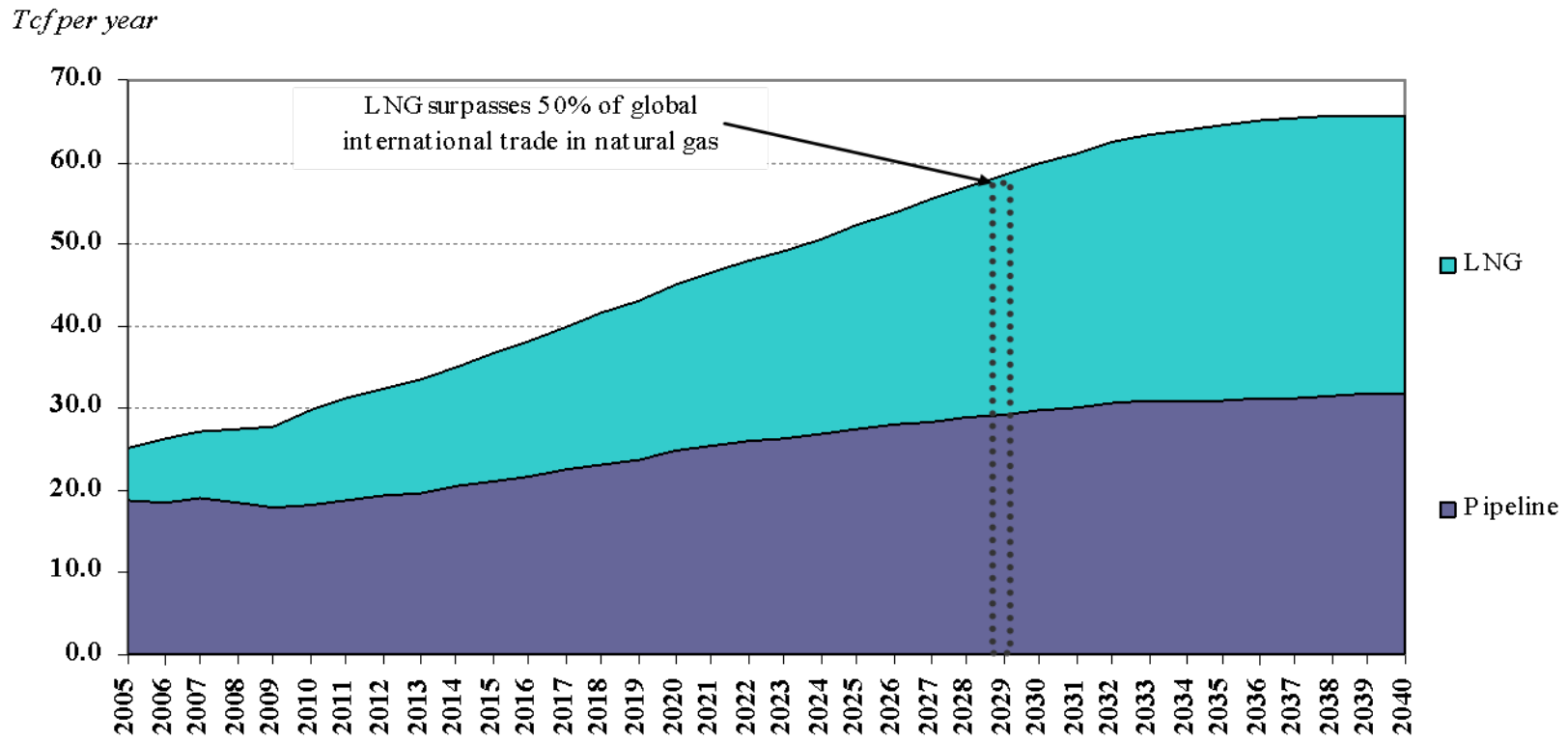
Reference Case (cont.)

- Demand
  - Strongest growth in developing Asia, but regional demands increase everywhere.
  - Demand growth abates post 2030 due to emergence of alternatives.



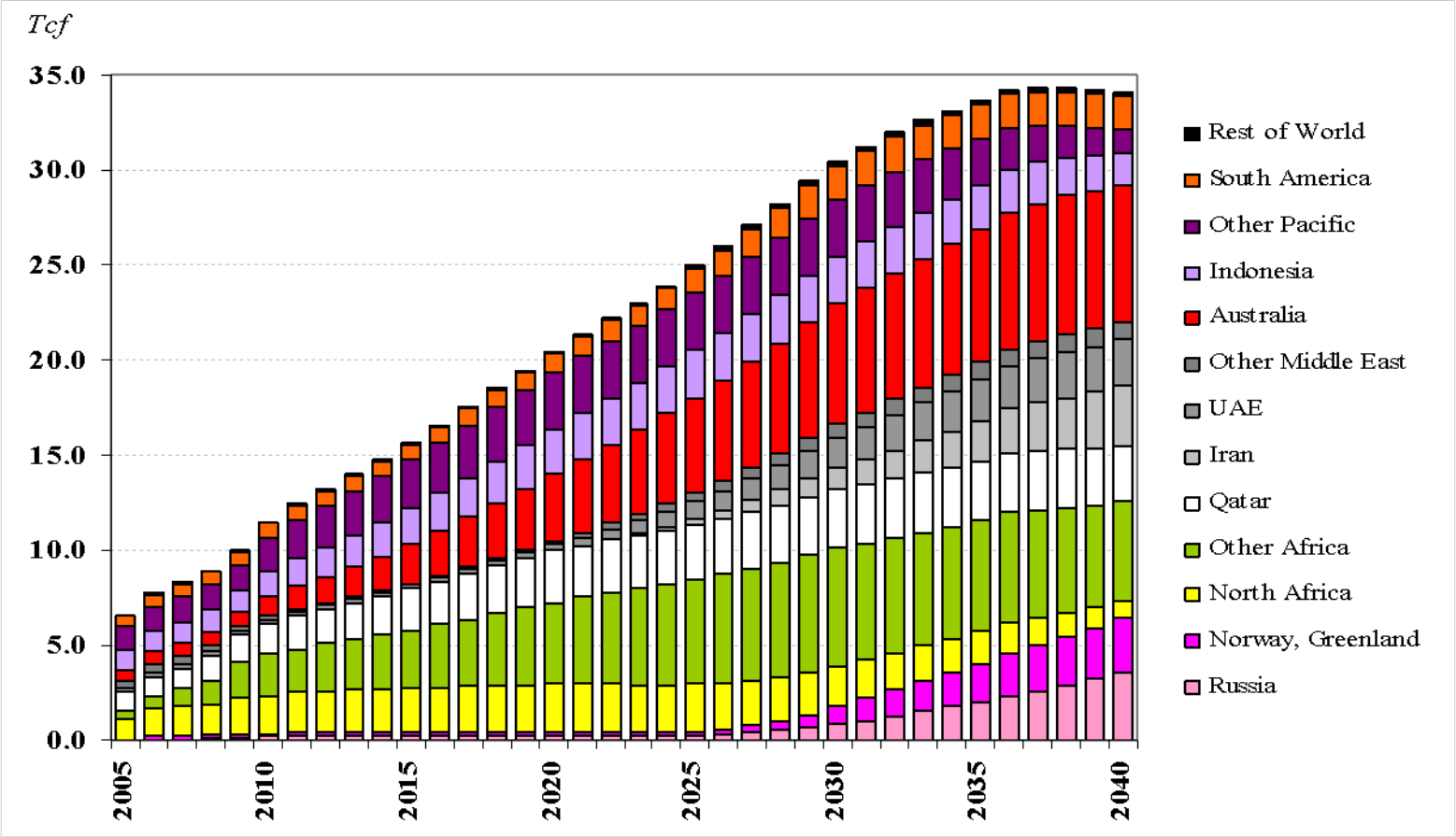
Global Gas Trade: LNG vs. Pipeline

- Geology and geography dictate the LNG trade ultimately dominates the international gas trade. In fact, it reaches about 50% of total international natural gas trade by the late 2020s.
  - This date moves under different scenarios, but the pace of growth in LNG is generally stronger than pipeline trade.



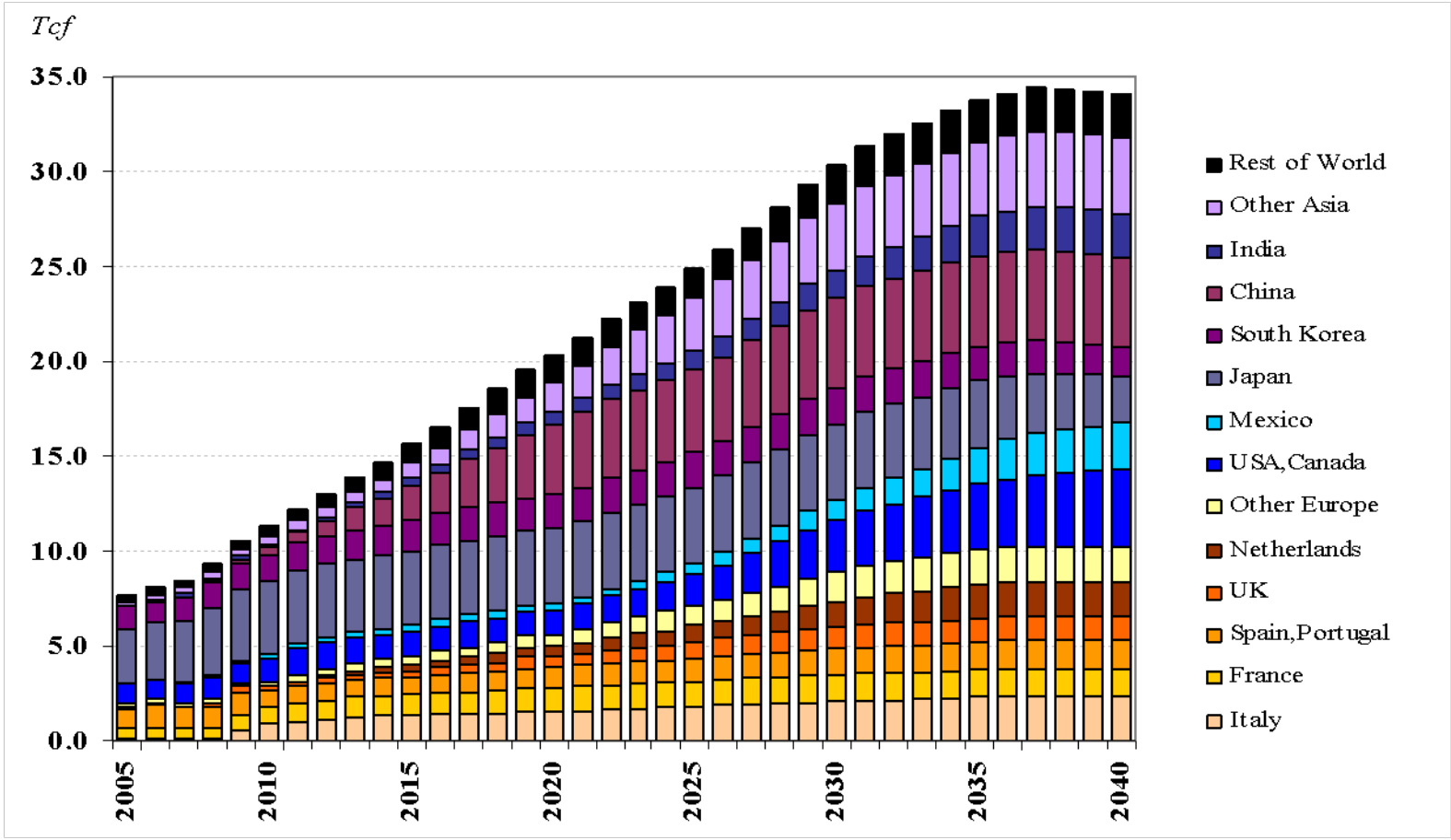
Reference Case (cont.)

- LNG Exports
  - Substantial growth from the Middle East and Australia



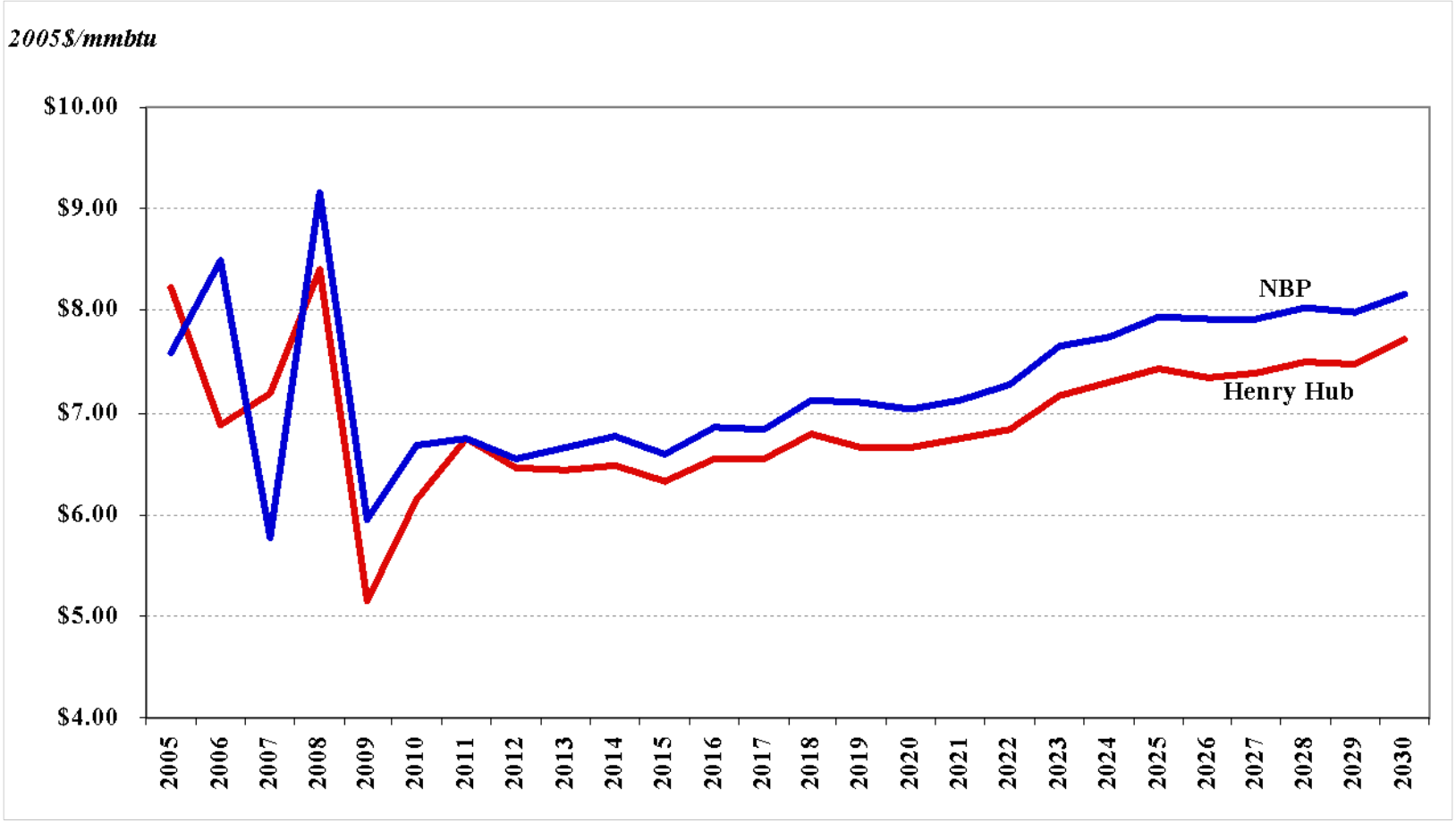
Reference Case (cont.)

- LNG Imports
  - Substantial growth In Europe and Asia throughout time horizon.
  - Late growth in North America and demand outstrips domestic production, but there is little change through early 2020s.



Selected Regional Natural Gas Prices

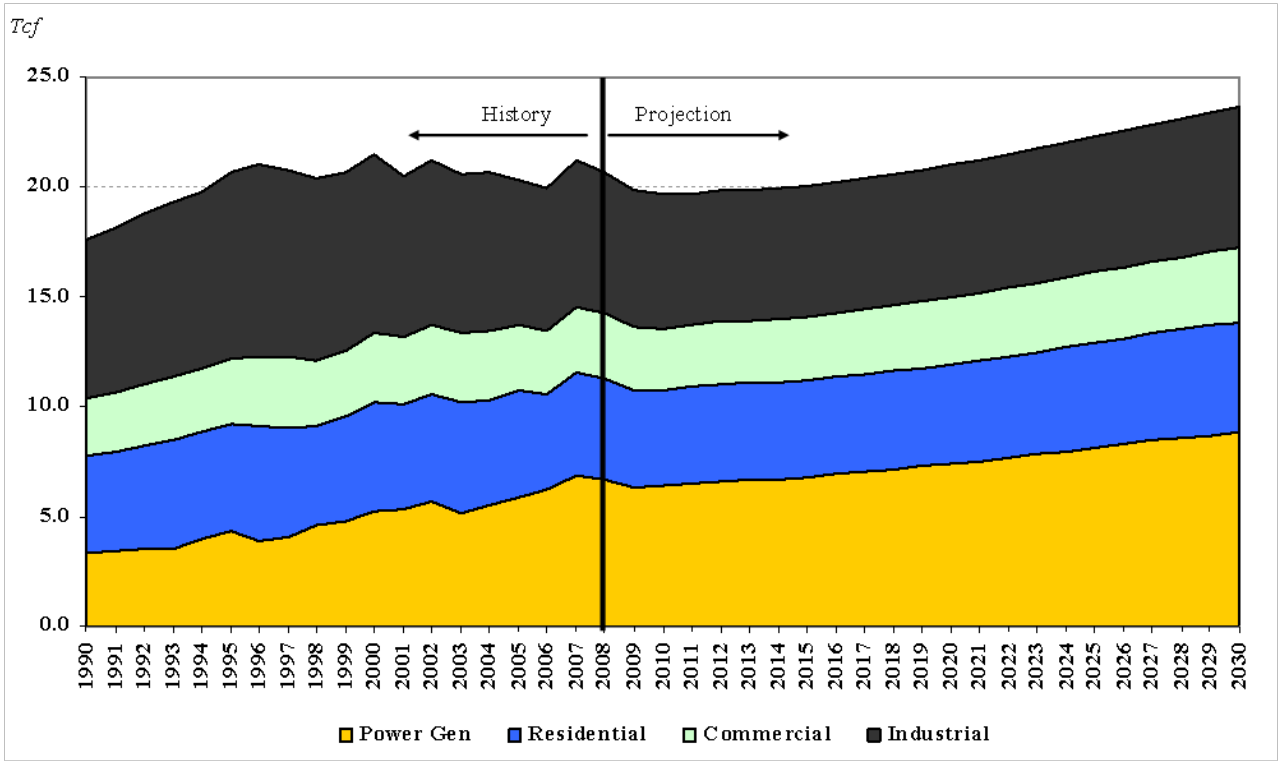
- Increased trade leads to price differentials that reflect transport differentials
- Longer term prices at Henry Hub (averages)
  - 2010-2020: $ 6.52 2021-2030: $ 7.29



North America in Focus

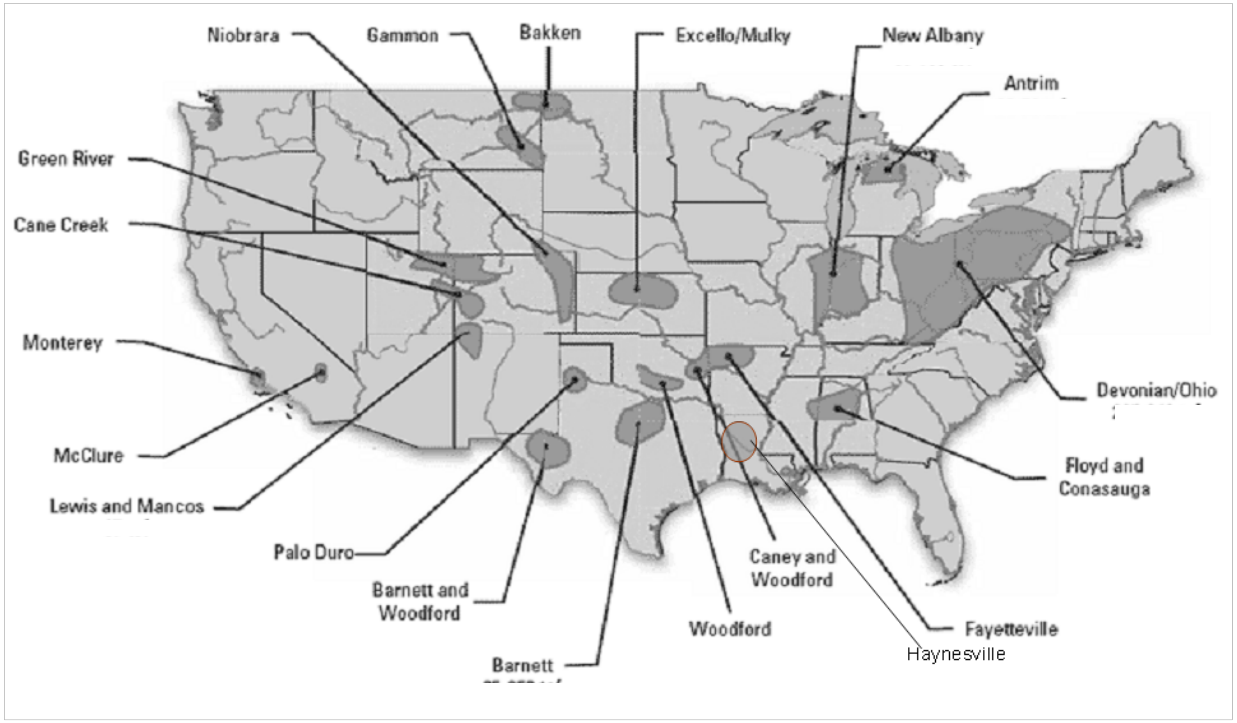
Demand: U.S.

- Demand growth strongest in the power generation sector.
  - Industrial Sector (2008-2030): -0.03% pa
  - Residential Sector (2008-2030): 0.35% pa
  - Commercial Sector (2008-2030): 0.63% pa
  - Power Sector (2008-2030): 1.29% pa
    - Note: CO2 Constrained Cases push growth to 3.03% pa, with a minor offset in industry.



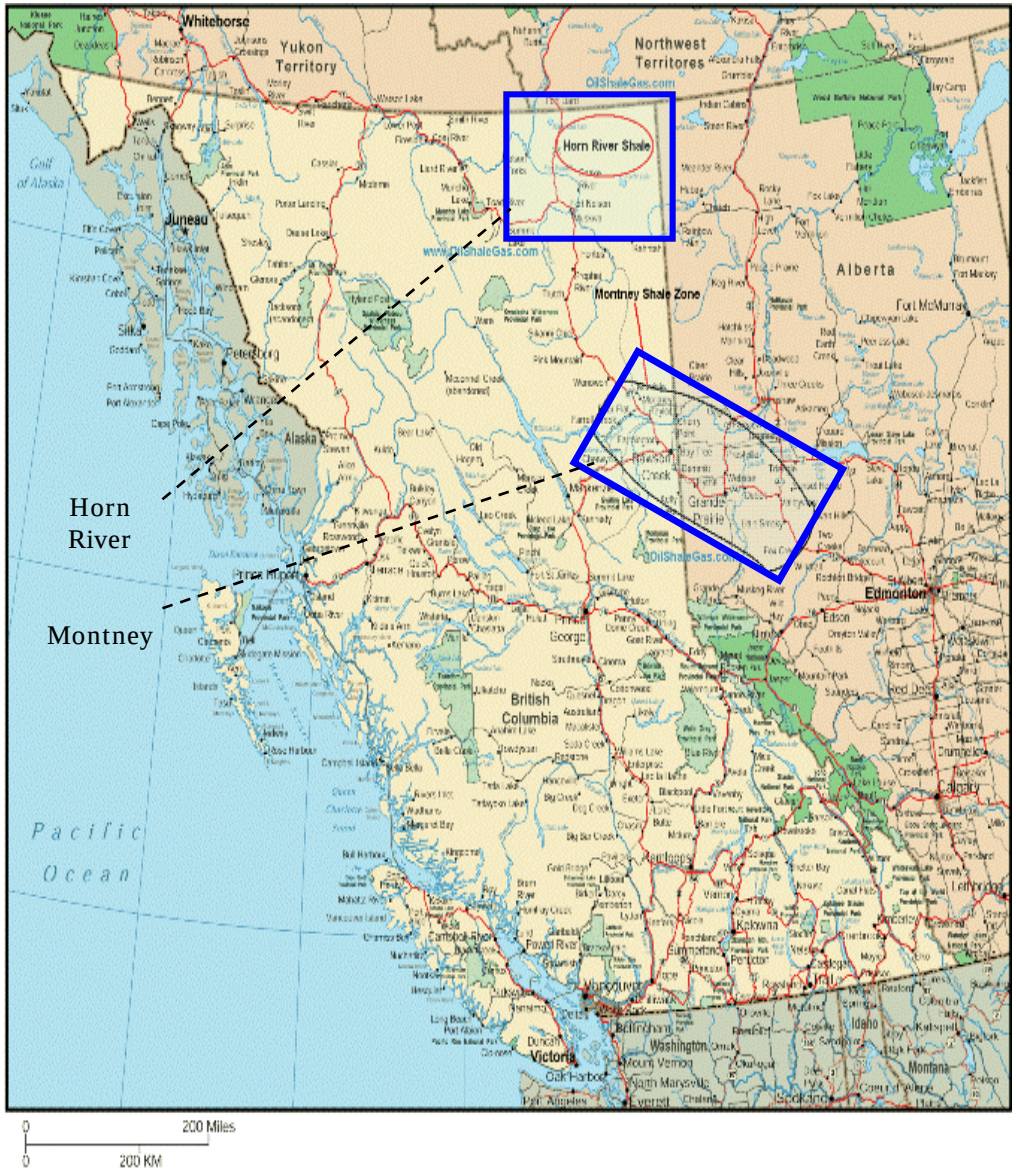
Supply: Developments in Shale Gas

- Very active area of exploration and development
  - Assessments indicates 125-840 tcf of technically recoverable shale gas
    - EIA AEO2008 is at the low end (125 tcf) with PGC2006 very close (131 tcf).
      - *Do not* include Canada (Montney, Horn River, Utica).
    - NCI2008 high case is among the higher assessments (840 tcf)
    - These are all *technically* recoverable estimates. Thus, costs may be an impediment.
      - Breakeven estimated at roughly $7/mcf in most plays. Favors Appalachian developments.
  - Various studies are ongoing.



Supply: Developments in Shale Gas (cont.)

- Shale plays in Canada are also being developed.
- Most active areas are in the Horn River and Montney plays in BC and Alberta.
- Supply potential in BC, in particular, has pushed the idea of LNG exports targeting the Asian market
  - Asia is a premium market.
  - Competing projects include pipelines from Russia and the Caspian States, as well as LNG from other locales.
- BC is a basis disadvantaged market, but selling to Asia could provide much more value to developers.
- Utica Shale in Quebec has been compared to the Barnett in Texas, and price is even more favorable.



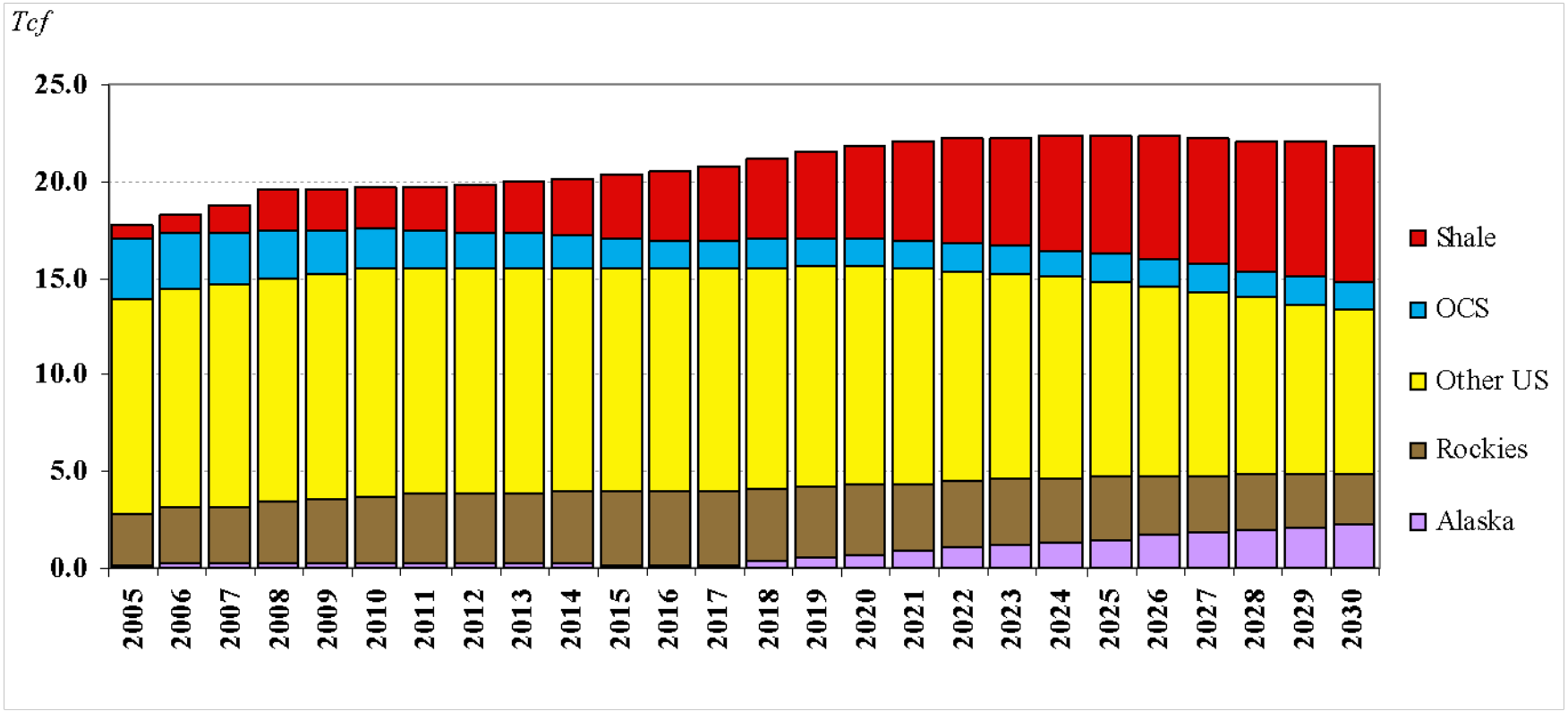
Shale Gas Assessment in the RWGTM

- Economically Recoverable Assessment is smaller
  - Development costs based on the breakeven economics from various consultants
- Assessed volumes could be much larger. As activity progresses, the assessments change.
  - Note: Haynesville and Marcellus shales have been recently modified. Each assessment is larger and separated into multiple costs layers. The total increase is 115.8 tcf. These modifications are not reflected in these results.
- Technology is also a major X-factor that will change both the technically recoverable and economically recoverable assessments.

	Shale Play	Basin	Mean technically recoverable gas
US	Antrim	Michigan Basin	13.2
	Devonian/Ohio	Appalachian Basin	133.4
	Marcellus	Appalachian Basin	100.0
	New Albany	Illinois Basin	3.8
	Floyd/Chatanooga	Black Warrior Basin	2.1
	Haynesville	Gulf Coast Onshore	90.0
	Fayetteville	Arkoma Basin	26.0
	Woodford Arkoma	Arkoma Basin	8.0
	Caney and Woodford	Arkoma Basin	No Data
	Woodford Ardmore	Ardmore Basin	4.2
	Barnett	Fort Worth Basin	26.2
	Barnett and Woodford	Permian Basin	35.4
	Palo Duro	Palo Duro Basin	4.7
	Lewis	San Juan Basin	10.2
	Cane Creek	Paradox Basin	No Data
	Excello/Mulky	Cherokee Platform	No Data
	Bakken	Williston Basin	1.8
	Gammon	Williston Basin	No Data
	Niobrara (incl. Wattenburg)	Denver Basin	1.3
	Hilliard/Baxter/Mancos	SW Wyoming	11.8
	Lewis	SW Wyoming	13.5
	Mowry	SW Wyoming	8.5
	Monterrey/McClure	San Joaquin Basin	No Data
Canada	Horn River	WCSB	49.0
	Montney	WCSB	14.0
	Utica	Quebec	8.0
	Total Shale Gas Assessment		**471.1**

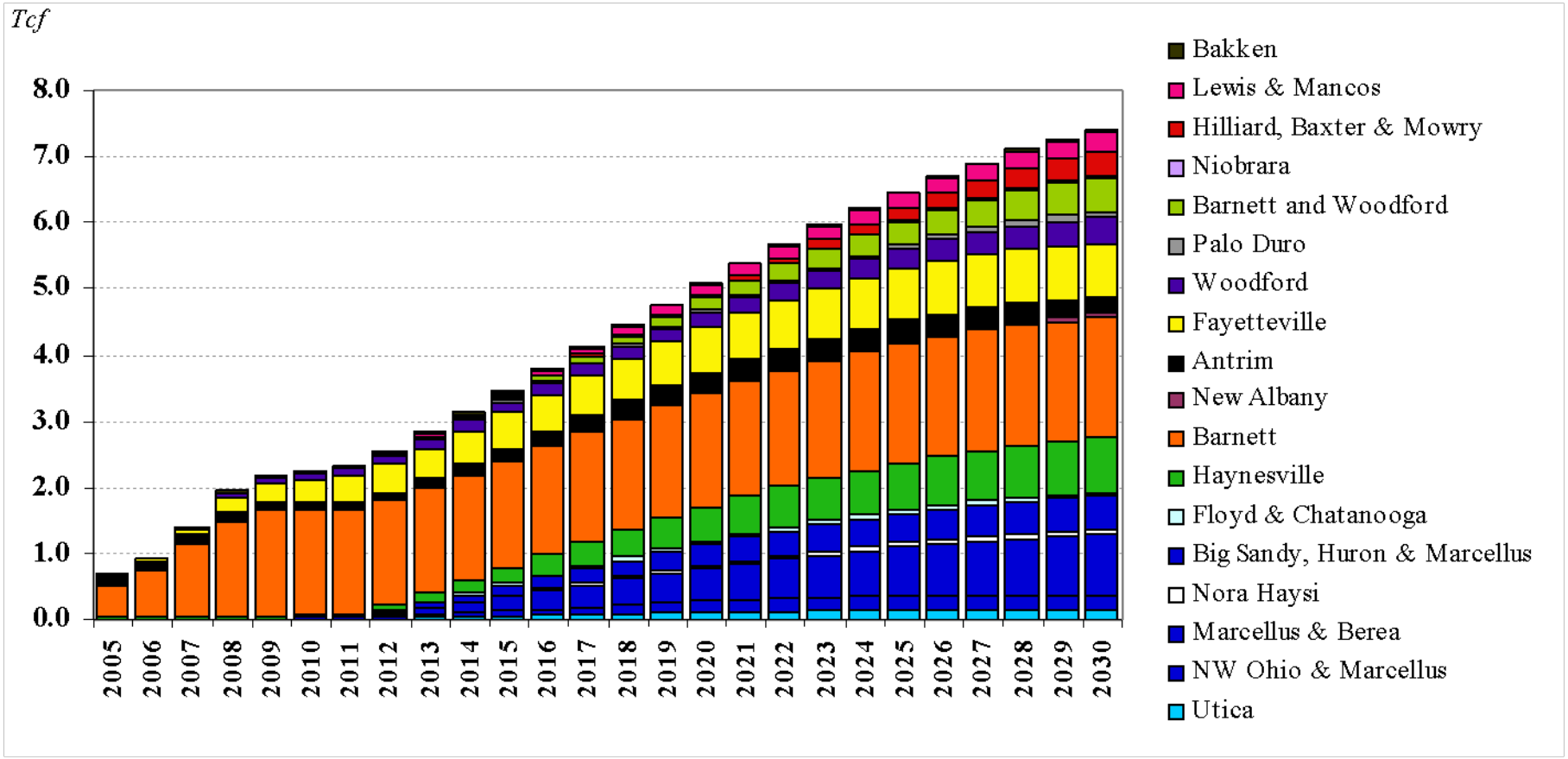
Supply: U.S.

- Growth in U.S. production comes from expansion in shale basins.
- Steady declines in OCS and other regions.
- Medium term growth in Rockies.
- Alaska PL develops early 2020s.



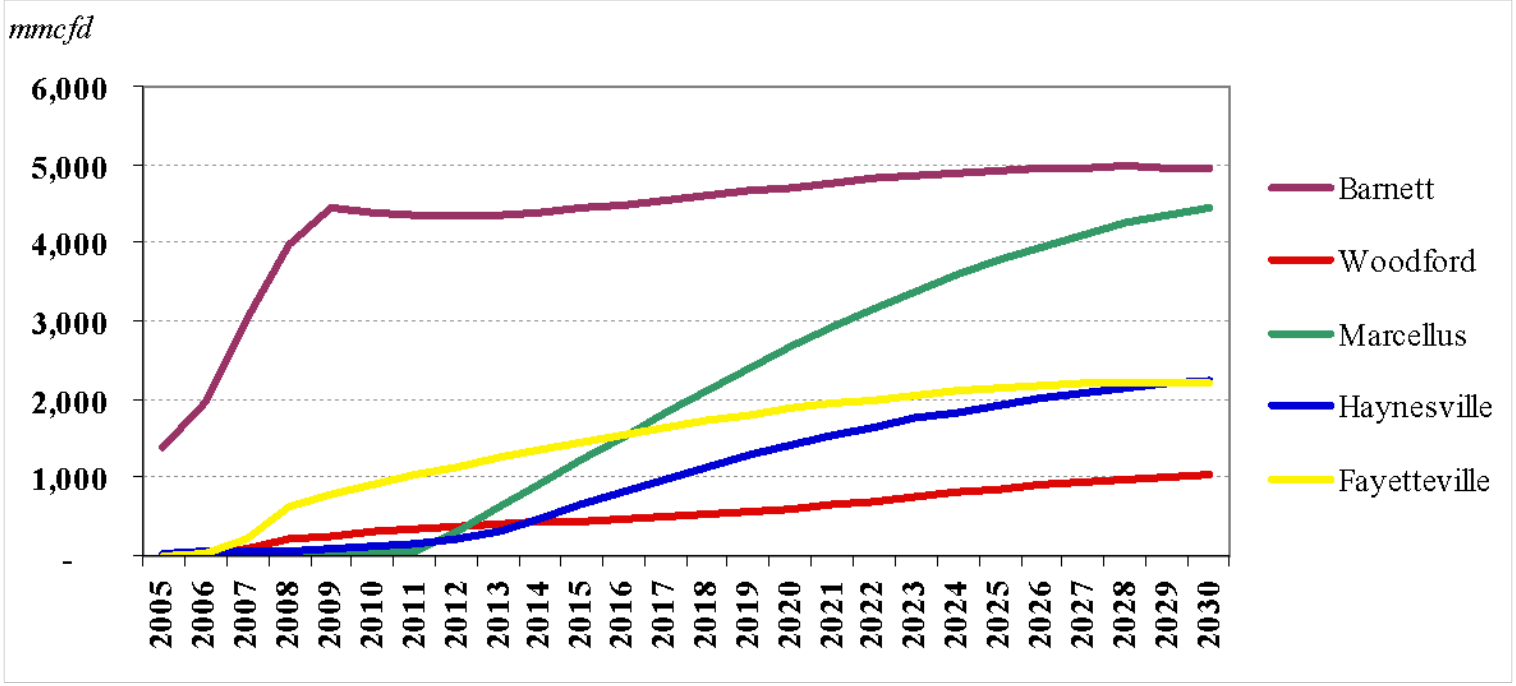
Supply: U.S. (cont.)

- Strongest shale production is in Barnett.
- There is strong growth in the Marcellus, Fayetteville, and Haynesville shales in particular, with modest growth in several others.



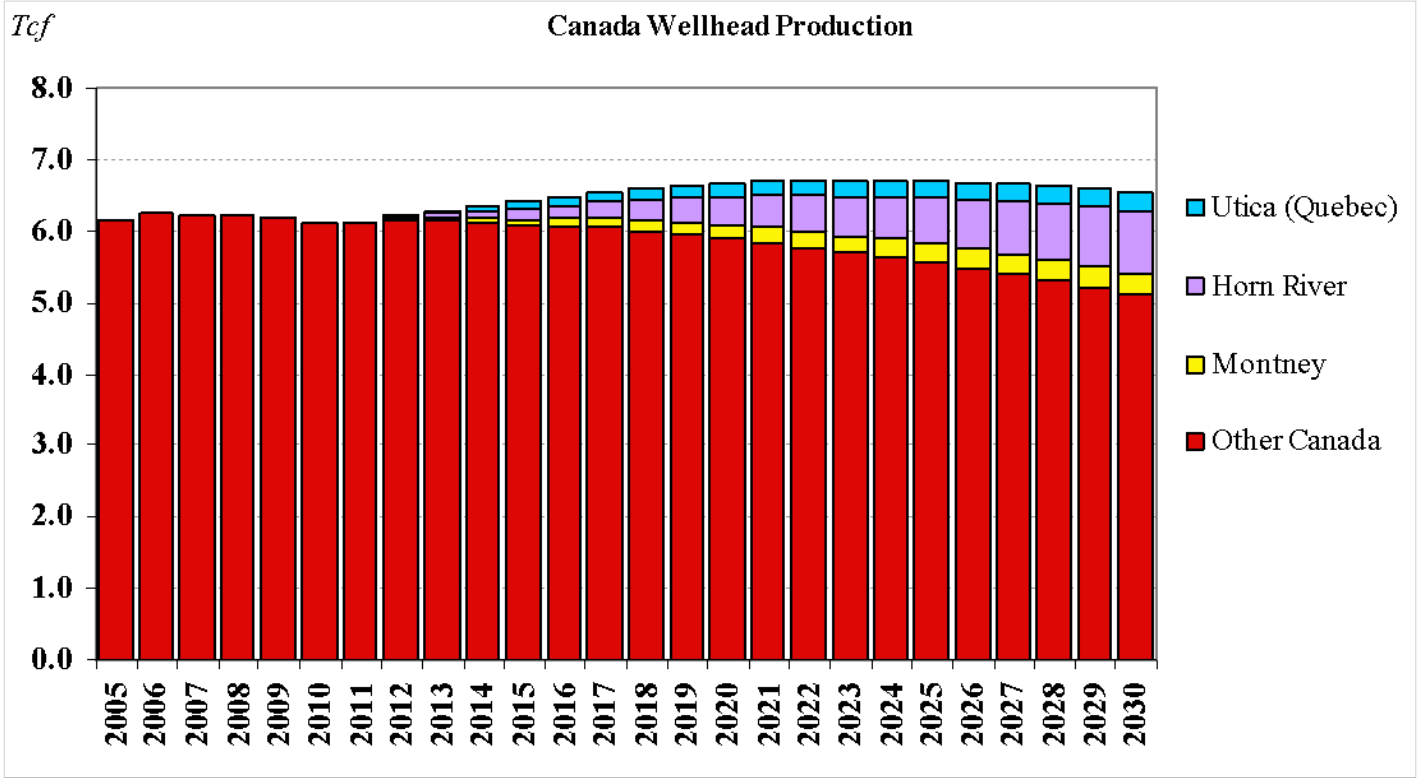
Supply: U.S. (cont.)

- Barnett, Marcellus, Fayetteville, and Haynesville up close.
  - Haynesville and Marcellus shale assessments have been modified – larger size but with multiple cost layers – but this is not reflected in these results.



Supply: Canada

- Growth in Canadian production comes largely from British Columbia in the Horn River Shale. However, the growth does not support LNG exports.
- Overall, shale production in Canada offsets decline in other regions and supports expanded tar sands production.

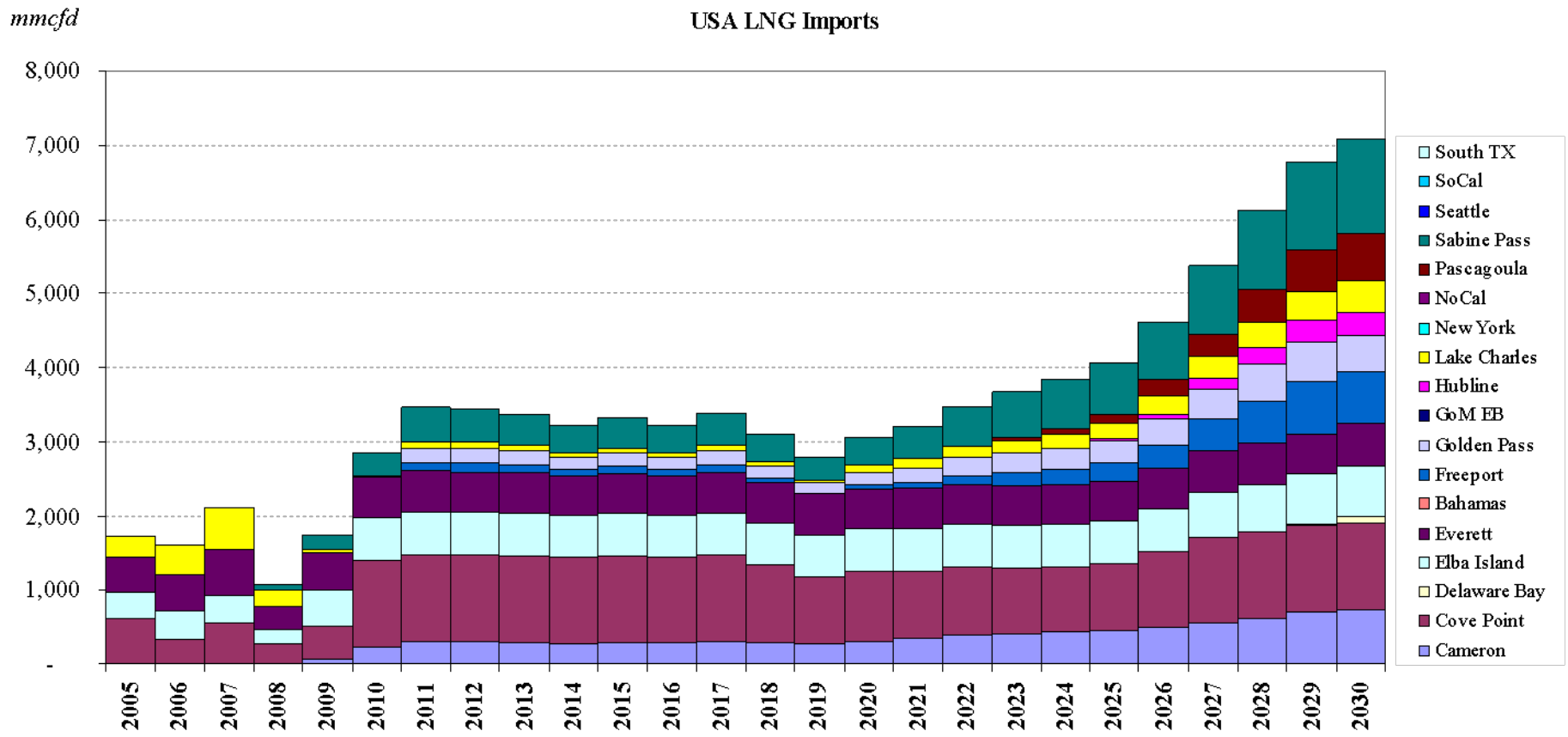


What about LNG?

- The rush to build new import facilities has passed. Nevertheless, capacity has increased substantially in the last few years.
- Lower prices and strong domestic production growth (largely from shale) has left the current regas infrastructure largely unutilized... and it will likely continue to do so.
- Do we repeat the 1970s experience?
  - There are forces pushing stronger demand growth, such as climate policy and energy security concerns
  - Will shale growth be enough to offset these forces and leave the US as a destination of last resort for LNG?
- Modeling at BIPP suggests that shale production could push lower utilization for the next decade, and access to the OCS could extend that period for several years. Nevertheless, LNG imports will rise, gradually at first, then much more aggressively.
  - A large influence on utilization is the pace at which alternatives take market.
  - The effect of CO2 regulation on demand is also very important.
  - Regas capacity, which represents 10-20% of the value chain cost, provides a real option to LNG developers.

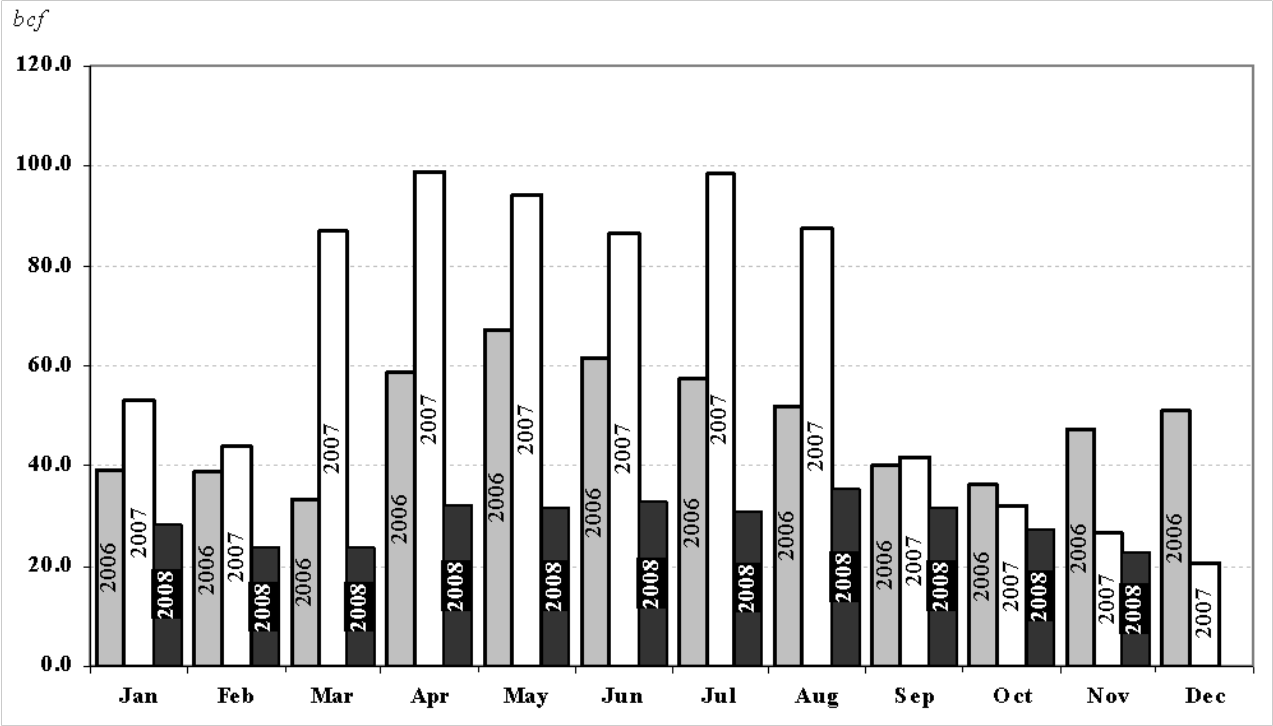
LNG Imports to the US

- Growth out of 2008 but stagnant from 2011-early 2020s. Low annual load factors on LNG regas facilities.



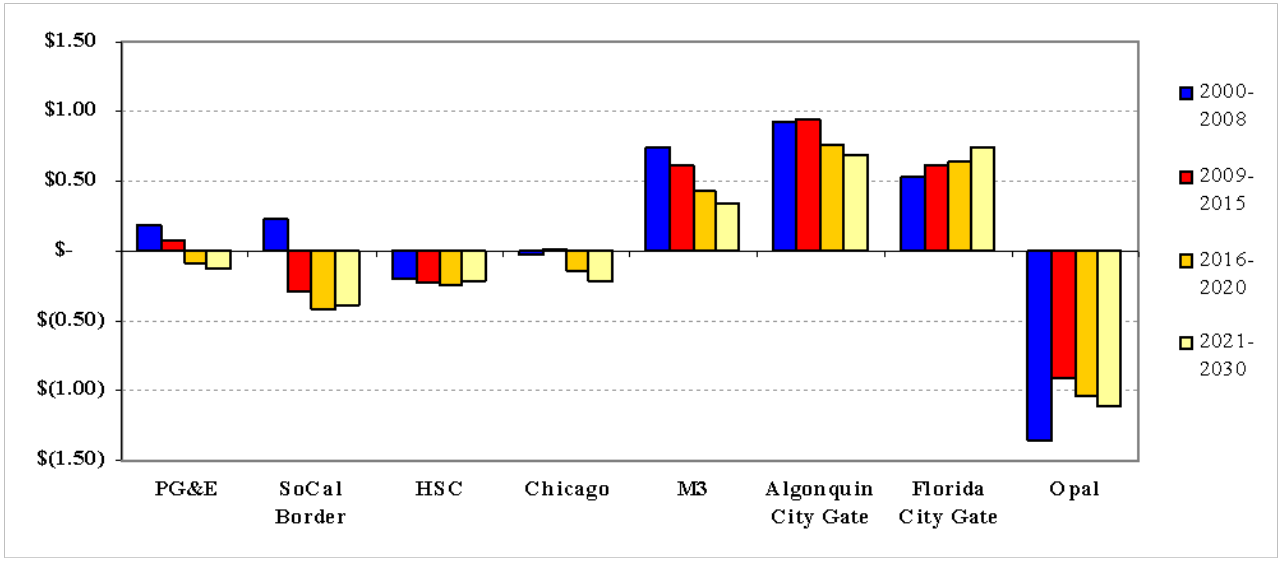
A Comment on Seasonal LNG Imports to the US

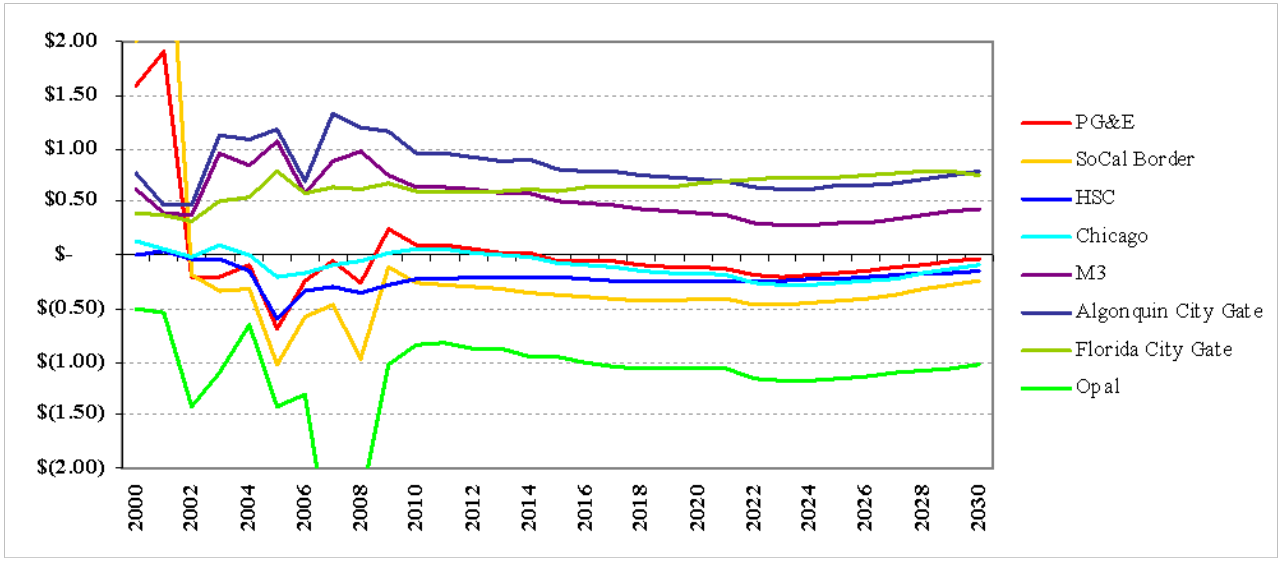
- The next three to five years will be interesting…
- LNG deliveries to the US have shown a seasonal pattern in the past. In particular, when markets in Europe cannot absorb supplies, they tend to be delivered to the US, which has ample storage capacity – hints at seasonal arbitrage.
- 2008 was an aberration due to demand in Asia. Reactivation of nukes in Japan likely to exacerbate the seasonal trends.



Select Basis Differentials

- Domestic shale and LNG regas developments do not significantly impact basis differentials as pipeline capacity expands to alleviate bottlenecks.
- Some regions soften slightly as regional supply developments offer lower average annual long haul pipeline utilization, others strengthen.
  - Regional policy differences can both offset and/or exacerbate this trend.





Uncertainty

Uncertainty in the Outlook

- The RWGTM indicates a very robust supply picture for North America.
- There are many uncertainties that influence this conclusion. Uncertainty influences investment behavior.
  - Policy, policy, policy…
    - Climate policy is very important in driving demand, which could force increased reliance on LNG imports.
    - Policies regarding expensing rules for upstream developments could marginalize some plays. Independents may not have the scale to absorb costs. There is likely a question of incidence here, but, at the margin, production will most likely be lower.
    - Regulation regarding fracking could be prohibitive. However, industry could circumvent much of this by being proactive rather than reactive.
    - Geopolitics…
  - Upstream costs. Typically related to the price of oil and gas, costs rise when price rises. This injects uncertainty into any forecast.
  - Uncertainty regarding technically recoverable assessments of resources.

Uncertainty in the Outlook (cont.)

- Other important sources of uncertainty include
  - Fuel price relationships, which can be altered by technology and policy, affect long term demand trends.
  - Economic growth and development and the effect of emerging nations on the world energy balance and flow of trade.
  - Sector-specific issues: industrial use, power generation.
    - Climate policy could drive declines in demand in industry and expansion in power gen. Which effect dominates and why? It is important to understand this.
  - NIMBY issues influence supply, demand and flow of trade within regions.
- Every one of these uncertainties can be handled in an appropriate framework, thus enabling an understanding of influential variables.
  - For example, what costs/benefits might a particular policy carry?

An example of long term market uncertainty: The Effects of Climate Change Policy

Some Recent Studies

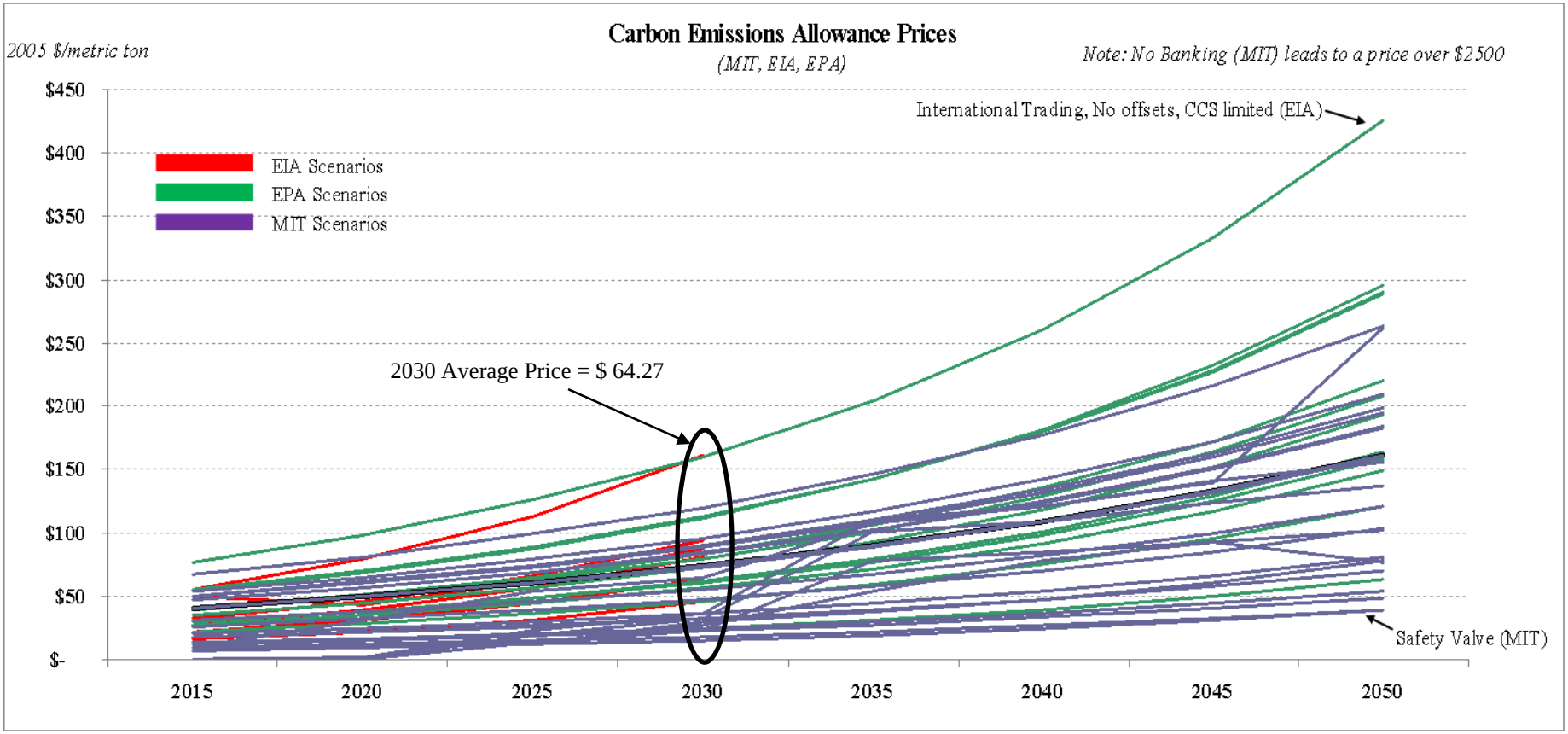
- EIA
  - Source: www.eia.doe.gov/oiaf/service_rpts.htm
  - Specific NEMS runs given S.2191, the Lieberman-Warner Climate Security Act of 2007 legislation. Aggressive adoption of nuclear.
  - Long run carbon price (2030) = $61; P_{NG}(2030) = $5.65 (2006$)
- EPA
  - Source: www.epa.gov/climatechange/economics/economicanalyses.html
  - Two exercises using different models: ADAGE and IGEM
  - Carbon price = ADAGE: $61 ($81 with constraints on nukes), IGEM: $82
  - Natural gas price = $5.76 (2005$)
- NGC
  - Used NEMS to dispute EIA on basis of nuclear power assessment
    - "... the EIA analysis incorrectly assumes 145 new nuclear power plants will be built by 2030. Another study by the Natural Gas Council (NGC) assumes that only 25 nuclear power plants will be built in that same time period. This figure is likely more accurate since only one nuclear power plant has been ordered in the last 30 years..."
    - Natural gas demand up by 14% (3.6 tcf) per year from 2020-2030 on average
    - Natural gas wellhead prices $1/mcf or more higher

Some Recent Studies (cont.)

- MIT
  - Focuses on the U.S. and aggregates the Rest of the World
  - Incorporates dynamic optimization logic and economic development principles.
  - "Carbon-free" backstop is assumed at a price of $50/ton. This is chosen via trial and error – anything more is above the 203bmt case so is irrelevant.
  - Assumes future supply curves in each period for fossil fuels and alternatives
- Stern Review
  - Received much attention as an authoritative source on the economics of dealing with climate change.
  - Key result: $85/metric ton CO2 equivalent for business as usual case
  - Critics point to various flaws, including a lack of appropriate discounting.
- McKinsey Report
  - Highly cited, especially on Capital Hill.
  - Constructs a marginal cost curve for CO2 abatement to identify a cost of $50/ton.
  - Critics point to low discount rate. McKinsey acknowledges a "social rate of discount".
- EPRINC
  - Notes cost of cap-and-trade, but argues opportunities will be created as well.

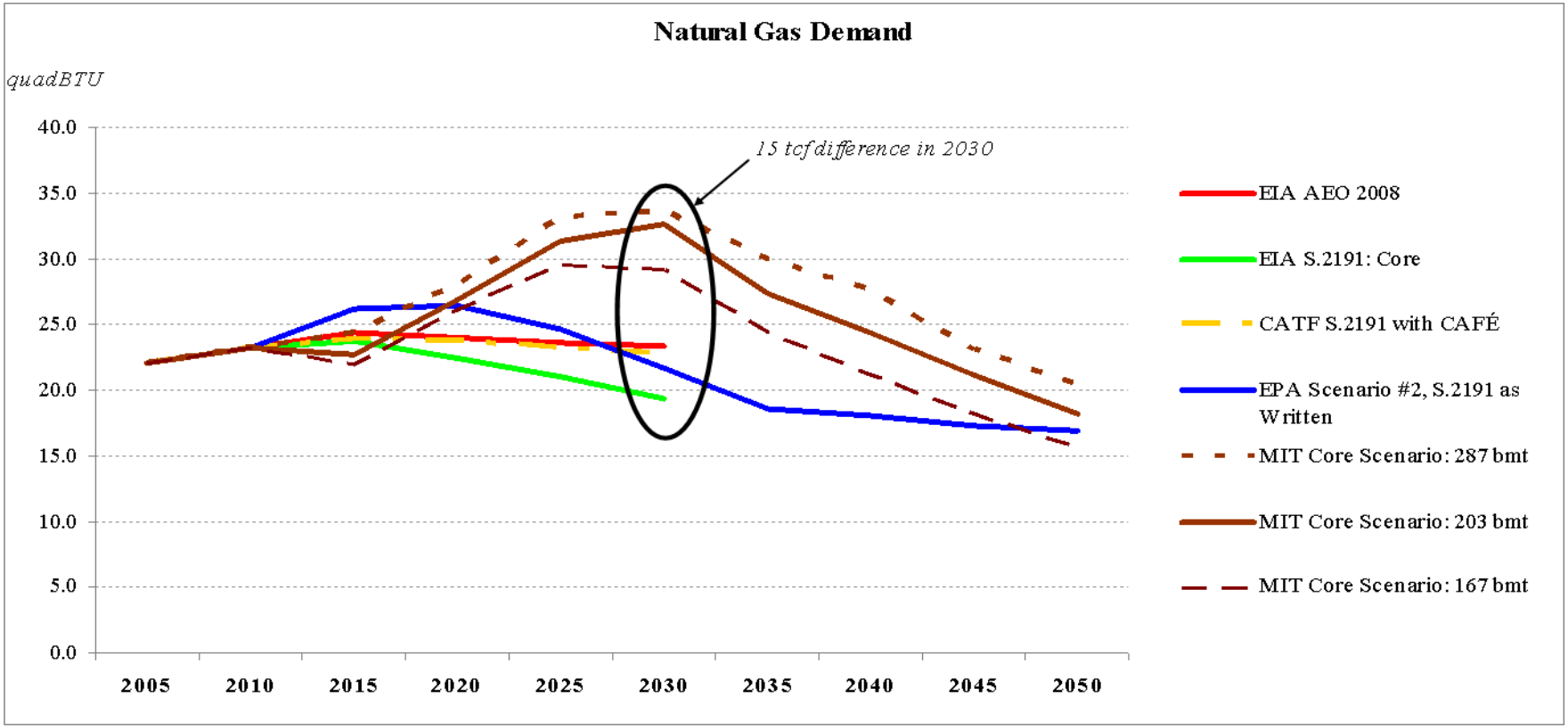
Carbon Prices (all cases)

- Carbon prices range significantly across scenarios.
  - Prices increase with restrictions and technology assumptions are crucial
  - Preliminary BIPP work puts carbon price at $100-$140 per ton
    - Price needed to stimulate significant investment in CCS and non-carbon fuels

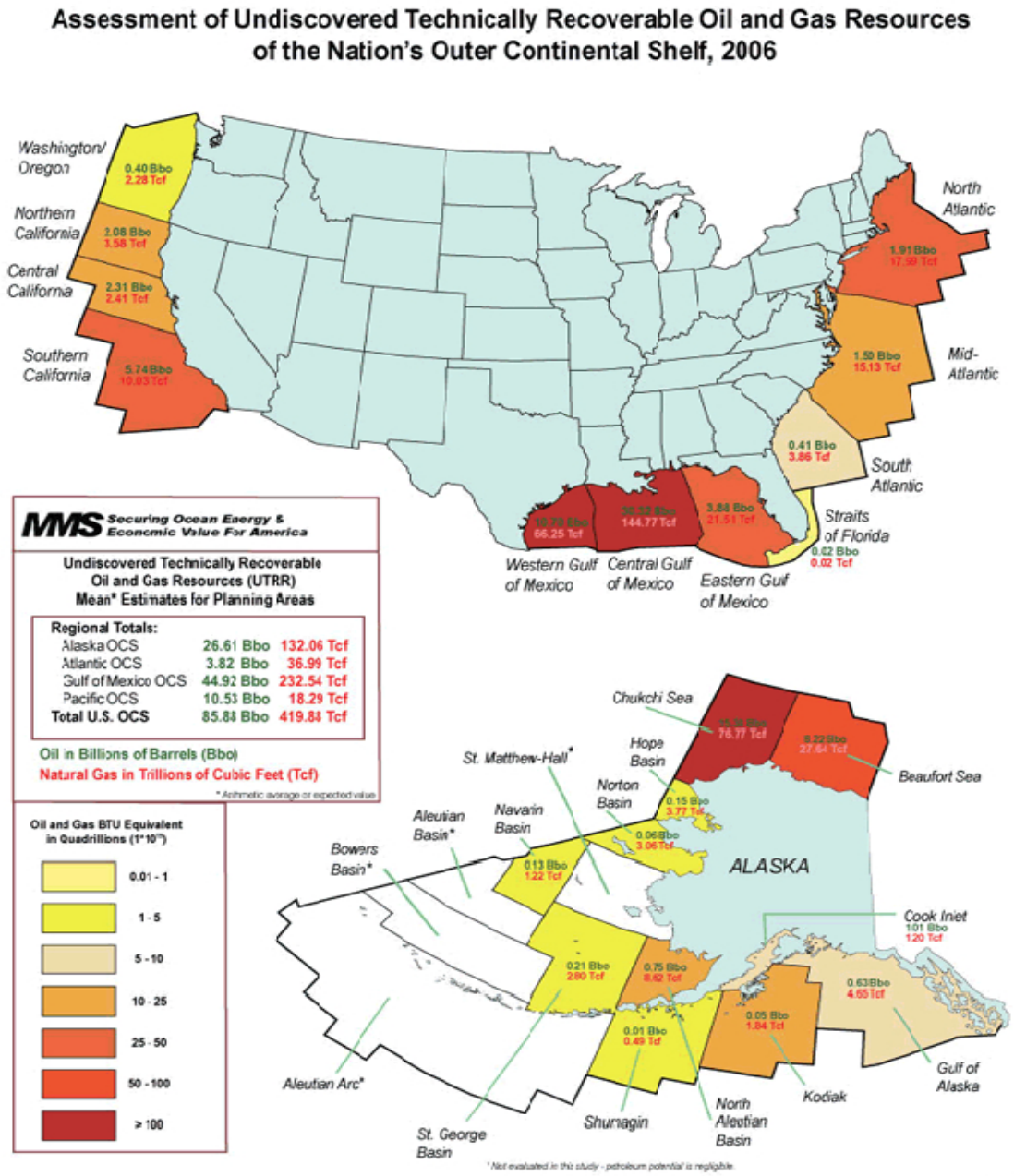


The Effect on Natural Gas Demand

- Trends vary significantly, as does timing.
  - Strong relationship between natural gas demand, CCS technology availability and assumptions regarding nuclear power.
  - Range of 15 tcf across core scenarios in models. Greater if non-core scenarios also considered.



Appendix



Access restrictions: A new call or greater awareness?

- Access restrictions have been lamented in NPC literature for well over a decade
- Lower48 OCS effected resource (mean est.)
  - 18 billion bbl oil
  - 76 tcf natural gas

Natural Gas impacted by restrictions

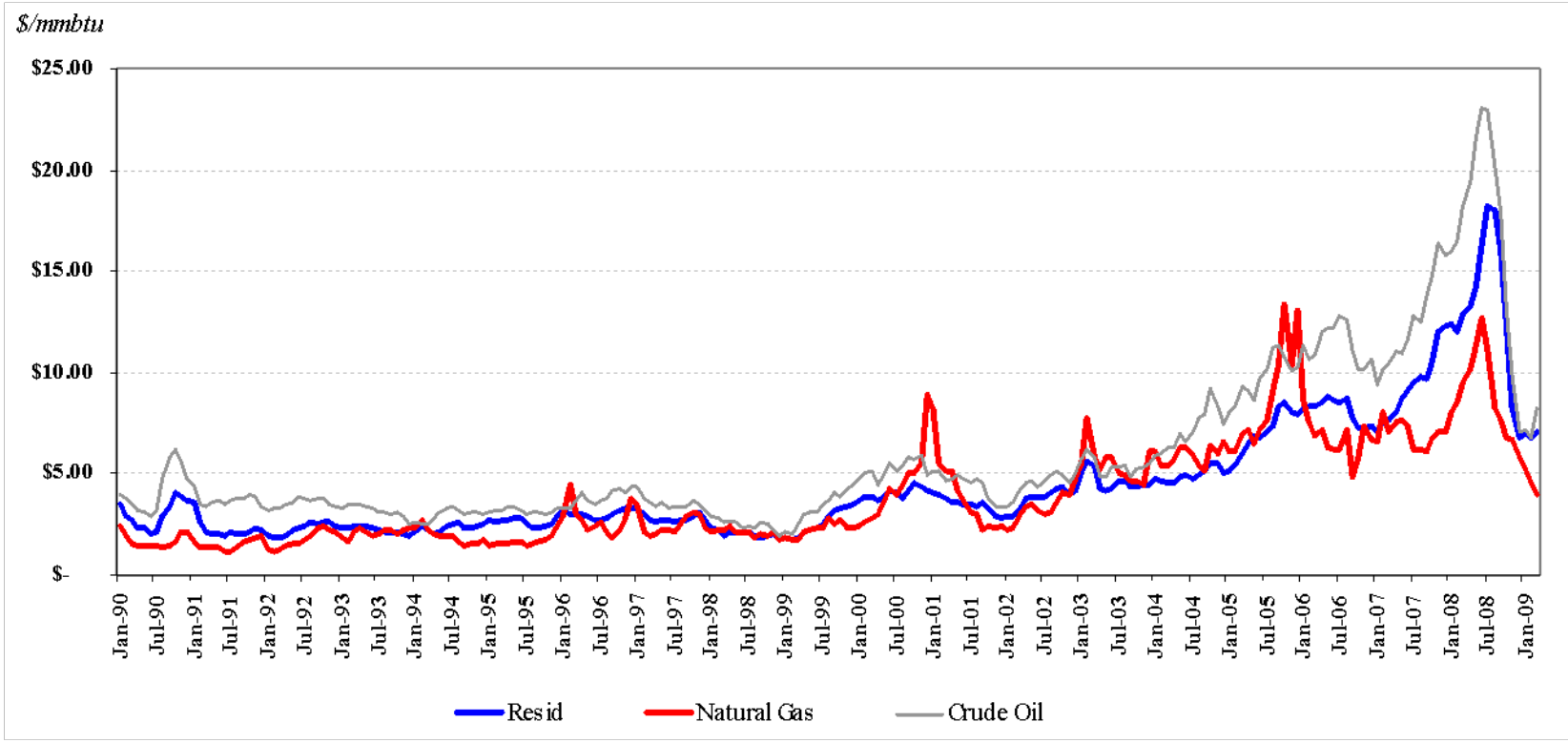
Planning Region/Basin		Resource Off-limits (Tcf)
Rocky Mountains	Montana	9.4
	Wyoming Thrust Belt	0.8
	Green River	39.5
	Powder River	6.0
	Uinta-Piceance	8.4
	San Juan	5.3
Total Lower 48 (incl. OCS)		**146.8**
Alaska	ANWR	8.6
	North Aleutian Basin	8.6
Total		**164.0**

Data Sources: NPC2003 Supply Task Group Report, MMS, Hartley and Medlock (2007)

Crude Oil and Natural Gas Prices

The Prices of Crude Oil and Natural Gas

- The prices of crude oil and natural gas tend to move together. There has been speculation as to the existence of a quantifiable relationship between the natural gas price at Henry Hub and WTI price of crude oil.
  - 10:1 ratio, 7:1 ratio, BTU parity, no relationship at all…
- Understanding this is especially important to firms with upstream activities and to traders in oil and gas.

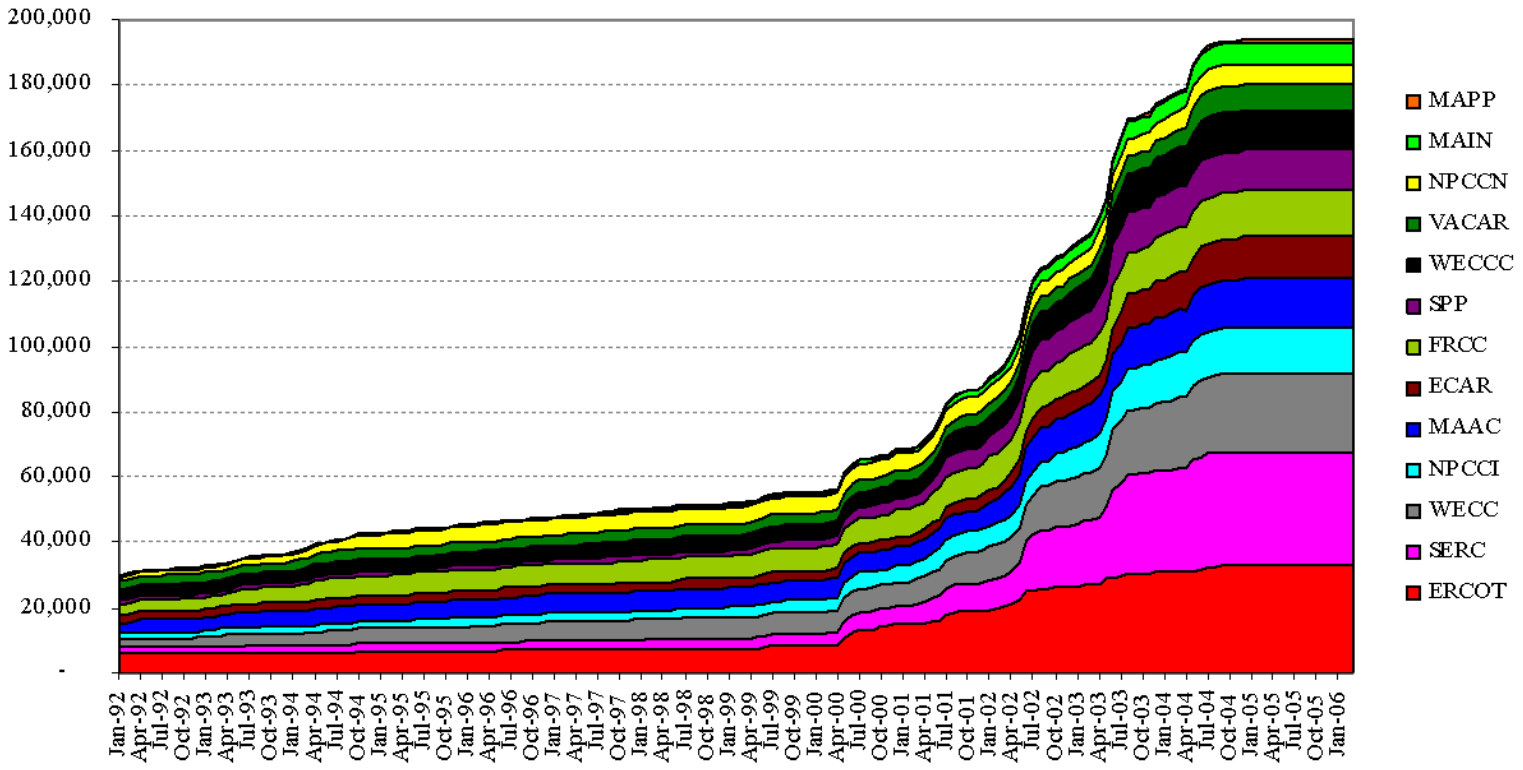


The Prices of Crude Oil and Natural Gas (cont.)

- The relationship appeared to change through the late 1990s early 2000.
- This led some to conclude a price relationship did not exist.
- But, rapid growth in NGCC capacity moved the average natural gas heat rate in power generation. Fuels compete on a cost basis in power, not price.
- Fuel competition for various fuels in end use delivered energy services should drive a price relationship as long as no impediments/constraints are present.
- Upstream investments should reinforce long run price relationships.
- Contractual links also exist, but these can lead to short run imbalances that alter investment behavior. So, contractual rigidities may actually have two impacts.
  - If demand is relatively strong, contracts reinforce the price link
  - If demand is relatively weak, contracts leave excess supply and drive short run disequilibria as product is dumped a low prices.
- What will the role of the long term contract be going forward?
  - Brito and Hartley (*EJ*, 2007) show physical liquidity will reduce the importance of fixed point-to-point contractual relationships.
  - Will likely remain important

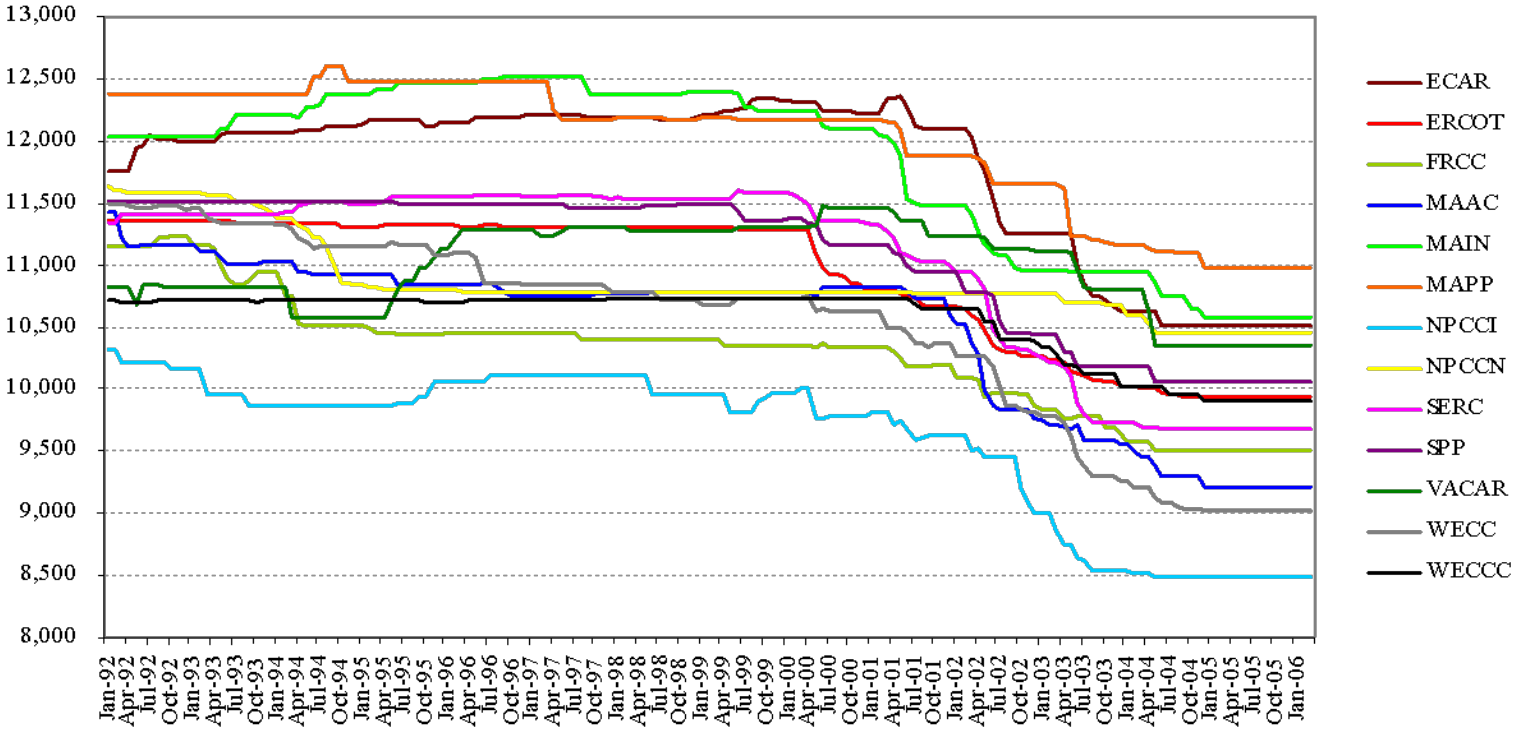
The Prices of Crude Oil and Natural Gas (cont.)

- Rapid growth in NGCC capacity in early 2000s...



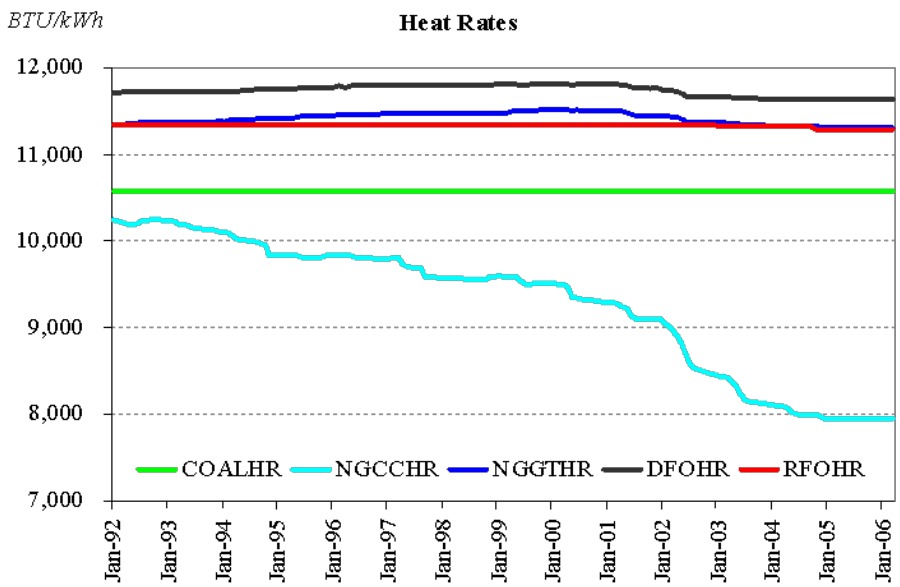
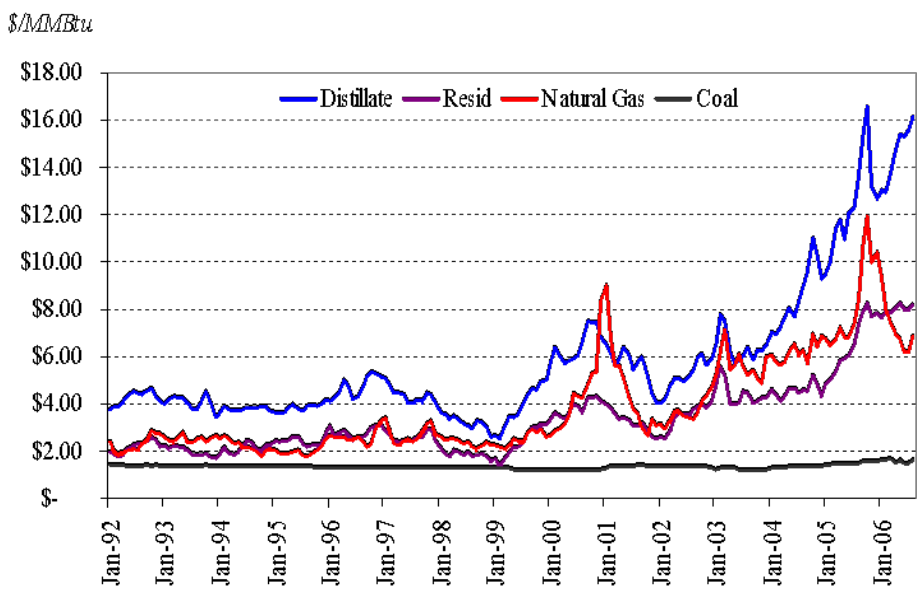
The Prices of Crude Oil and Natural Gas (cont.)

- ... shifted the capacity-weighted average heat rate (inversely related to thermal efficiency) for all gas-fired generation.



The Prices of Crude Oil and Natural Gas (cont.)

- Hartley, Medlock and Rosthal (*EJ*, 2008) found that there is a stable long run (or cointegrating) relationship between the prices of residual fuel oil and natural gas, when controlling for changes in technology in the power generation sector, and the prices of crude oil and residual fuel oil.

$$\ln P_t^{NG} = \underset{(0.0913)}{0.0701} + \underset{(0.0849)}{0.8779} \ln P_t^{rfo} - \underset{(0.5785)}{3.0032} \ln\left(\frac{HR_t^{NG}}{HR_t^{rfo}}\right) + \varepsilon_t^{NG}$$

$$\ln P_t^{rfo} = \underset{(0.0339)}{-0.2931} + \underset{(0.0234)}{0.9637} \ln P_t^{WTI} + \varepsilon_t^{rfo}$$