Gas-Electricity Nexus

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Acknowledgement

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Overview

1. Terminology and background
2. Hydraulic fracturing
3. Gas growth
4. What are the risks?
5. Gas-electric investment coordination

Terminology and Background

Interstate pipelines do not take ownership of the natural gas commodity; instead they offer only the transportation component.

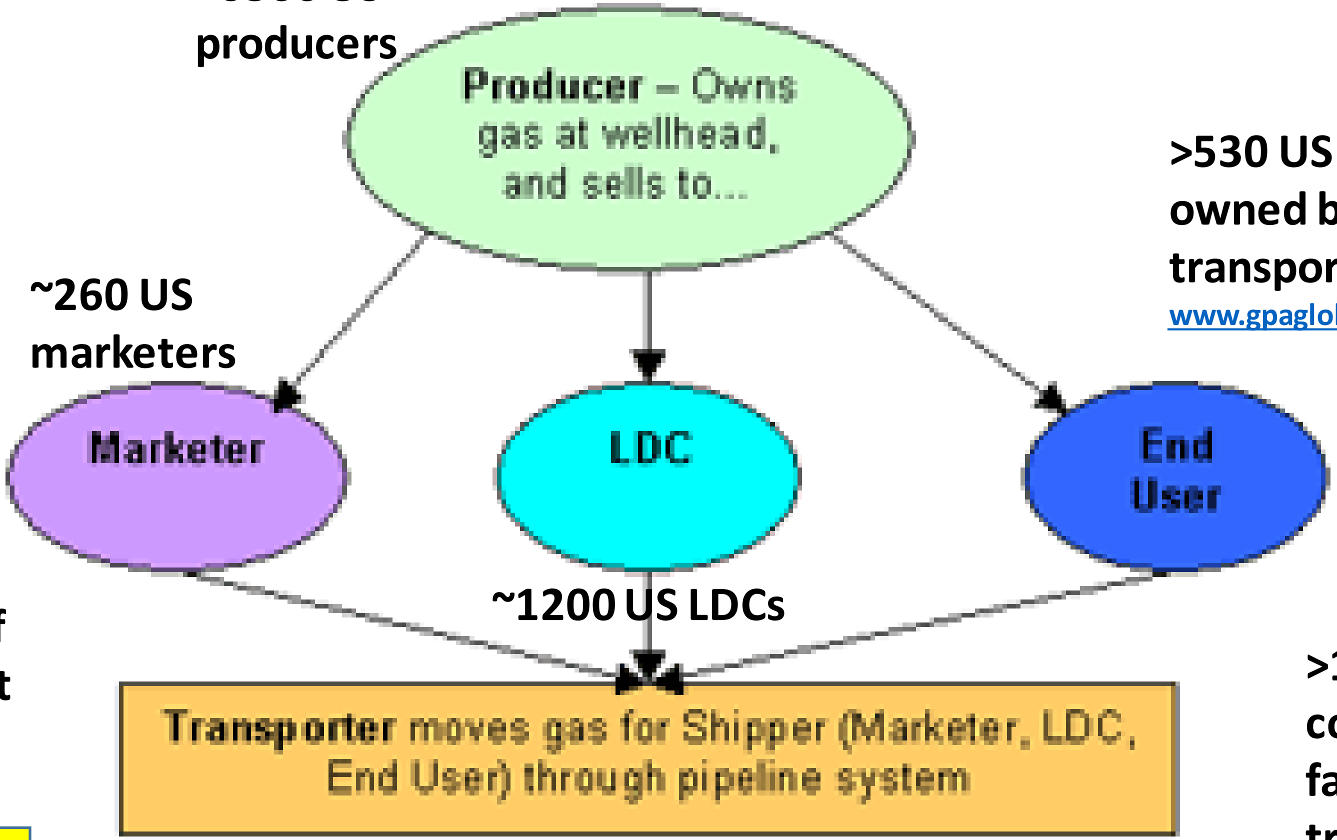
End users may purchase natural gas directly from producers or LDCs.

Marketers may be present between any 2 parties to facilitate the sale or purchase of natural gas or they may contract for transportation & storage.

Marketers, LDCs, or end-users purchase from producers at the wellhead price and then purchase the pipeline service from the transporters.

>6300 US producers

~260 US marketers



~1200 US LDCs

>160 US pipeline companies with >300k miles of pipe

>530 US processing plants, owned by producers, transporters, & marketers. See www.gpaglobal.org/membership/companies/

>123 US storage operators controlling ~400 storage facilities, owned mostly by transporters, see www.ferc.gov/industries/gas/indus-act/storage/fields-by-owner.pdf

TERMINOLOGY

Conventional natural gas: gas trapped in a geologic formation caused by folding and/or faulting of sedimentary layers that permits its extraction using conventional techniques.

Unconventional natural gas: gas trapped in the source rock from which is generated or that migrates to a formation of impermeable rock and therefore is not trapped in a conventional deposit and requires unconventional extraction techniques such as hydraulic fracturing.

Natural gas liquids (NGLs): general term used for all liquid hydrocarbons separated from natural gas during processing activity. They consist of lease condensate and natural gas plant liquids.

Lease condensate: mix of pentanes and some other heavy hydrocarbons that can be extracted from the gas stream as a liquid at normal pressures and temperatures; normally enters crude oil stream after production.

Natural Gas Plant Liquids (NGPLs): general term for all liquid products separated from natural gas at a gas processing plant, and includes ethane, propane, butane, and pentanes. Excludes lease condensate.

When NGLs are present with methane, which is the primary component of natural gas, the natural gas is referred to as "wet gas." Once the NGLs are removed from the methane, the natural gas is referred to as "dry gas," which is what most consumers use.

Associated gas: wet gas; usually comes from fields also have oil.

Non-associated gas: dry gas; usually comes from fields not having oil.

Liquid natural gas: Not an NGL but rather conversion from dry gas at very low temperature.

Compressed natural gas: Not an NGL but rather conversion from dry gas at very high pressure.

NATURAL GAS PRODUCTION

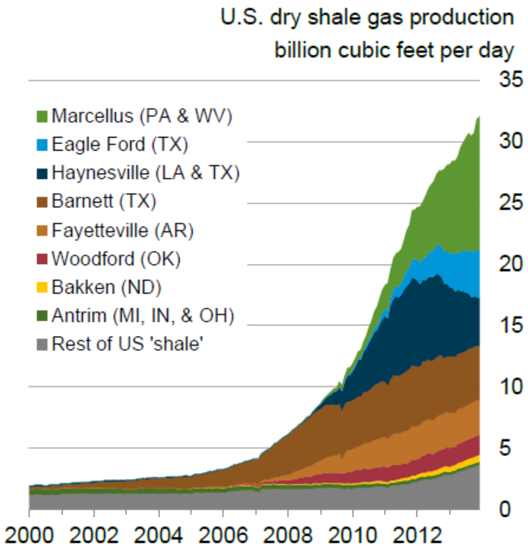
- NG from unconventional geological formations
  - Sea floor and below for deep waters and shallow artic seas
    - Gas hydrates
  - Trapped in coal deposits
    - Coalbed methane
  - Trapped in rock formations
    - Shale gas
    - Tight gas
- NG from conventional geological formations
  - Trapped in rock formations
    - Conventional gas

Similar chemical compositions but different geological characteristics of their reservoirs

One darcy is the permeability of a solid through which 1 cc of fluid, having a viscosity of 1 centipoise, will flow in 1 sec through a section 1 cm thick and 1 cm^2 in cross section, if the pressure difference between the two sides of the solid is 1 atmosphere. Permeability has the same units as area; since there is no SI unit of permeability, m^2 are used. One darcy is equal to 0.98692E-12 m^2

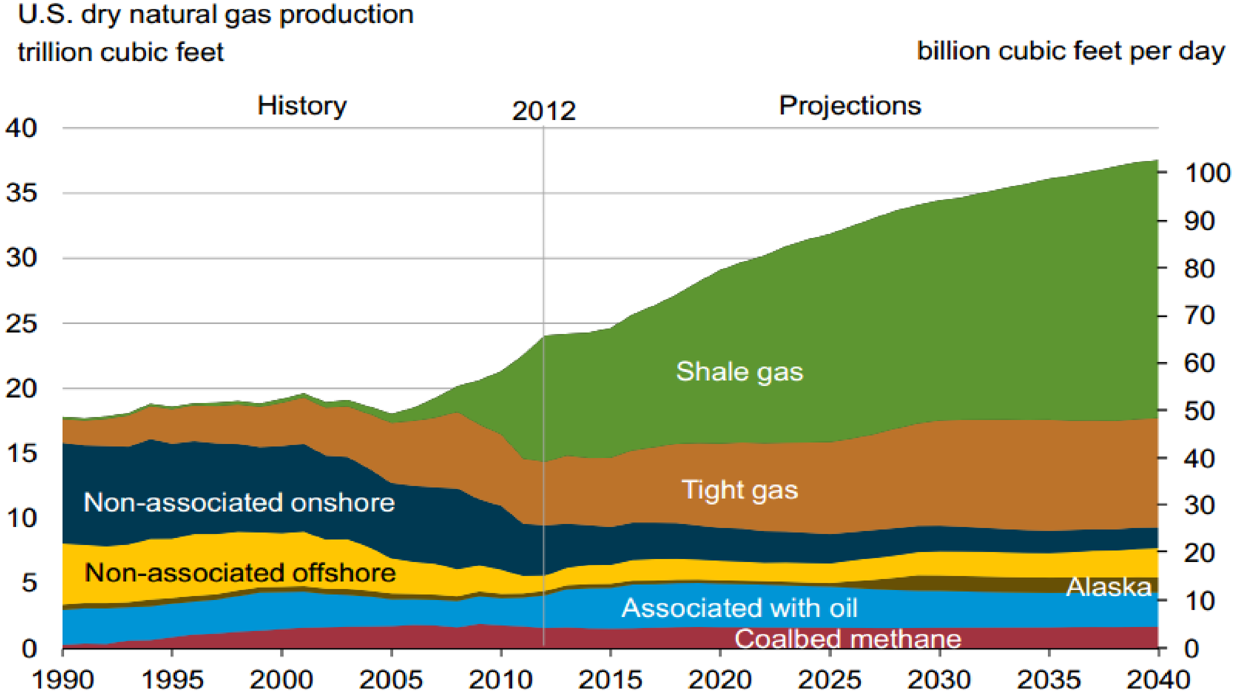
Sources: http://total.com/en/energies-expertise/oil-gas/exploration-production/strategic-sectors/unconventional-gas/presentation/specific-fields
http://www.dmp.wa.gov.au/documents/132499_Resources_Type_Fact_Sheet.pdf

NATURAL GAS PRODUCTION



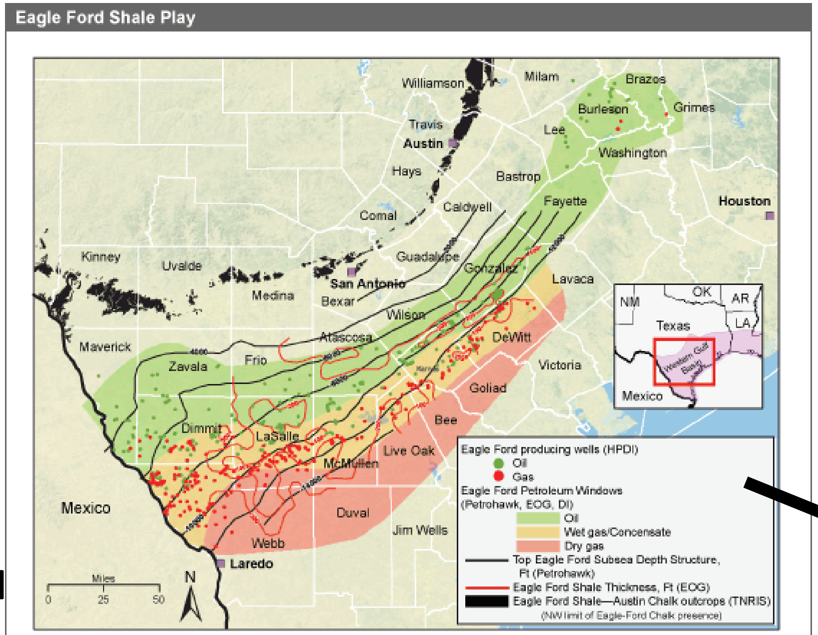
Five shale plays (Eagle Ford, Bakken, Permian for oil, and Marcellus, Haynesville, Eagle Ford for gas) have allowed a rapid increase in natural gas and oil production over the last few years.

The Bakken and Eagle Ford plays produce both natural gas & oil, but the oil and gas condensate areas are most attractive today (the oil to gas price ratio is high enough).



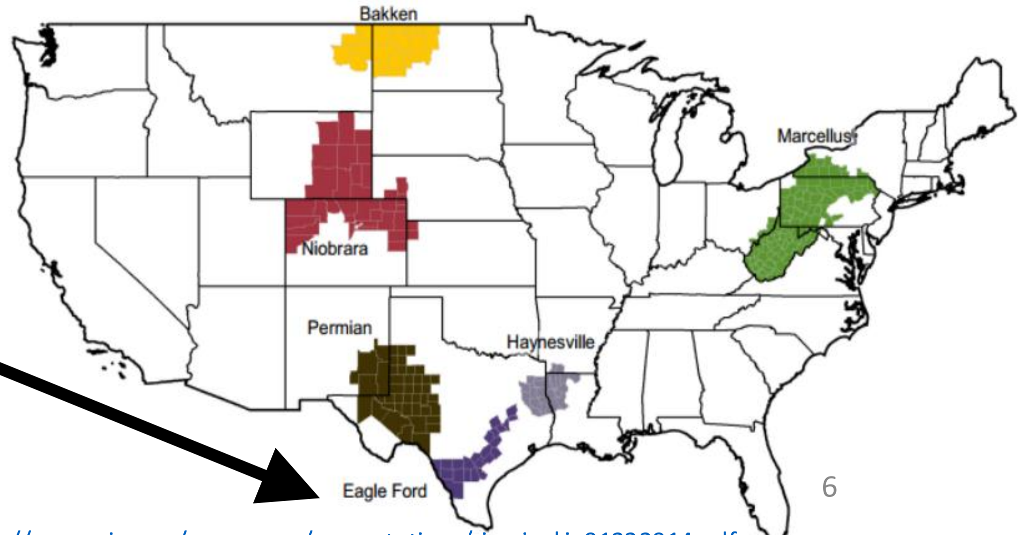
Source: EIA – Annual Energy Outlook 2014 Reference Case

Eagle Ford contains both natural gas in the southern part of the formation and NGLs/oil in the northern region. This allows operators to move to the most lucrative part of the area depending on the price of commodities. In contrast, most other plays produce either primarily oil (such as Bakken) or gas (such as Barnett).



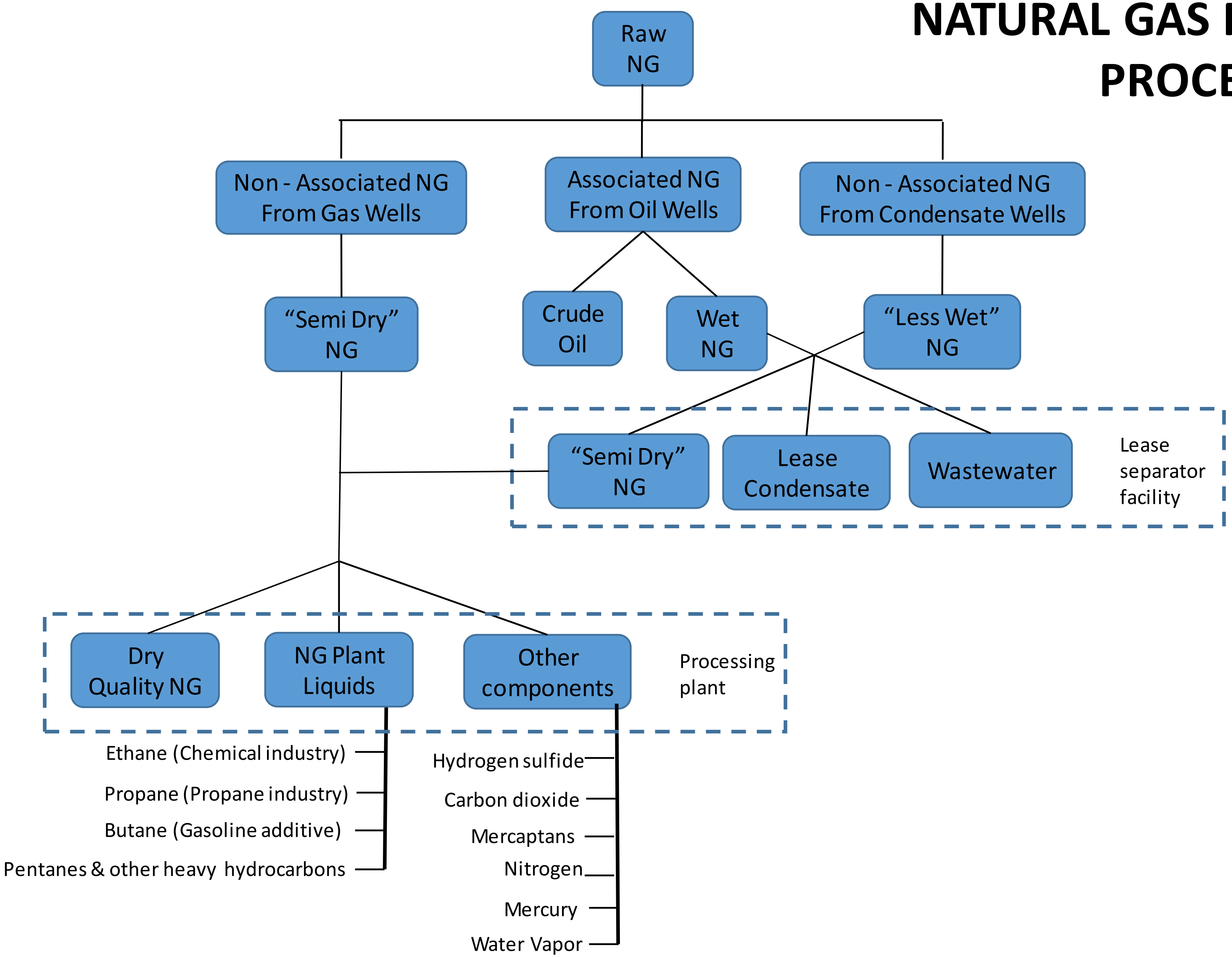
Source: Energy Information Administration.

Source: http://www.standardandpoors.com/ratings/articles/en/us/?assetID=1245363507565



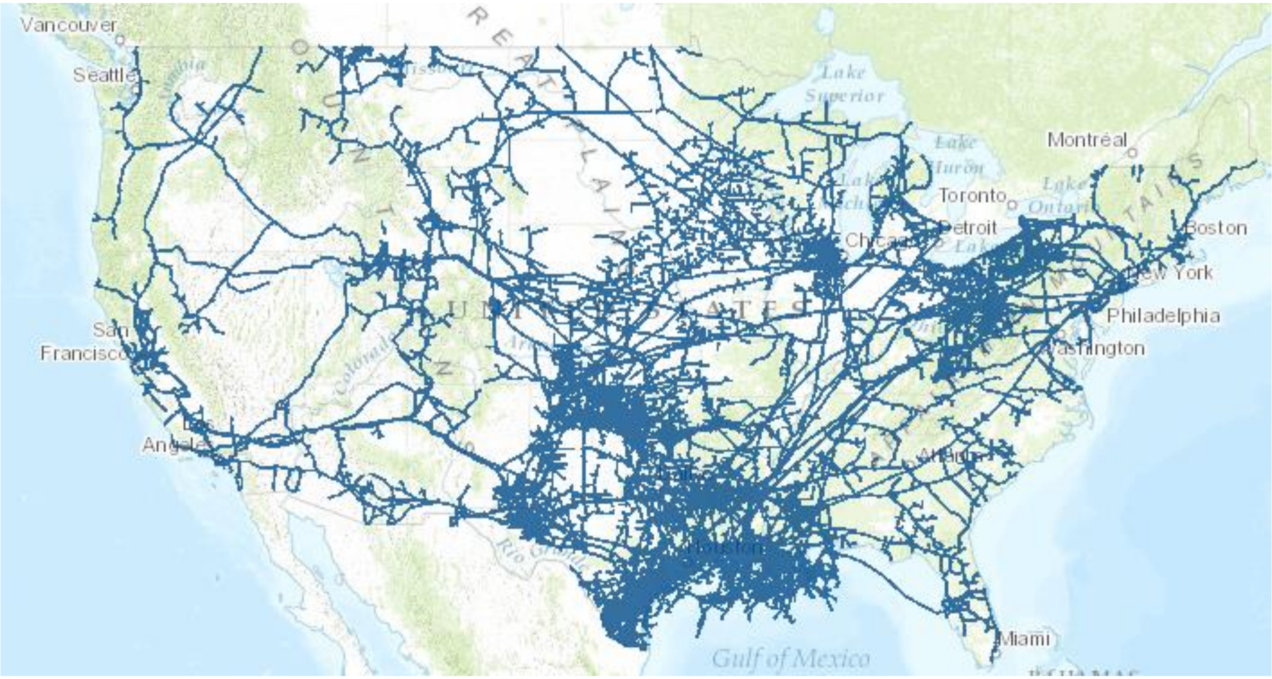
Source: http://www.eia.gov/pressroom/presentations/sieminski_01222014.pdf

NATURAL GAS PRODUCTION & PROCESSING



NATURAL GAS TRANSPORTATION

U.S. NATURAL GAS TRANSMISSION NETWORK (2012)
INTERSTATE & INTRASTATE PIPELINES

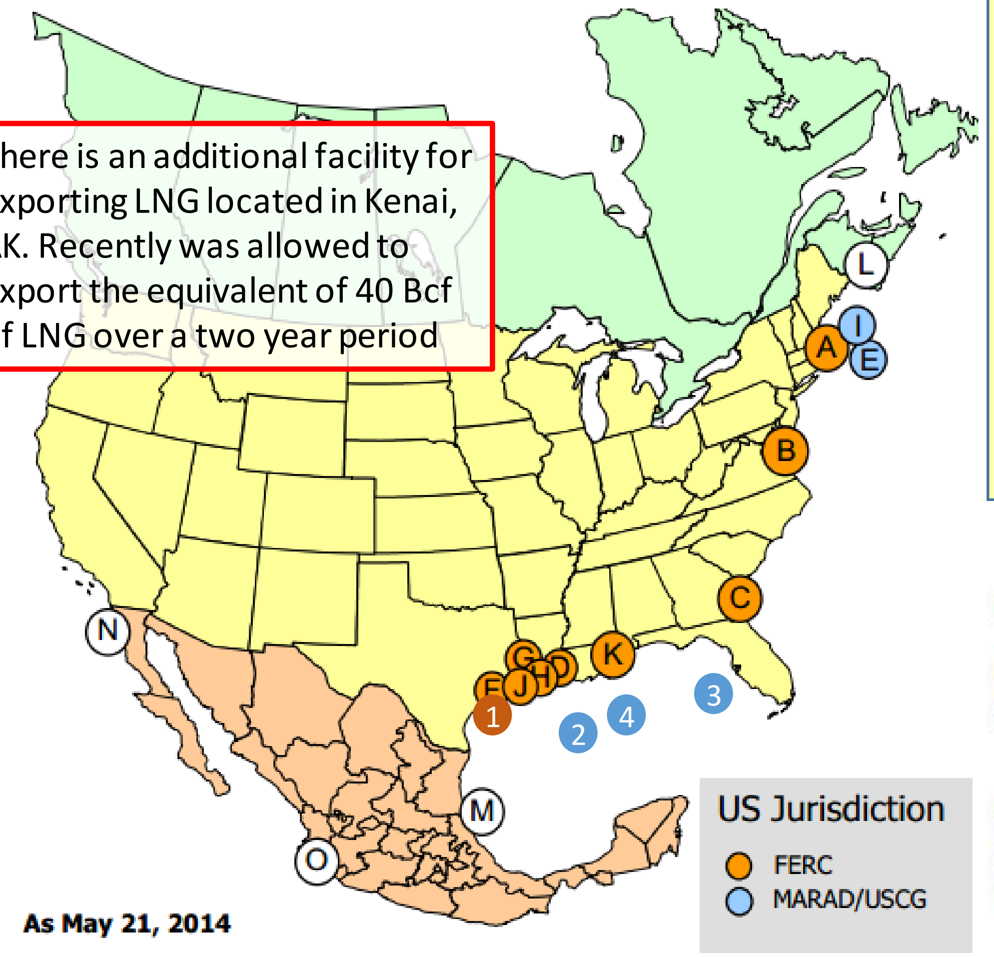


- More than 210 natural gas pipeline systems.
- More than 300,000 miles of interstate and intrastate transmission pipelines
- More than 1,400 compressor stations that maintain pressure on the pipeline network
- More than 11,000 delivery points, 5,000 receipt points, and 1,400 interconnection points
- More than 400 underground natural gas storage facilities
- Near 50 locations where natural gas can be imported/exported via pipelines

http://www.eia.gov/state/maps.cfm?v=Natural%20Gas
http://www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/ngpipeline/index.html

LNG TERMINALS IN U.S. EXISTING AND APPROVED

There is an additional facility for exporting LNG located in Kenai, AK. Recently was allowed to export the equivalent of 40 Bcf of LNG over a two year period



As May 21, 2014

Note: There is an existing import terminal in Peñuelas, PR. It does not appear on this map since it can not serve or affect deliveries in the Lower 48 U.S. states.

★ *Authorized to re-export delivered LNG*

EXISTING TERMINALS

U.S.

- **A. Everett, MA :** 1.035 Bcfd (GDF SUEZ - DOMAC) → Import
- **B. Cove Point, MD :** 1.8 Bcfd (Dominion - Cove Point LNG) → Import
- **C. Elba Island, GA :** 1.6 Bcfd (El Paso - Southern LNG) → Import
- **D. Lake Charles, LA :** 2.1 Bcfd (Southern Union - Trunkline LNG) → Import
- **E. Offshore Boston:** 0.8 Bcfd, (Excelerate Energy – Northeast Gateway) → Import
- **F. Freeport, TX:** 1.5 Bcfd, (Cheniere/Freeport LNG Dev.)★ → Import
- **G. Sabine, LA:** 4.0 Bcfd (Cheniere/Sabine Pass LNG)★ → Import
- **H. Hackberry, LA:** 1.8 Bcfd (Sempra - Cameron LNG)★ → Import
- **I. Offshore Boston, MA :** 0.4 Bcfd (GDF SUEZ – Neptune LNG) → Import
- **J. Sabine Pass, TX:** 2.0 Bcfd (ExxonMobil – Golden Pass) (Phase I & II) → Import
- **K. Pascagoula, MS:** 1.5 Bcfd (El Paso/Crest/Sonangol - Gulf LNG Energy LLC) → Import

IMPORT!

LNG Existing Import Capacity: 18.5 Bcfd

NG Average consumption in the U.S. in 2013 : 71.3 Bcfd

(Source: EIA, it includes lease and plant fuel, T&D use, and end users)

It represents 26% of the country demand

APPROVED TERMINALS

Import Terminal

APPROVED - NOT UNDER CONSTRUCTION

U.S. - FERC

1. Freeport, TX: 2.5 Bcfd (Cheniere/Freeport LNG Dev. - Expansion)*

U.S. - MARAD/Coast Guard

2. Gulf of Mexico: 1.0 Bcfd (Main Pass McMoRan Exp.)
3. Offshore Florida: 1.2 Bcfd (Hoëgh LNG - Port Dolphin Energy)
4. Gulf of Mexico: 1.4 Bcfd (TORP Technology-Bienville LNG)

Export Terminal

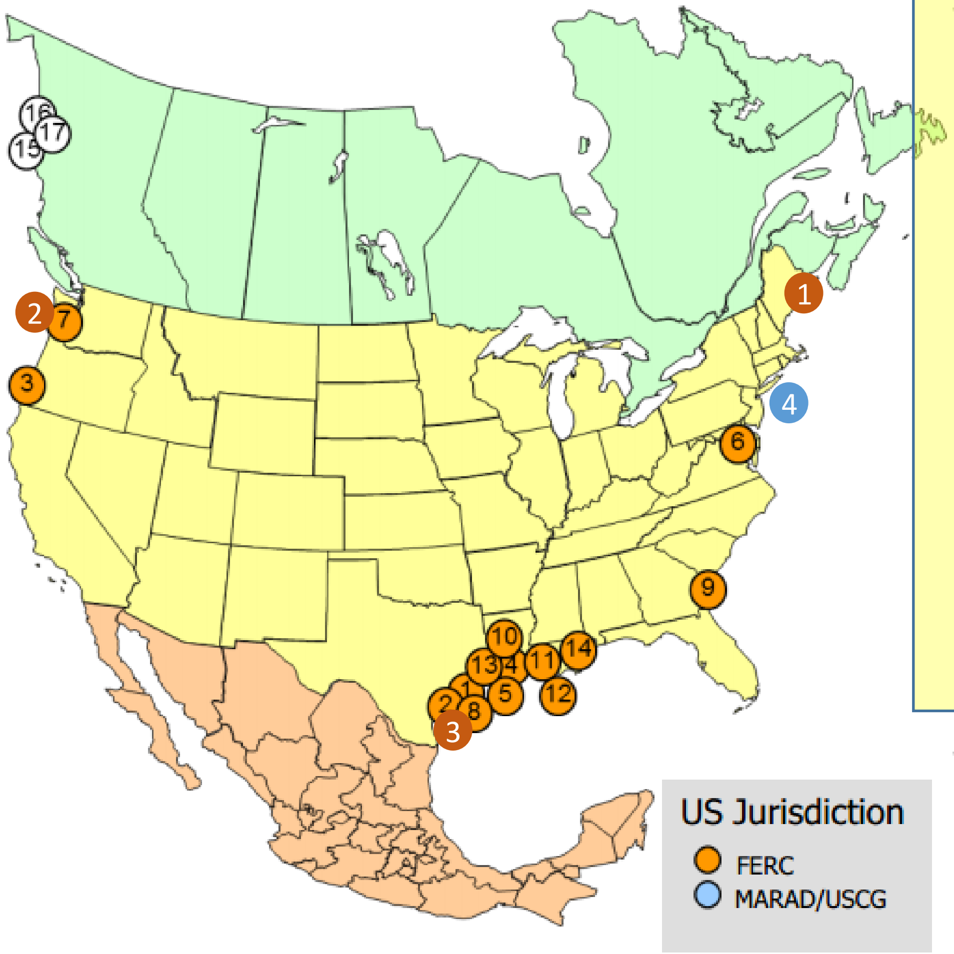
APPROVED - UNDER CONSTRUCTION

U.S. - FERC

8. Sabine, LA: 2.76 Bcfd (Cheniere/Sabine Pass LNG)

http://www.ferc.gov/industries/gas/indus-act/lng.asp

LNG TERMINALS IN U.S. PROPOSED



As of May 21, 2014

** Filed Certificate Application*

EXPORT!

Export Terminal

PROPOSED TO FERC

1. **Freeport, TX:** 1.8 Bcfd (Freeport LNG Dev/Freeport LNG Expansion/FLNG Liquefaction) (CP12-509)
2. **Corpus Christi, TX:** 2.1 Bcfd (Cheniere – Corpus Christi LNG) (CP12-507)
3. **Coos Bay, OR:** 0.9 Bcfd (Jordan Cove Energy Project) (CP13-483)
4. **Lake Charles, LA:** 2.2 Bcfd (Southern Union - Trunkline LNG) (CP14-120)
5. **Hackberry, LA:** 1.7 Bcfd (Sempra – Cameron LNG) (CP13-25)
6. **Cove Point, MD:** 0.82 Bcfd (Dominion – Cove Point LNG) (CP13-113)
7. **Astoria, OR:** 1.25 Bcfd (Oregon LNG) (CP09-6)
8. **Lavaca Bay, TX:** 1.38 Bcfd (Excelerate Liquefaction) (CP14-71 & 72)
9. **Elba Island, GA:** 0.35 Bcfd (Southern LNG Company) (CP14-103)
10. **Sabine Pass, LA:** 1.40 Bcfd (Sabine Pass Liquefaction) (CP13-552)
11. **Lake Charles, LA:** 1.07 Bcfd (Magnolia LNG) (CP14-347)
12. **Plaquemines Parish, LA:** 1.07 Bcfd (CE FLNG) (PF13-11)
13. **Sabine Pass, TX:** 2.1 Bcfd (ExxonMobil – Golden Pass) (PF13-14)
14. **Pascagoula, MS:** 1.5 Bcfd (Gulf LNG Liquefaction) (PF13-4)

PROPOSED CANADIAN SITES IDENTIFIED BY PROJECT SPONSORS

15. **Kitimat, BC:** 1.28 Bcfd (Apache Canada Ltd.)
16. **Douglas Island, BC:** 0.23 Bcfd (BC LNG Export Cooperative)
17. **Kitimat, BC:** 3.23 Bcfd (LNG Canada)

Import Terminal

PROPOSED TO FERC

1. **Robbinston, ME:** 0.5 Bcfd (Kestrel Energy - Downeast LNG)
2. **Astoria, OR:** 0.5 Bcfd (Oregon LNG)
3. **Corpus Christi, TX:** 0.4 Bcfd (Cheniere – Corpus Christi LNG)

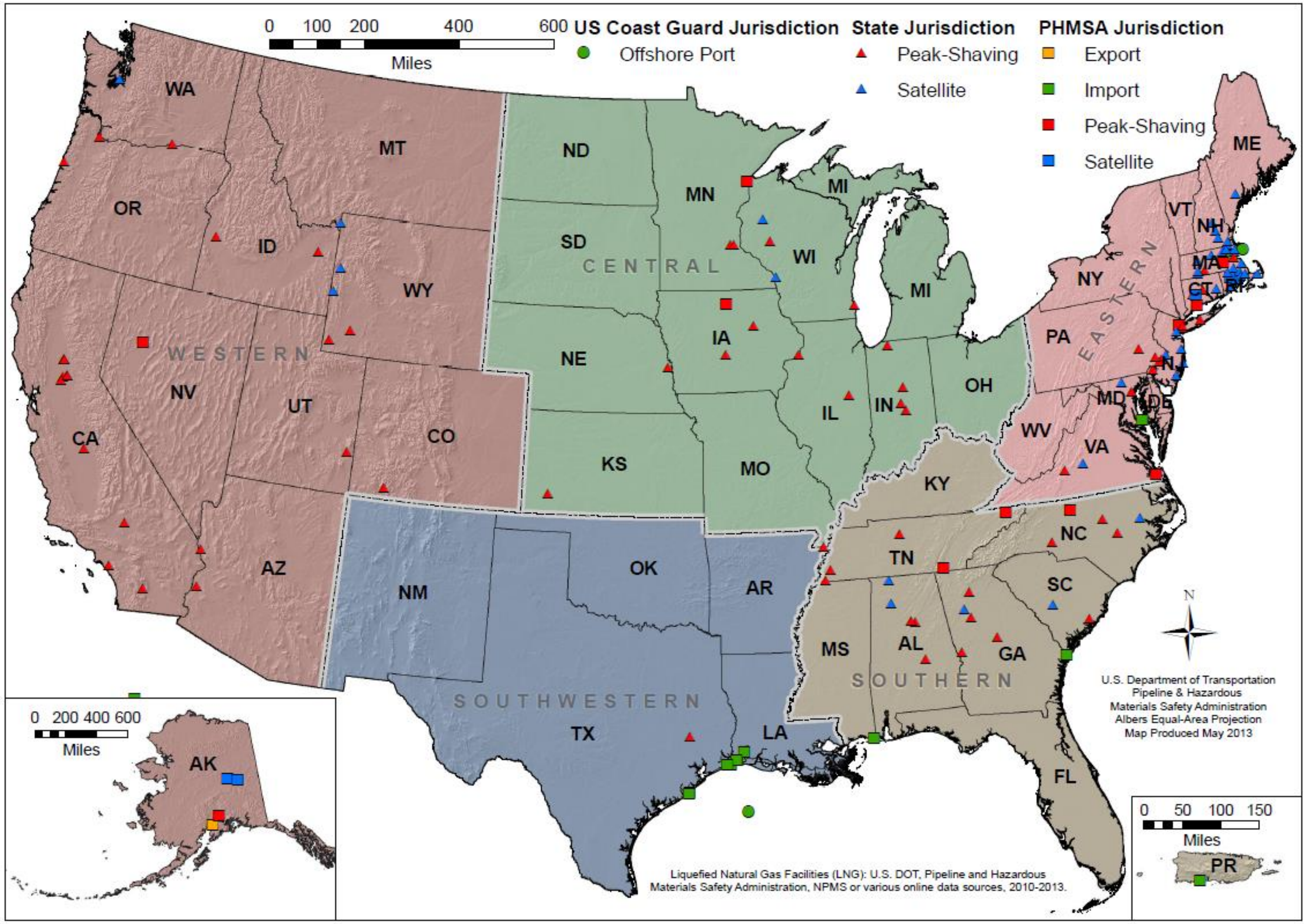
POTENTIAL U.S. SITES IDENTIFIED BY PROJECT SPONSORS

4. **Offshore New York:** 0.4 Bcfd (Liberty Natural – Port Ambrose)

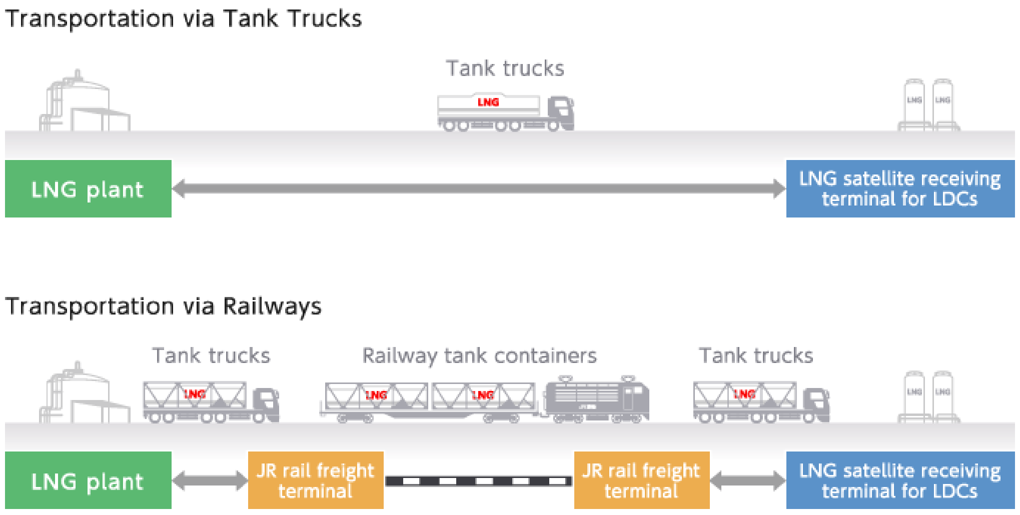
http://www.ferc.gov/industries/gas/indus-act/lng.asp

LNG TRANSPORTATION

Triangles are distribution points; squares are mainly import points and LNG conversion facilities. Red is large, blue is smaller. Peak-shaving plants can convert to LNG and store it until demand is high. During periods of high demand, the LNG is vaporized and injected into the gas transmission or distribution system. Satellite peak-shaving plants are unable to convert to LNG. Instead, trucks deliver LNG for storage on site. Satellite peak-shaving plants typically inject natural gas into distribution systems.



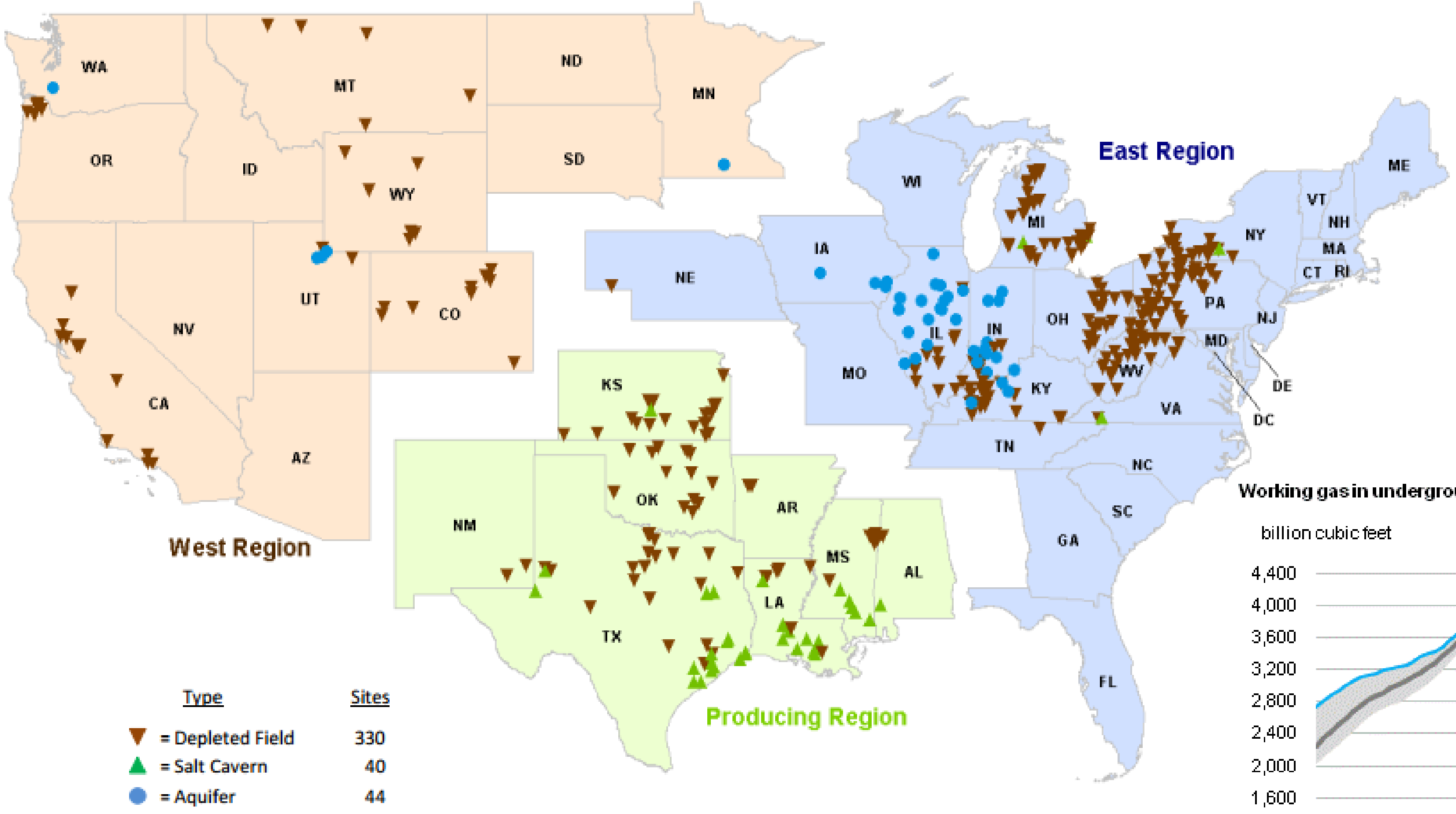
Source: https://primis.phmsa.dot.gov/comm/LNG_Map.htm?nocache=8580



Source: http://www.japex.co.jp/english/business/japan/lng.html

Above illustrates the two ways that LNG is moved from squares on the map to triangles.

EXISTING NATURAL GAS UNDERGROUND STORAGE FIELDS, 2012

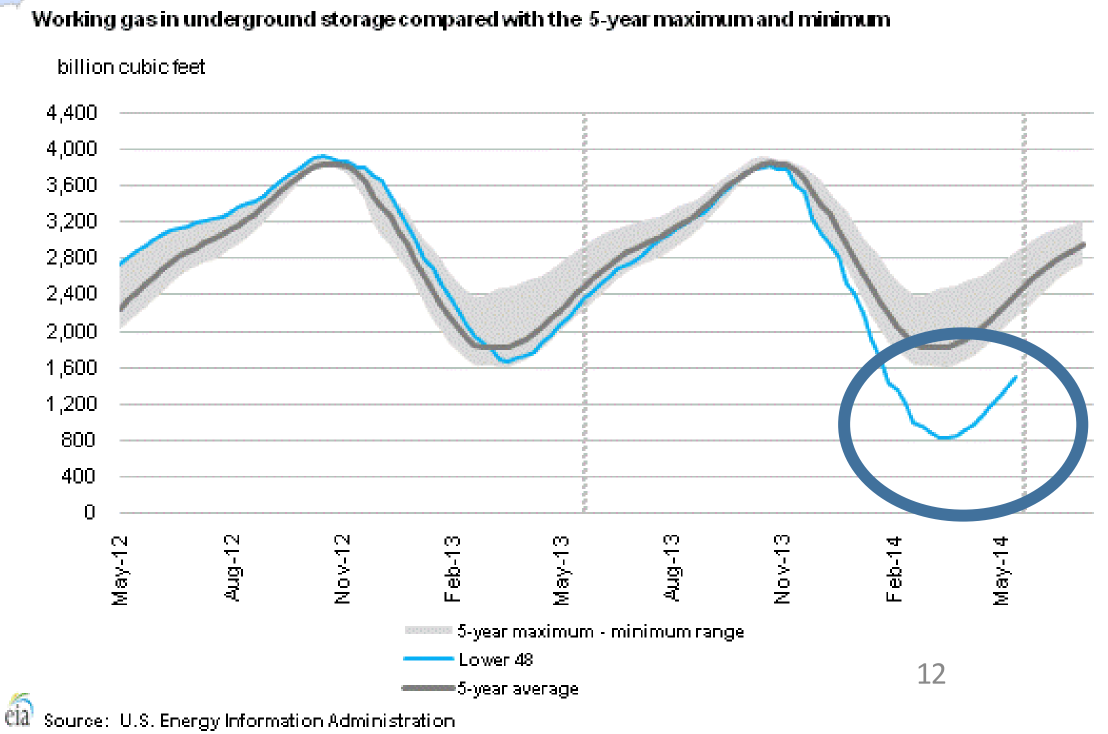


Source: http://www.eia.gov/naturalgas/annual/pdf/nga12.pdf

Storage sites are generally in locations

(a) where there are geological formations which facilitate them, especially depleted fields already having infrastructure.

(b) that are close to high demand or supply areas, e.g., the east/midwest because of demand & in KS/OK/TX/LA because of supply. Demand & supply benefit from increased flexibility of storage.

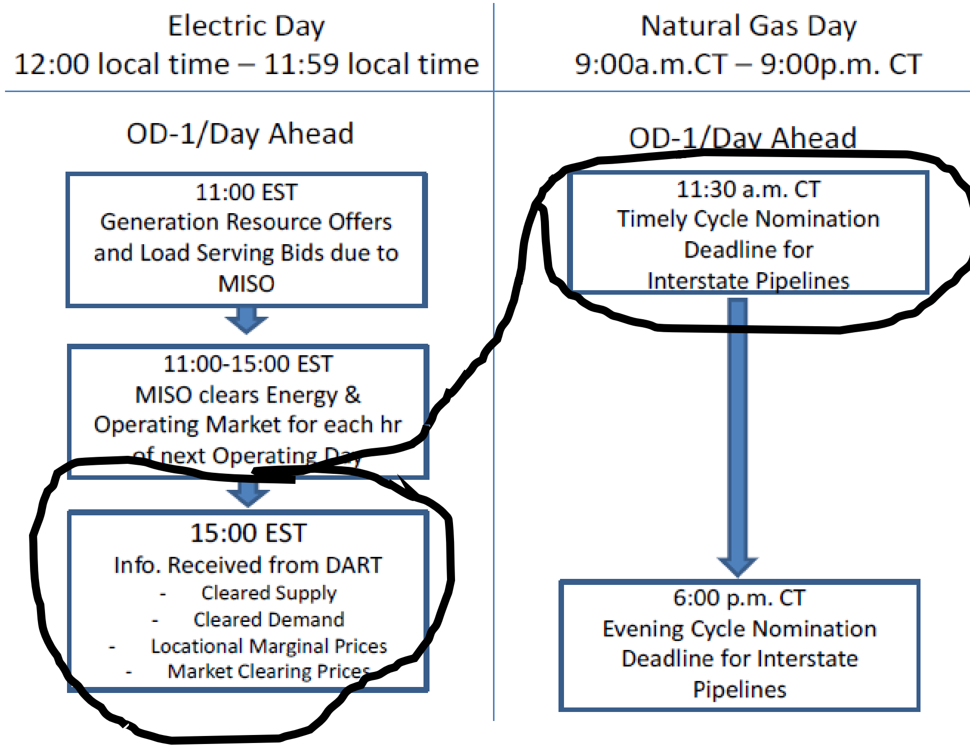


5-year maximum/minimum are operational (not capacity). Storage inventories peak in November in preparation for heating needs of January and February.

THREE OPERATING ISSUES

1. EMERGENCY PIPELINE CAPACITY: "What am I worried about? I am worried about losing a large nuke unit on a day when all my NGCC units are running high (could be a peak summer day or could be a peak winter/spring day when I happen to have many units down for maintenance), and I instantaneously must bring up 2000 MW of gas-fired gen. Can the pipelines do this?"

2. DAY-AHEAD MISALIGNMENT: Electric gens must submit their NG nominations 2.5 hours before gens receive their day-ahead commitment notifications from MISO. This causes fuel-risk for gas-fired gen owners.



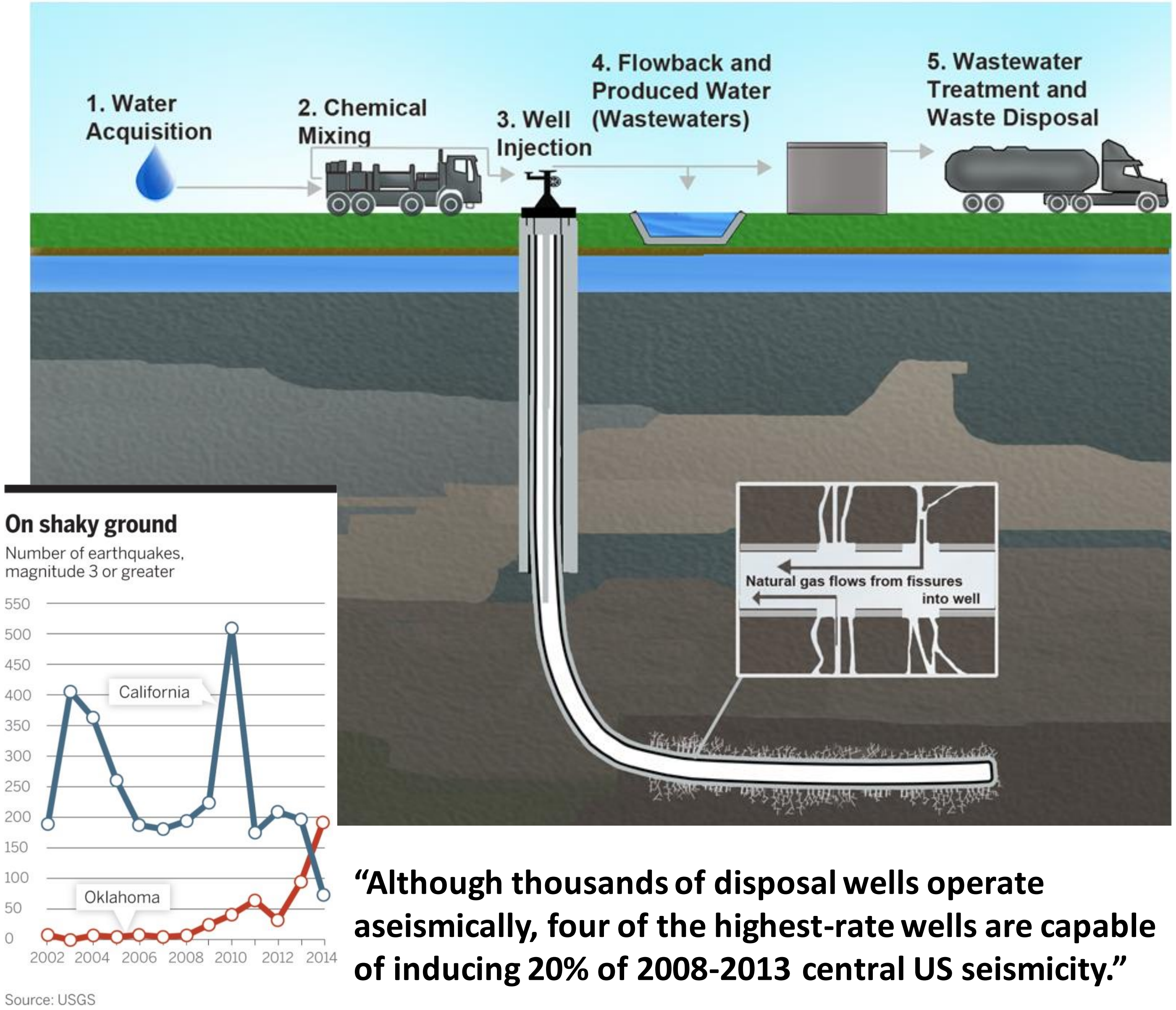
3. BUMPING: When pipeline capacity is reached, firm gas transportation holders can "bump" interruptible holders during the early part of the nominating process but not during the latter part. The no-bumping rule during the latter part gives interruptible holders some certainty and reduces flexibility for firm holders.

Source: MISO Electric and Natural Gas Coordinating Task Force. Misalignment of Natural Gas & Electric Operating Day and Scheduling

Hydraulic Fracturing

Hydraulic Fracturing & potential impacts

Source: http://www2.epa.gov/hfstudy/hydraulic-fracturing-water-cycle



Source: USGS

"Although thousands of disposal wells operate aseismically, four of the highest-rate wells are capable of inducing 20% of 2008-2013 central US seismicity."

Source: K. Keranen, M. Weingarten, G. Abers, B. Bekins, & S. Ge, **Sharp increase in central Oklahoma seismicity since 2008 induced by massive wastewater injection** Science, 3 July 2014

WATER

Water Acquisition
- -Change in the quantity of water available for drinking.
- -Change in drinking water quality

Chemical Mixing
- Release to surface and ground water through on-site spills and/or leaks

Well Injection
- -Release of hydraulic fracturing fluids to ground water due to inadequate well construction or operation.
- -Movement of hydraulic fracturing fluids from the target formation to drinking water aquifers through local man-made or natural features
- -Movement into drinking water aquifers of natural substances found underground, such as metals or radioactive materials, which are mobilized during hydraulic fracturing activities.

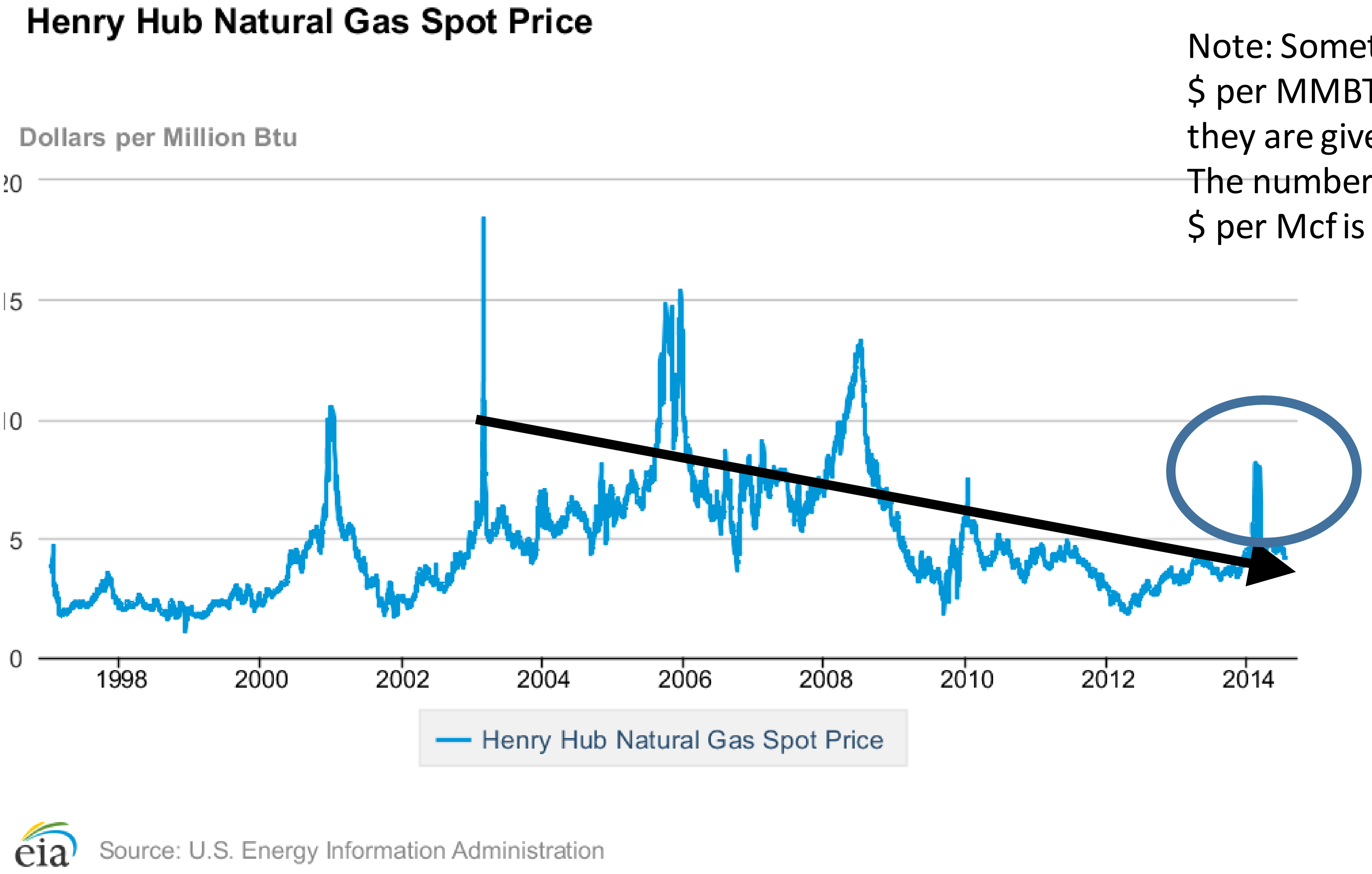
Flowback and Produced Water
- Release to surface or ground water through spills or leakage from on-site storage

Wastewater Treatment and Waste Disposal
- -Contaminants reaching drinking water due to surface water discharge and inadequate treatment of wastewater
- -Byproducts formed at drinking water treatment facilities by reaction of hydraulic fracturing contaminants with disinfectants

The United States Environmental Protection Agency is developing a study to look at potential impacts of hydraulic fracturing at each stage of the cycle.

Gas Growth

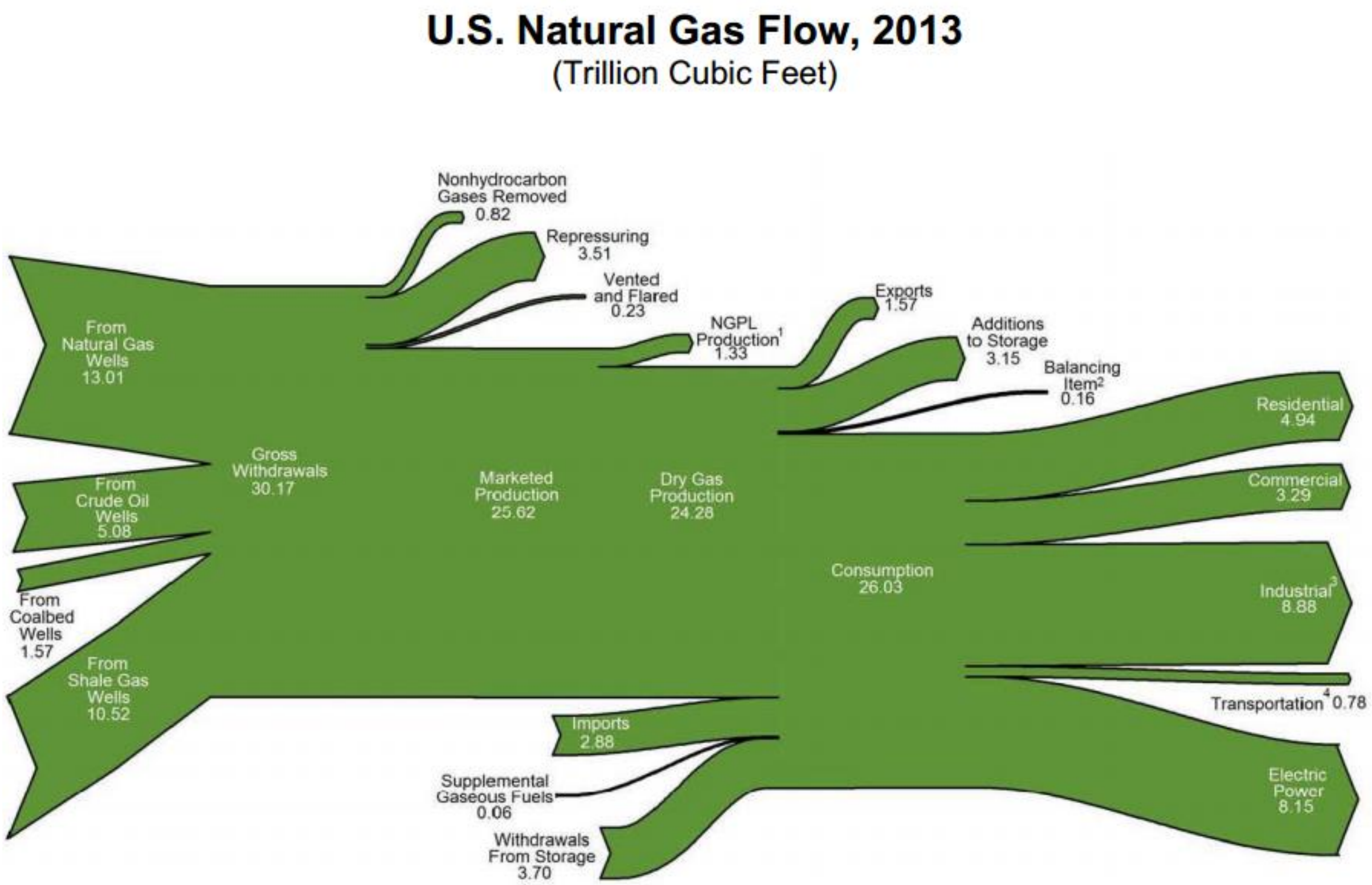
Declining nature gas prices!

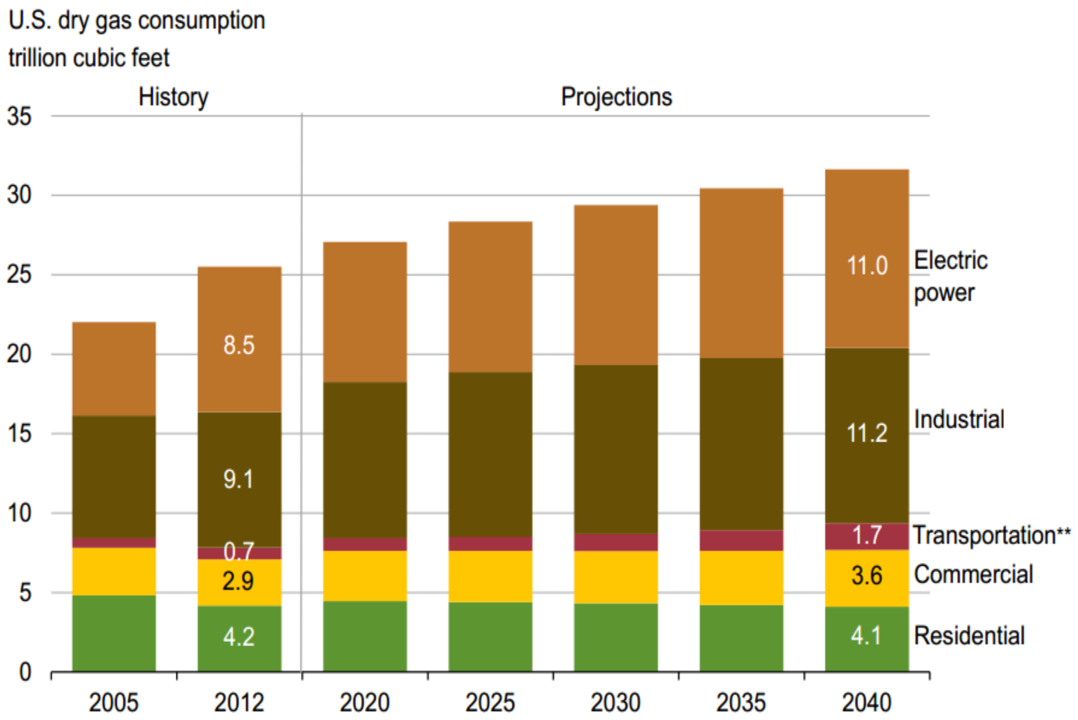


Note: Sometimes gas prices are given in $ per MMBTU as they are here, and sometimes they are given in $ per Mcf.
The numbers will be almost the same, because $ per Mcf is 1.025 times $ per MMBTU.

http://www.eia.gov/dnav/ng/hist/rngwhhdd.htm

NATURAL GAS CONSUMPTION

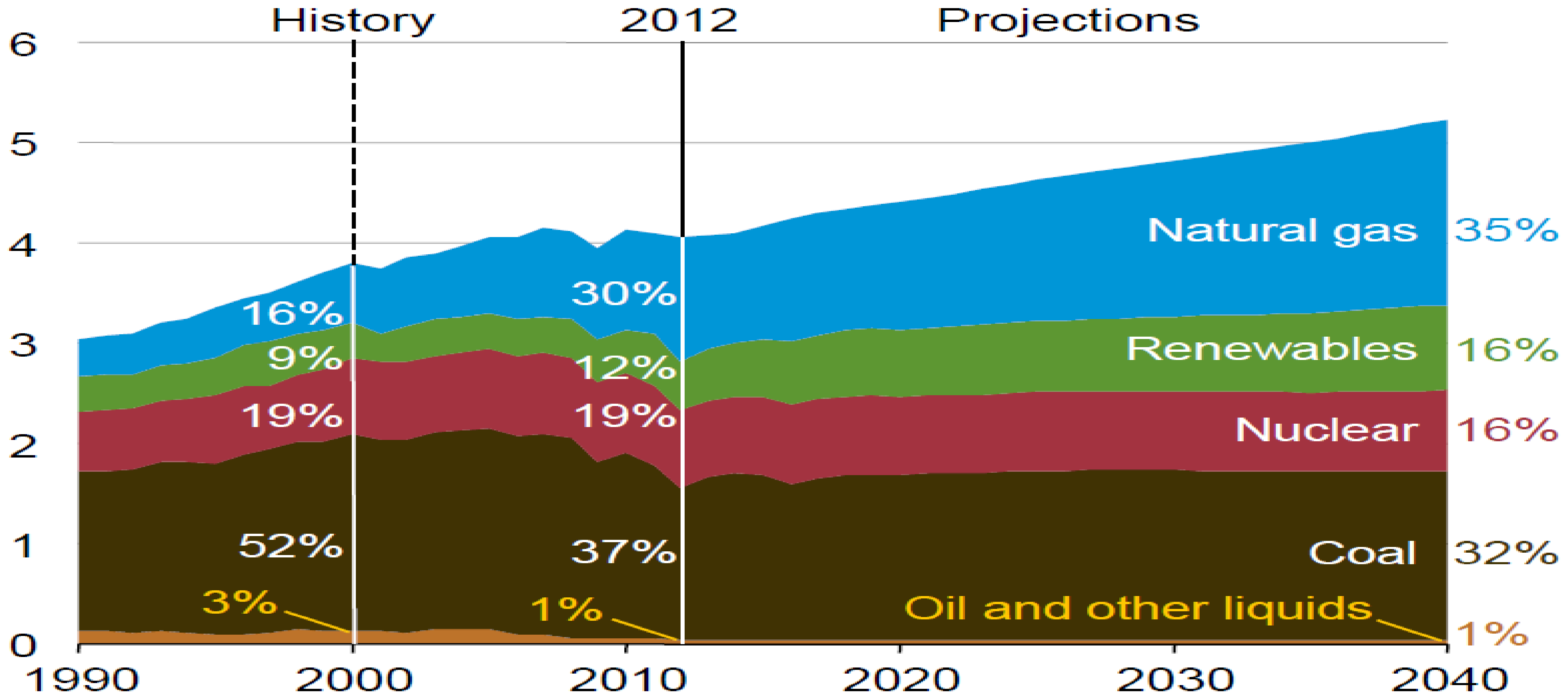




3. Include lease condensates
4. NG consumed in the operation of pipelines for transmission and distribution plus a small quantity used as vehicle fuel
Source: EIA.
http://www.eia.gov/totalenergy/data/monthly/pdf/flow/natural_gas.pdf

Change in US Electric Energy Portfolio

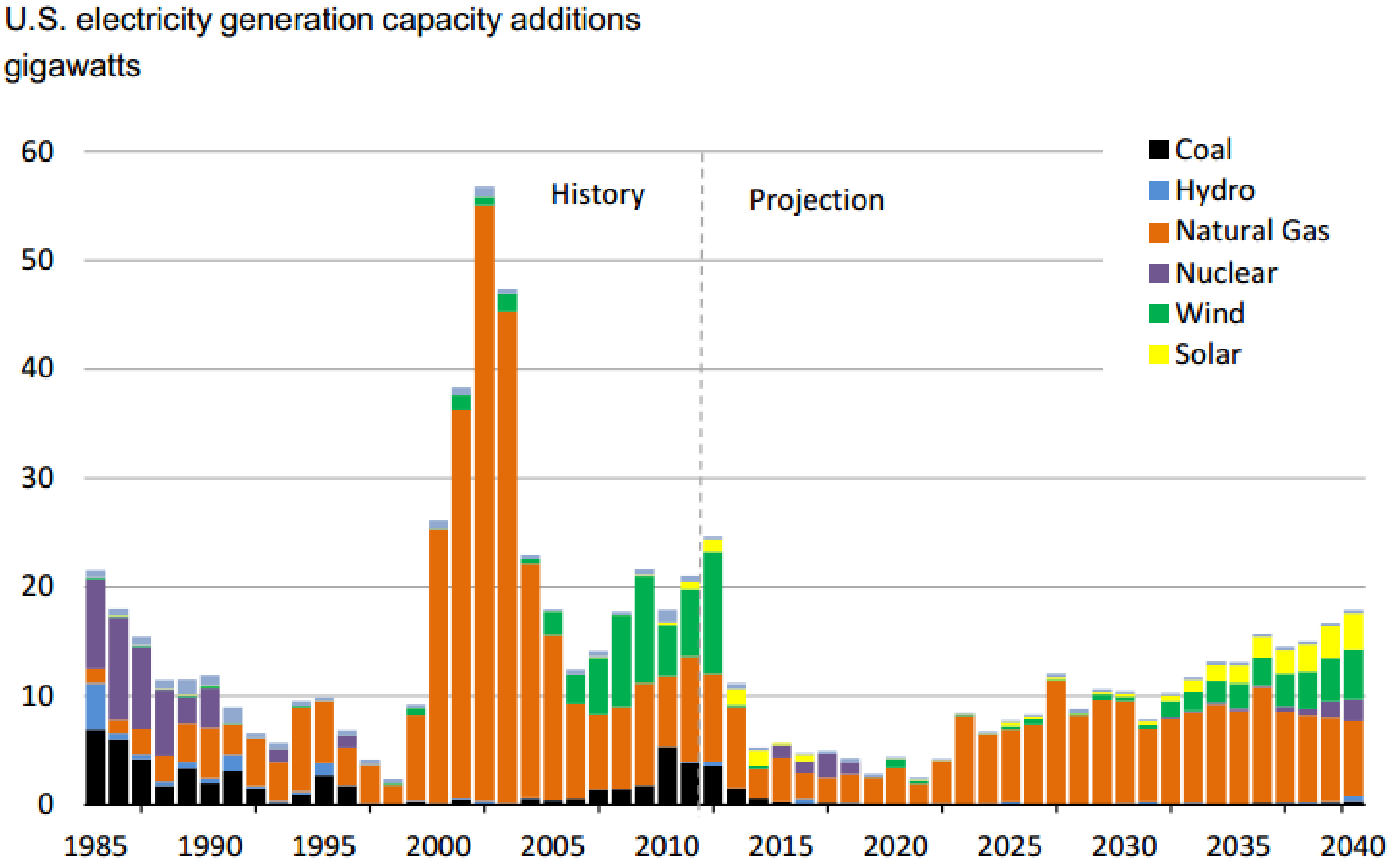
Electric energy generation by fuel, 1990-2040 (trillion kW-hrs)



US Energy Information Administration, "Annual Energy Outlook 2014: Early Release Overview," available http://www.eia.gov/forecasts/aeo/er/pdf/0383er(2014).pdf.

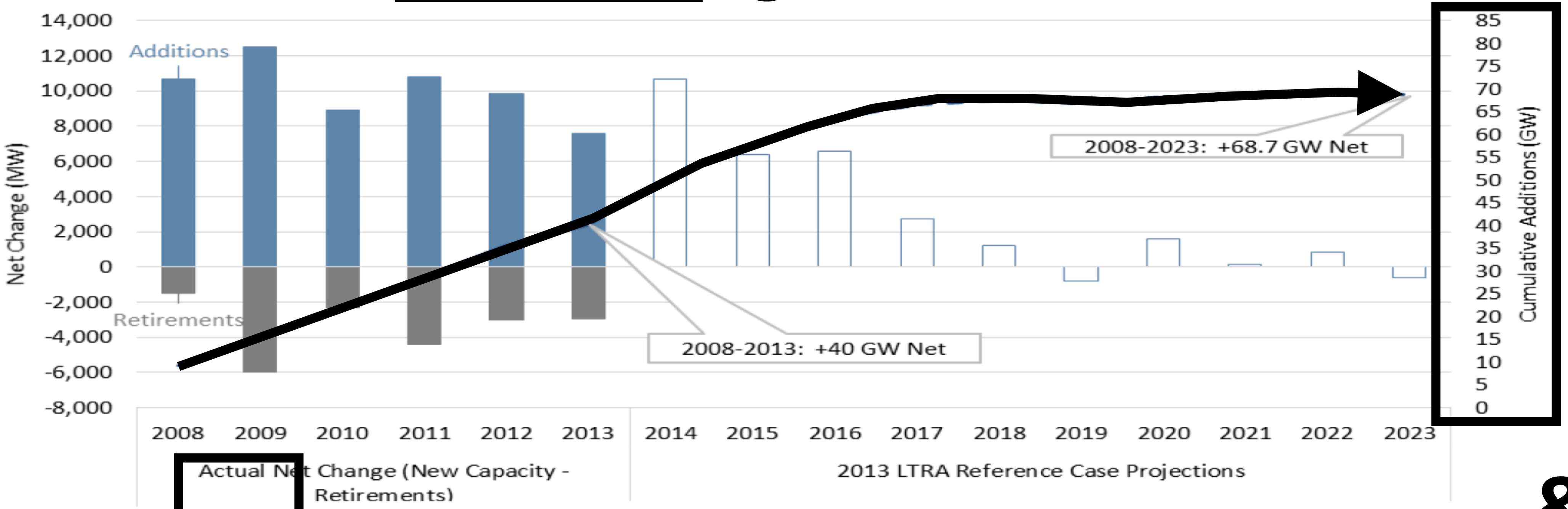
Growth in Capacity: All

Additions to electricity generation capacity, 1985-2040

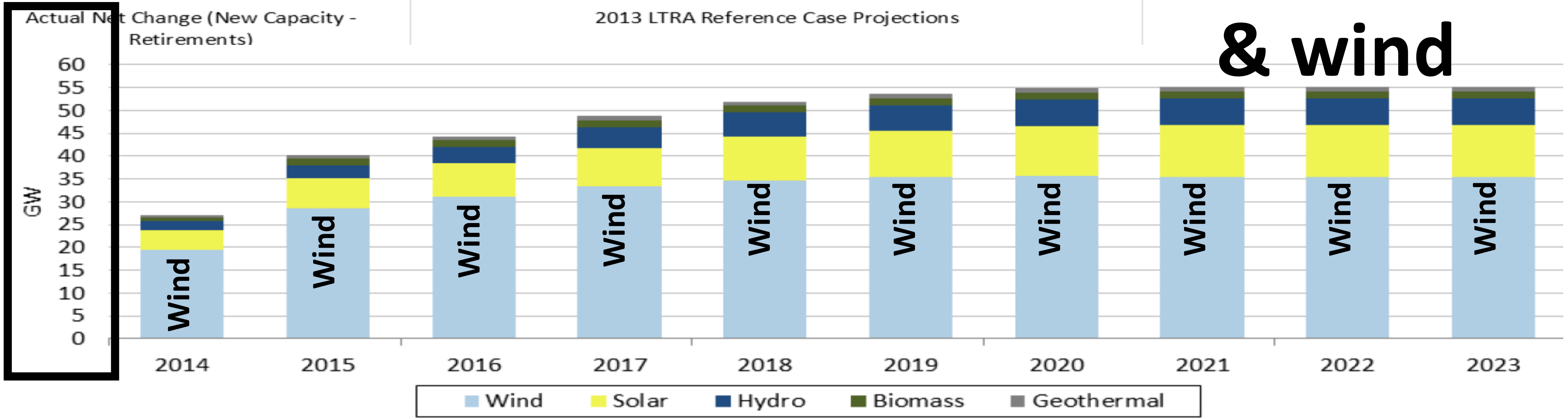


Source: EIA Form 860 & EIA, Annual Energy Outlook 2013

Growth in capacity: gas



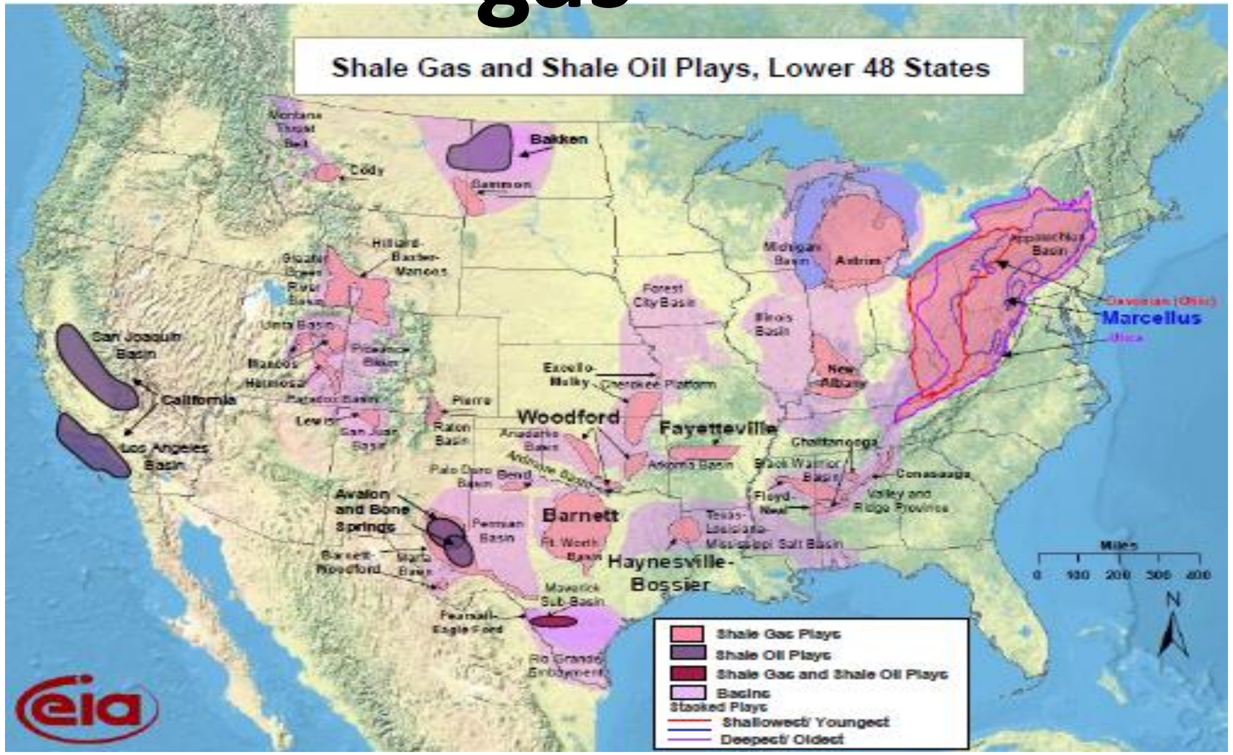
& wind



North American Reliability Corporation (NERC), "Long-term reliability assessment, 2013," available http://www.nerc.com/pa/rapa/ra/reliability%20assessments%20dl/2013_ltra_final.pdf.

How much do we have?

gas



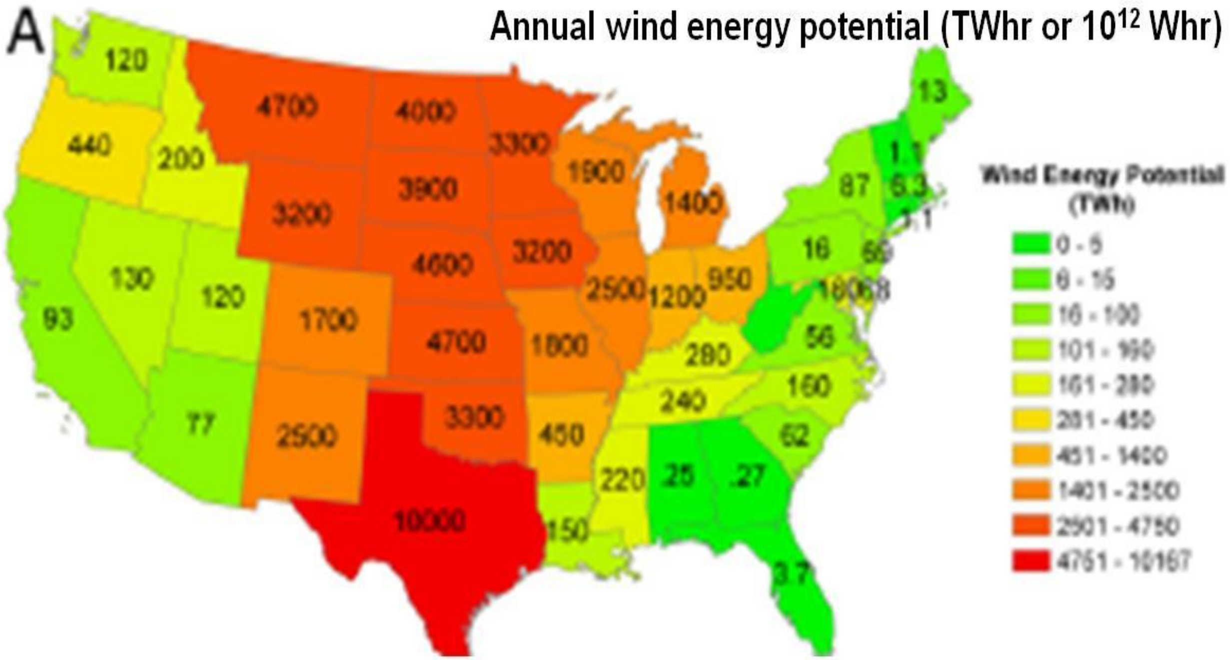
Tcf=trillion cubic feet

Cur US natgas production= 24Tcf/yr
Tech rcrvble dry gas=1698Tcf: R/P=71yrs
Tech rcrvble dry shale gas=637Tcf: R/P=27yrs

Note: Tech rcrvble dry gas is that which could be produced with current technology, regardless of cost. It includes "economically rcrvble dry gas."

Source: US EIA, "Technically Recoverable Shale Oil and Shale Gas Resources: An Assessment of 137 Shale Formations in 41 Countries Outside the United States," June, 2013, http://www.eia.gov/analysis/studies/worldshalegas/

wind



Total onshore energy potential is 62Pwhr which is over 2.1 × Total annual US energy consumption of 100 Quads

20x20 DOE Report: "The nation has more than 8,000 GW of available land-based wind resources that industry estimates can be captured economically ." (~24528 TWhrs)

Analysis assumes (a) sites having capacity factor > 20% included; (a) loss of 20% and 10% of potential power for onshore and offshore, respectively, caused by interturbine interference, (c) offshore siting distance within 50 nm (92.6 km) of nearest shoreline.

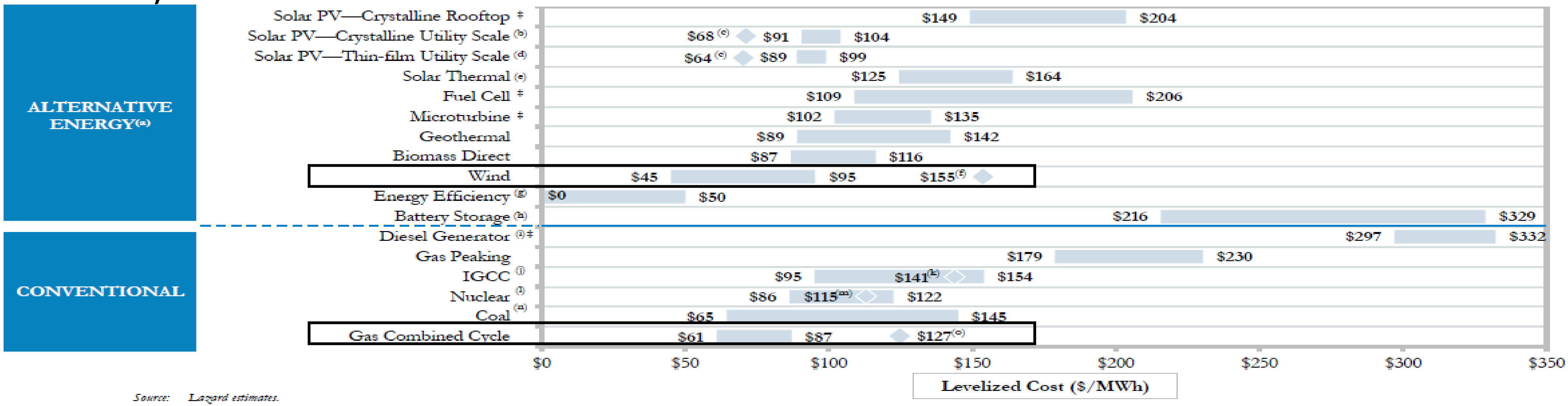
Source: Xi Lua, M. McElroya, and J. Kiviluomac, "Global potential for wind-generated electricity," Proc. of the National Academy of Sciences, 2009, www.pnas.orgcgidoi10.1073pnas.0904101106.

What are the risks?

Levelized cost of energy

$$LCOE = \frac{\text{Levelized Annual Revenue Requiremnt}}{\text{Average Annual Energy Production}}$$

(Unsubsidized)



Source: *Lazard estimates.*

Note: Assumes 60% debt at 8% interest rate and 40% equity at 12% cost for conventional and Alternative Energy generation technologies. Assumes Powder River Basin coal price of $1.99 per MMBtu and natural gas price of $4.50 per MMBtu. As many have argued, current solar pricing trends may be masking material differences between the inherent economics of certain types of thin-film technologies and crystalline silicon.

‡ Denotes distributed generation technology.

(a) Analysis excludes integration costs for intermittent technologies. A variety of studies suggest integration costs ranging from $2.00 to $10.00 per MWh.

(b) Low end represents single-axis tracking. High end represents fixed-tilt installation. Assumes 10 MW system in high insolation jurisdiction (e.g., Southwest U.S.). Not directly comparable for baseload.

(c) Diamonds represent estimated implied levelized cost of energy in 2015, assuming $1.50 per watt for a crystalline single-axis tracking system and $1.50 per watt for a thin-film single-axis tracking system.

(d) Low end represents single-axis tracking. High end represents fixed-tilt installation. Assumes 10 MW fixed-tilt installation in high insolation jurisdiction (e.g., Southwest U.S.).

(e) Low end represents solar tower without storage. High end represents solar tower with storage capability.

(f) Represents estimated midpoint of levelized cost of energy for offshore wind, assuming a range of $3.10 – $5.00 per watt.

(g) Estimates per National Action Plan for Energy Efficiency; actual cost for various initiatives varies widely. Estimates involving demand response may fail to account for opportunity cost of foregone consumption.

(h) Indicative range based on current and future stationary storage technologies; assumes capital costs of $400 – $750/KWh for 6 hours of storage capacity, $60/MWh cost to charge, one full cycle per day (full charge and discharge), efficiency of 66% – 75% and fixed O&M costs of $5 to $20 per KWh installed per year.

(i) Low end represents continuous operation. High end represents intermittent operation. Assumes diesel price of $4.00 per gallon.

(j) High end incorporates 90% carbon capture and compression. Does not include cost of transportation and storage.

(k) Represents estimate of current U.S. new IGCC construction with carbon capture and compression. Does not include cost of transportation and storage.

(l) Does not reflect decommissioning costs or potential economic impact of federal loan guarantees or other subsidies.

(m) Represents estimate of current U.S. new nuclear construction.

(n) Based on advanced supercritical pulverized coal. High end incorporates 90% carbon capture and compression. Does not include cost of transportation and storage.

(o) Incorporates 90% carbon capture and compression. Does not include cost of transportation and storage.

Lazard's levelized cost of energy analysis- Version 7.0, August 2013, available http://gallery.mailchimp.com/ce17780900c3d223633ecfa59/files/Lazard_Levelized_Cost_of_Energy_v7.0.1.pdf

Gas and wind: overall comparison (yellow is winner)

	WIND	NATURAL GAS
Overall cost (see last slide)	Low	Low
Fuel production - land	None	Some
Fuel production - water	None	Much
Fuel production – GHG emissions	None	Some (methane)
Fuel transport - land	None	Some
Fuel transport – public resistance	None	Some
Power plant - land	Some	Some
Power plant - water	None	Much
Power plant – CO_2 emissions	None	Some
Power plant - other	Bats and birds	None
Electric transmission - land	Much	Some
Electric transmission – public resistance	Much	Some
Future risk (see next slide)	Little	Much

Gas and wind: risk comparison

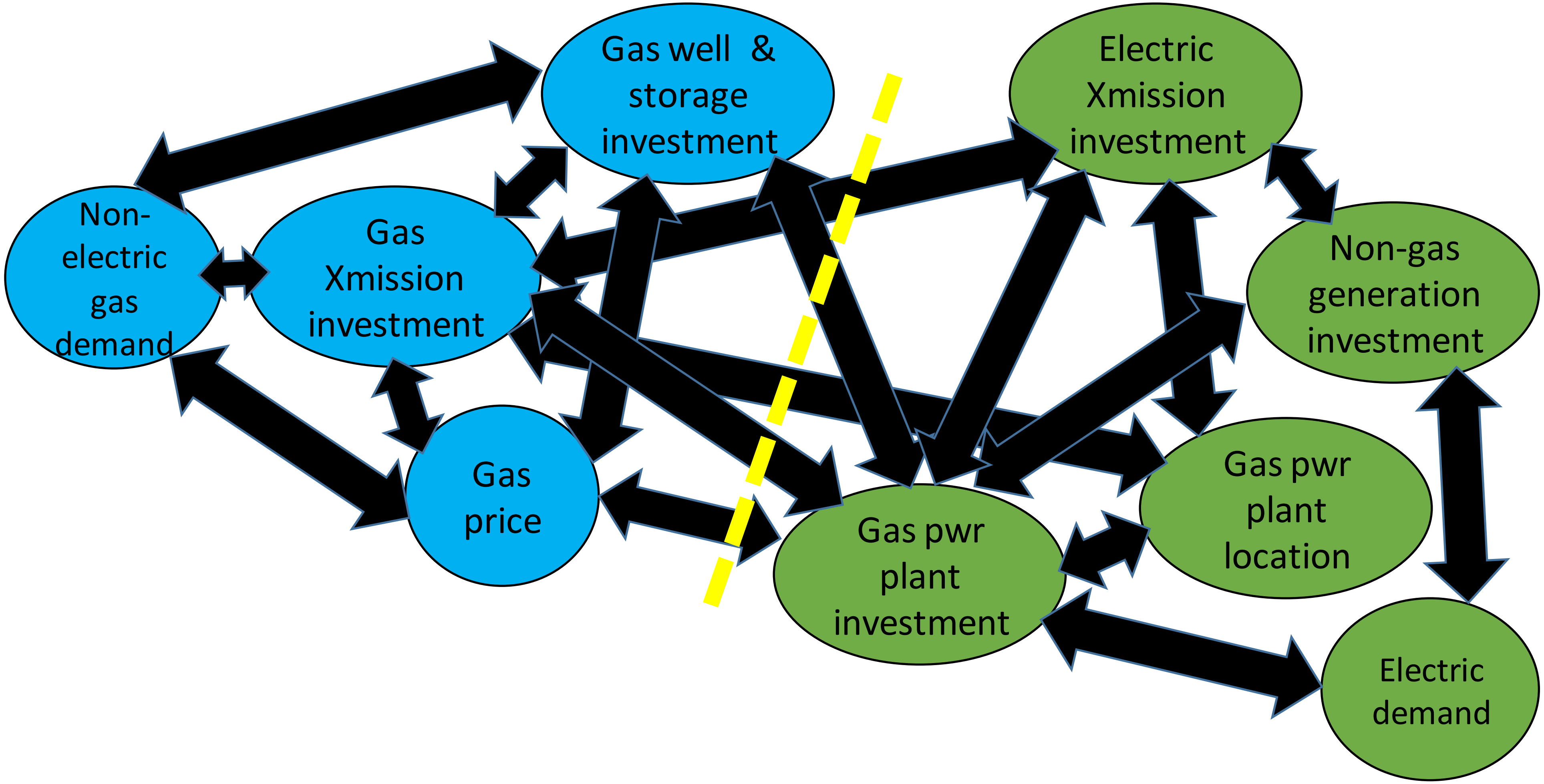
<u>Risks of heavy gas portfolio</u>:

1. Gas price goes up due to <u>gas demand increase</u> (pwr plnts, trnsprtn, exports) or <u>gas supply decrease</u>: (gas depletion will occur but could happen sooner due to major fracking impact via water poisoning or earthquake)
2. GHG-induced climate change occurs rapidly re-quiring gas use reduction

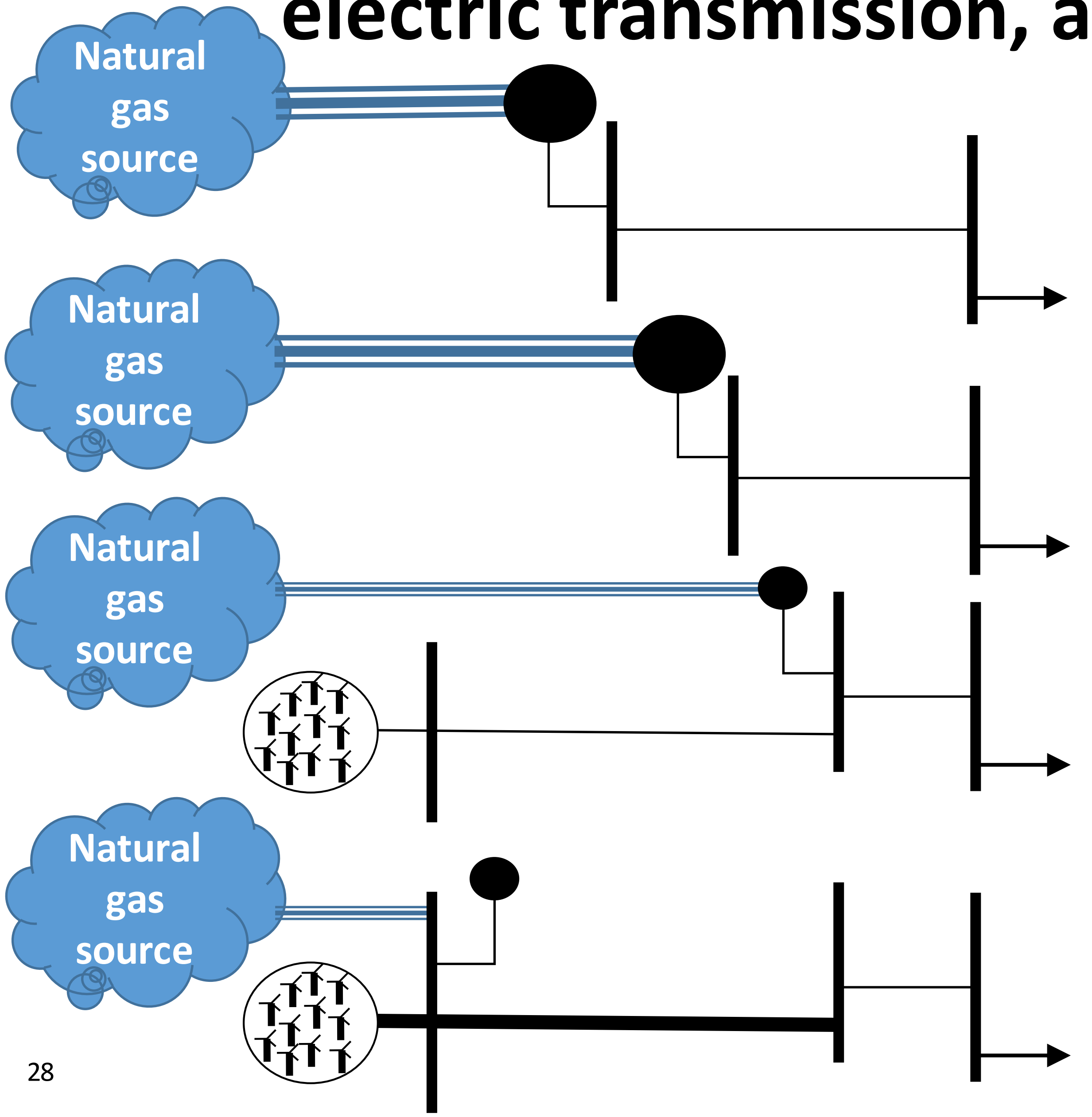
<u>Risks of heavy wind portfolio</u>:

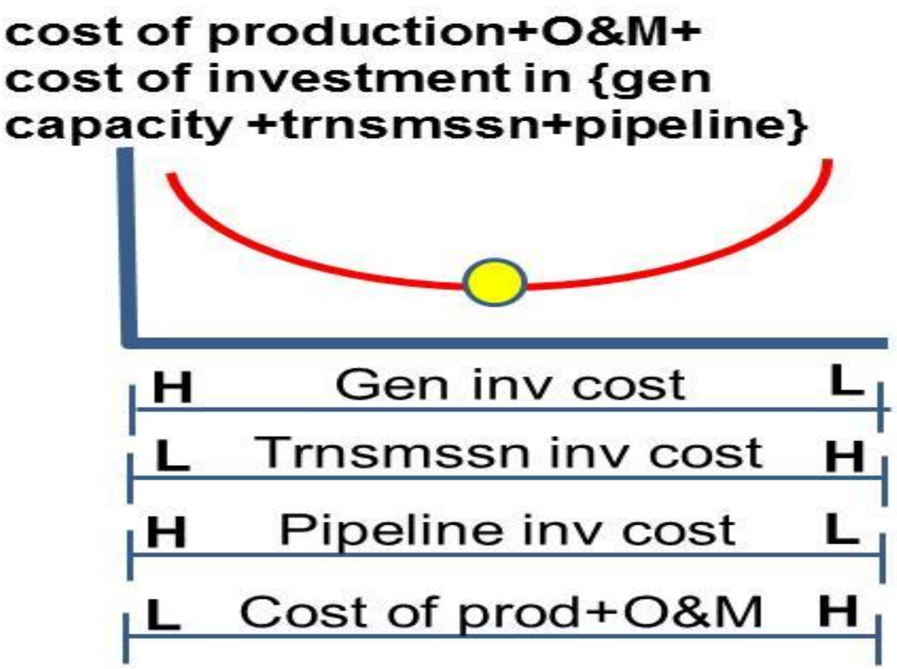
1. Climate change reduces wind speeds
2. Major bat/bird impact
3. LCOE does not decrease
4. No new transmission

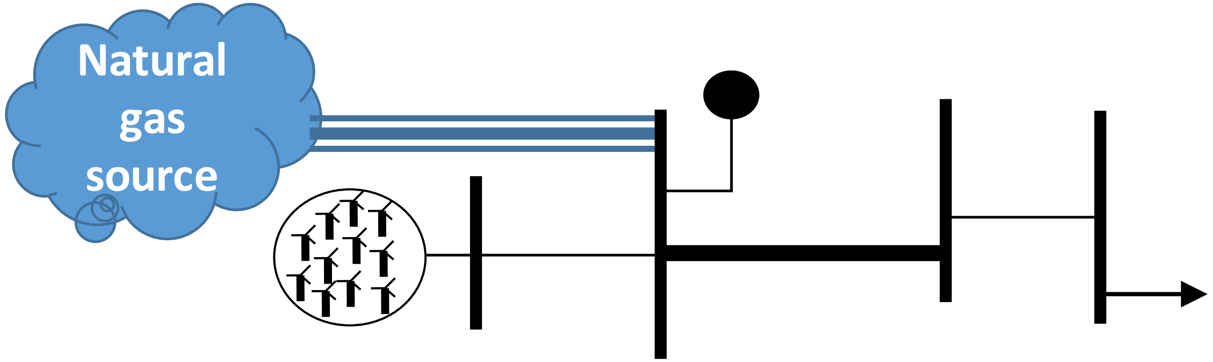
Gas-electric investment coordination



Co-optimization of electric generation, electric transmission, and natural gas pipeline







PIPELINES INVESTMENT COST

NATURAL GAS CHARACTERISTICS	
Energy Content (MMBTU/MMcf)	1,027

PIPELINE CHARACTERISTICS	
Diameter (inch)	42
Transmission Capacity (MMcf/day)	1,800.0
Transmission Capacity (MMcf/hour)	75.00

COMPRESSOR STATION CHARACTERISTICS	
Distance between stations (miles)	50
Power (HP per station)	25,000

PIPELINE INVESTMENT COSTS	
Pipeline Investment Cost (*) ($ per inch - mile)	155,000
Pipeline Investment Cost ($ per mile)	6,510,000

This is high.

COMPRESSOR STATION COSTS	
Compressor Station Inv. Cost (*) ($ per HP)	2,600
Compressor Station Inv. Cost ($ per mile)	1,300,000

(*) Source: North America Midstream Infrastructure through 2035: Capitalizing on Our Energy Abundance. The INGAA Foundation. March 18, 2014

$$6{,}510{,}000\$/mile + \$1{,}300{,}000\$/mile = \$7{,}810{,}000\$/mile$$

$$\frac{7{,}810{,}000\$/mile}{75 mmcf\ /hr} = 104{,}133\$/(mmcf\ /hr \times mile)$$

$$\frac{104{,}133\$/mmcf\ /hr \times mile)}{1027 mmbtu/mmcf} = 101.4\$/(mmbtu/hr \times mile)$$

PIPELINE SYSTEM INVESTMENT COSTS	
Pipeline System Investment Cost ($ per mile)	7,810,000
Pipeline System Investment Cost ($ per (MMcf/hr x mile))	104,133
Pipeline System Investment Cost ($ per (MMBTU/hr x mile))	101.40

TRANSMISSION LINES INVESTMENT COST

CONVENTIONAL COMBINED CYCLE PLANT CHARACTERISTICS	
Heat Rate (MMBTU/GWh)	7,196

This calculation provides a "pre-combustion" value to enable comparability with natural gas, i.e., flow on transmission lines is energy after conversion losses, whereas flow on gas pipelines is energy before conversion losses.

$$\frac{1{,}000{,}000\$/GWmile}{7196 MMBTU\ /GWhr} = 139.0 mmbtu/hr \times mile$$

TRANSMISSION LINE INVESTMENT COSTS	
Transmission Line Investment Cost ($ per GW - mile)	1,000,000
Transmission Line Investment Cost ($ per (MMBTU/h x mile))	139.0

This is low. Could be $1.5M/gw-m

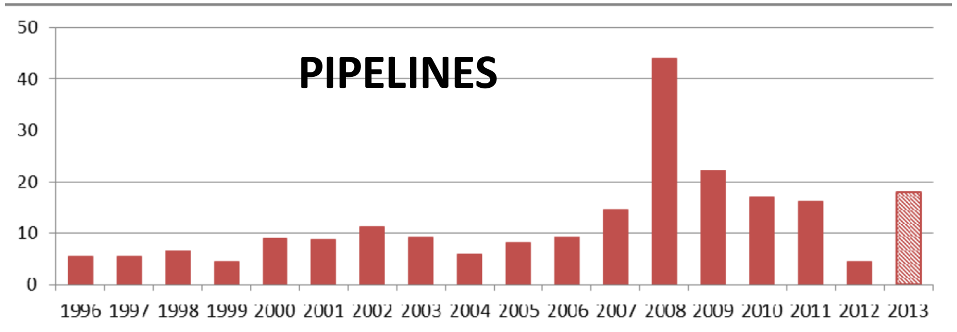
You can also obtain "post-combustion" values: 101.4*7196=730,000$/GW-mile

Similar analysis, but of a specific case, done by BPA and AGA, is here:
www.northwestchptap.org/NwChpDocs/Transmission_and_N_Gas_Comparing_Pipes_and_Wires_032304.pdf

Gas-electric investment growth

Figure 2. U.S. Natural Gas Transmission Pipeline Capacity Additions

(Billion cubic feet per day)

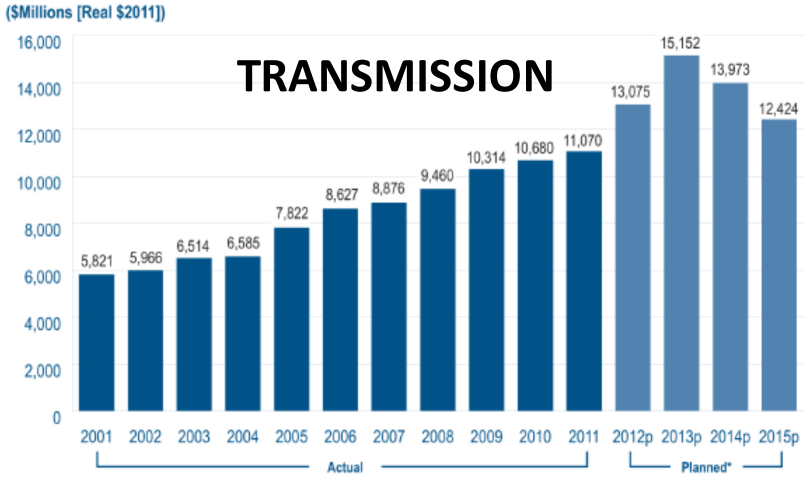


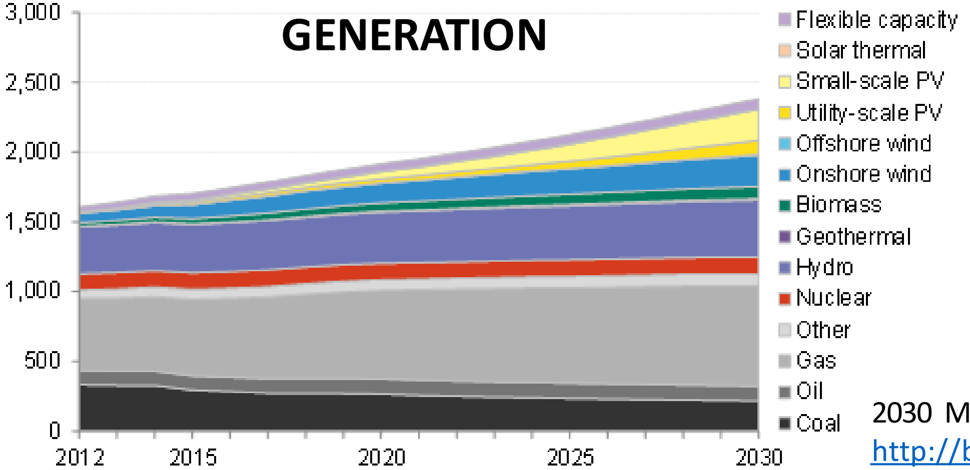
Source: Energy Information Administration, "U.S. Natural Gas Pipeline Projects," spreadsheet, January 25, 2103, http://www.eia.gov/naturalgas/data.cfm. Figures are based on regulatory filings, industry information and company reports.

Notes: 2013 figures are anticipated. Generally, only transmission lines are included; gathering lines, distribution lines, and liquefied natural gas marine terminals are excluded. Both interstate and intrastate transmission pipelines are included.

P. Parfomak, "Interstate Natural Gas Pipelines: Process and Timing of FERC Permit Application Review," Nov. 19, 2013, Congressional Research Service, http://fas.org/sgp/crs/misc/R43138.pdf.

Actual and Planned Transmission Investment by Shareholder-Owned Electric Utilities (2001-2015)





p = preliminary

Note: The Handy-Whitman Index of Public Utility Construction Costs used to adjust actual investment for inflation from year to year. Forecasted investment data are adjusted for inflation using the GDP Deflator.

*Planned total industry expenditures are preliminary and estimated from 85% response rate to EEI's Electric Transmission Capital Budget & Forecast Survey. Actual expenditures from EEI's Annual Property & Plant Capital Investment Survey and from the FERC Form 1 reports.

Source: Edison Electric Institute, Business Information Group

Edison Electric Institute, "Transmission Investment: Adequate Returns and Regulatory Certainty Are Key," June 2013, http://www.eei.org/issuesandpolicy/transmission/Documents/transmission_investment.pdf

2030 Market Outlook, Bloomberg New Energy Finance, http://bnef.folioshack.com/document/v71ve0nkrs8e0/1fp9ha

PIPELINE FLOW MODEL

ASSUMPTIONS

One-dimensional, horizontal, compressible, isothermal, steady-state flow

Isothermal flows are used for modeling slow transients, like normal operational demand changes.

ACCURATE MODEL

SET OF PARTIAL DIFFERENTIAL EQUATIONS
- Mass conservation law
- Momentum conservation law
- Energy conservation law

APPROXIMATE MODEL

SET OF NONLINEAR ALGEBRAIC EQUATIONS

$$G_{W_k} = \left[\frac{\rho_i^2 - \rho_j^2}{K_k} \right]^{1/n}$$

Weymouth: n=2; K_k depends on specific pipeline k

K_k and n are dependent of the equation used for the calculation of the **friction factor**

Turbulent flows in hydraulically smooth pipes
- Panhandle A Equation
- AGA Partially Turbulent Equation
- White Equation

Turbulent flows in rough pipes
- Panhandle B Equation
- AGA Partially Turbulent Equation
- Weymouth Equation

$$\rho_i^2 - \rho_j^2 = K_k G_{W_k} \left| G_{W_k} \right|$$

Weymouth equations are frequently used in the design of transmission networks, because they usually overestimate the pressure drop calculations and are thus conservative – see Mohitpour et al. (2003)

LINEARIZING WEYMOUTH EQUATIONS USING A TAYLOR SERIES EXPANSION REPRESENTATION

- Existing pipelines

$$K_d\left(G_{W_d}^2 - G'^2_{W_d}\right) = \rho_{B_d}{}^2 - \rho_{E_d}{}^2$$

$$K_d'\left(G_{W_d} - G'_{W_d}\right) = c_{B_d}\rho_{B_d} - c_{E_d}\rho_{E_d}$$

- Candidate pipelines

$$-\left(1-S_d\right)M \le \rho_{B_d}{}^2 - \rho_{E_d}{}^2 - K_d\left(G_{W_d}^2 - G'^2_{W_d}\right) \le \left(1-S_d\right)M$$

$$-\left(1-S_d\right)M \le c_{B_d}\rho_{B_d} - c_{E_d}\rho_{E_d} - K_d'\left(G_{W_d} - G'_{W_d}\right) \le \left(1-S_d\right)M$$

$$c_{B_d} = \sqrt{\frac{\pi_{B_d}^{(0)}}{\left|\pi_{B_d}^{(0)} - \pi_{E_d}^{(0)}\right|}} \qquad c_{E_d} = \sqrt{\frac{\pi_{E_d}^{(0)}}{\left|\pi_{B_d}^{(0)} - \pi_{E_d}^{(0)}\right|}}$$

$$K_d' = \sqrt{K_d}$$

$$\pi_{B_d}^{(0)} = \left(\rho_{B_d}^{(0)}\right)^2$$

$$\pi_{E_d}^{(0)} = \left(\rho_{E_d}^{(0)}\right)^2$$

How to choose this point?

$\left(\rho_{B_d}^{(0)}, \rho_{E_d}^{(0)}\right)$ This is the point around which the Taylor Series Expansion Representation is done

MODEL 1 (MILP, DCPF/Transport Gas)

Minimize: Generation Costs & Transmission Lines Costs (operational & investment) **+** **Production & Storage Operational Costs and Pipelines Operational & Investments Costs**

subject to

ELECTRIC SYSTEM CONSTRAINTS

Electric Generating Units constraints
- Maximum power output (capacity credit)
- Maximum electricity output (capacity factor)

Transmission network constraints
- Node power balance equations
- **DC Power flow equations**
- Transmission lines capacity bounds

Power system security and reliability constraints
- Electric Generating Units reserves

Generation capacity constraints
- Balance (additions and retirements)
- Lower and upper bounds

Transmission lines investment constraints using a Disjunctive Model

INTEGERS

GAS SYSTEM CONSTRAINTS

NG Wells Production constraints
- Bounds on the production levels

Transmission network constraints
- Node gas balance equations
- ~~Gas flow – pressure equations~~
- Pipelines capacity bounds

NG Storage constraints
- Lower and upper storage levels (storage, injection, and withdrawal).
- Energy balance constraints

Pipelines investment constraints using a transportation model
- Balance (additions and retirements)
- Lower and upper investment bounds

Relaxed Model

MODEL 2 (MILP, DCPF/Linear Gas)

Minimize: Generation Costs & Transmission Lines Costs (operational & investment) **+** **Production & Storage Operational Costs and Pipelines Operational & Investments Costs**

subject to

ELECTRIC SYSTEM CONSTRAINTS

Electric Generating Units constraints
- Maximum power output (capacity credit)
- Maximum electricity output (capacity factor)

Transmission network constraints
- Node power balance equations
- **<u>DC Power flow equations</u>**
- Transmission lines capacity bounds

Power system security and reliability constraints
- Electric Generating Units reserves

Generation capacity constraints
- Balance (additions and retirements)
- Lower and upper bounds

<u>Transmission lines investment constraints using a Disjunctive Model</u>

INTEGERS

GAS SYSTEM CONSTRAINTS

NG Wells Production constraints
- Bounds on the production levels

Transmission network constraints
- Node gas balance equations
- **<u>Linearized gas flow – pressure equations</u>**
- Pipelines capacity bounds

NG Storage constraints
- Lower and upper storage levels (storage, injection, and withdrawal).
- Energy balance constraints

<u>Pipelines investment constraints using a Disjunctive Model</u>

INTEGERS

MODEL 3 (MINLP, DCPF/Nonlinear Gas)

Minimize: Generation Costs & Transmission Lines Costs (operational & investment) **+** **Production & Storage Operational Costs and Pipelines Operational & Investments Costs**

subject to

ELECTRIC SYSTEM CONSTRAINTS

Electric Generating Units constraints

- Maximum power output (capacity credit)
- Maximum electricity output (capacity factor)

Transmission network constraints

- Node power balance equations
- **DC Power flow equations**
- Transmission lines capacity bounds

Power system security and reliability constraints

- Electric Generating Units reserves

Generation capacity constraints

- Balance (additions and retirements)
- Lower and upper bounds

Transmission lines investment constraints using a Disjunctive Model

INTEGERS

GAS SYSTEM CONSTRAINTS

NG Wells Production constraints

- Bounds on the production levels

Transmission network constraints

- Node gas balance equations
- **Gas flow – pressure equations**
- Pipelines capacity bounds

NONLINEAR

NG Storage constraints

- Lower and upper storage levels (storage, injection, and withdrawal).
- Energy balance constraints

Pipelines investment constraints using a Disjunctive Model

INTEGERS

SOLUTION ALGORITHM

Candidate selection

- Determine the set of links, for the electric and natural gas transmission systems to be considered as expansion candidates in the co-optimization problem

Initial co-optimization

- Determine a set of optimal gas flows in the pipeline network for this optimization problem (node pressures for the gas system are not consider at this point).

Linearizing Weymouth Equations

- Determine a set of node pressures by solving the Weymouth Equations for the pipeline network considering the gas flows obtained before.
- Obtain a linear representation for the Weymouth Equations using a Taylor Series Expansion using the flows and pressures obtained before.

Final co-optimization

- Formulate and solve the co-optimization problem using a disjunctive model for the electric and natural gas system.

Candidate selection

- Two possible models:
  - Iterative minimum spanning tree method
  - Transportation model

MODEL 1: Initial co-optimization

- Disjunctive model for the electric system using DC power flow equations
- Transportation model with capacity expansion for the gas system using upper bounds for the transmission capacity

Linearize Weymouth Equations

- Non-linear set of Weymouth Equations for each simulation period.

MODEL 2: Final co-optimization

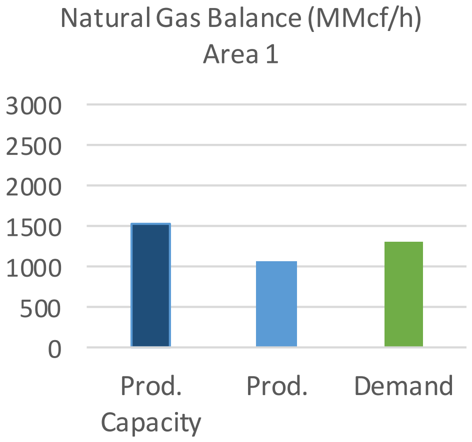
- Disjunctive model for the electric system using DC power flow equations
- Disjunctive model for the gas system using linearized Weymouth Equations

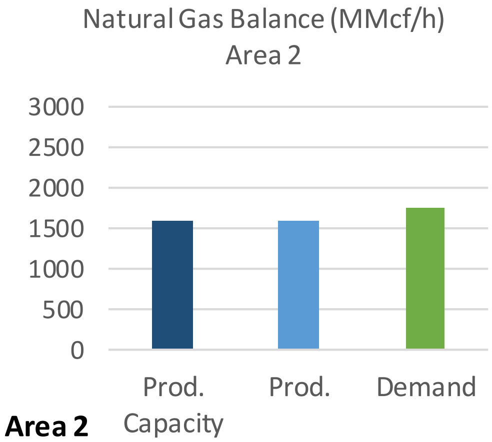
CAPACITY OF THE PIPELINES (MMcf/h)

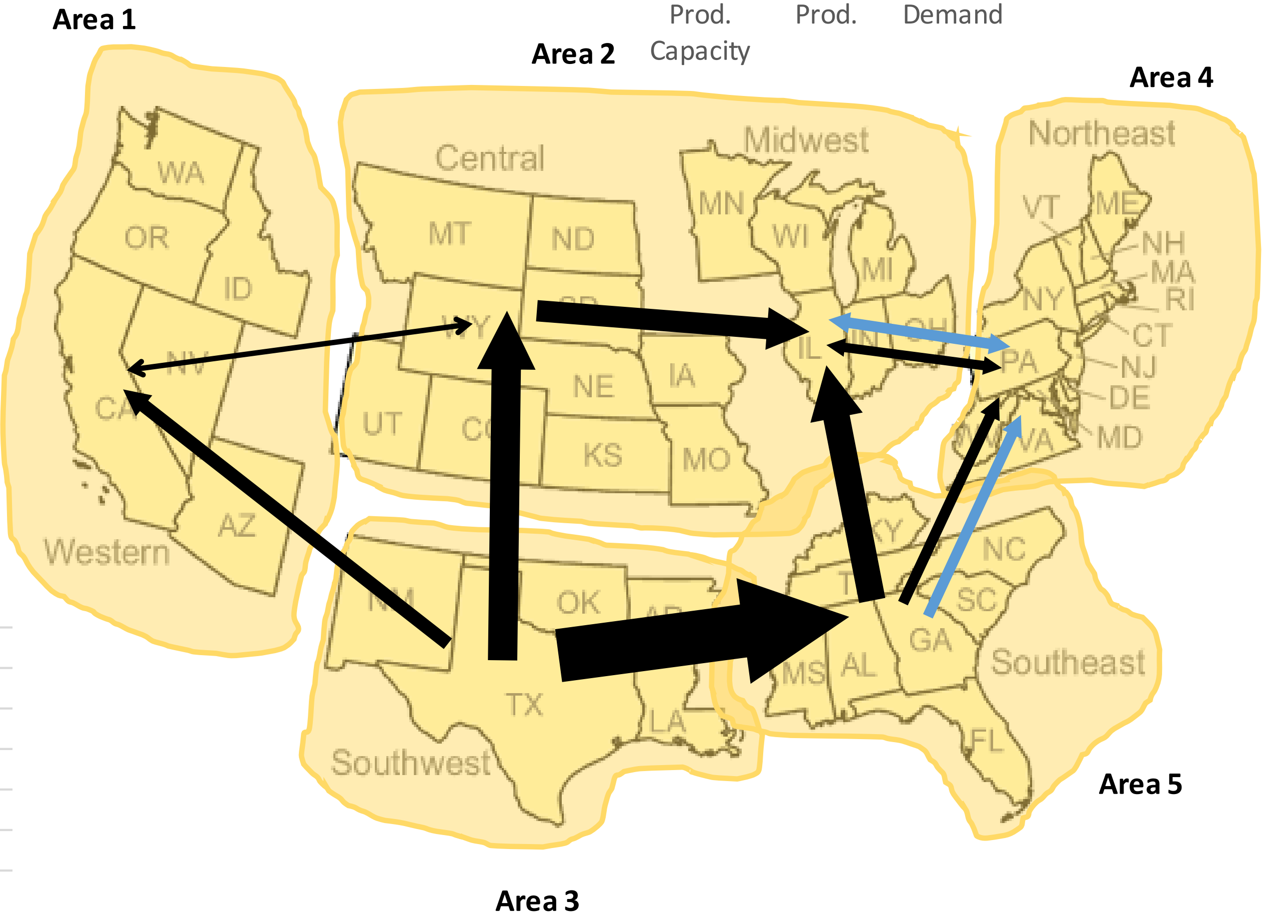
A bidirectional arrow means that the flows often change their direction for different time periods (different months, different load blocks, etc.)

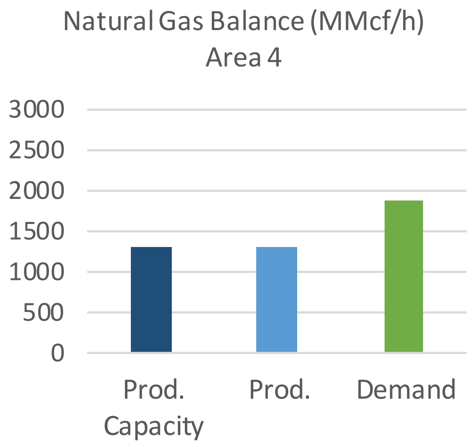
Existing Pipelines

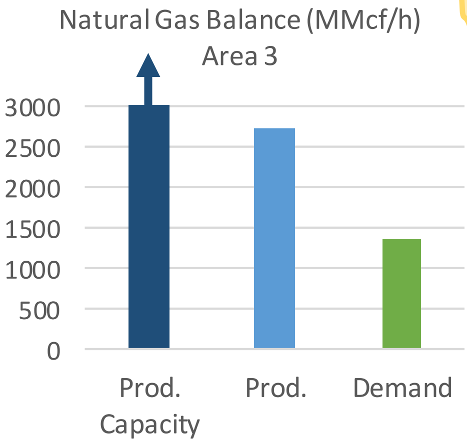
New Pipelines

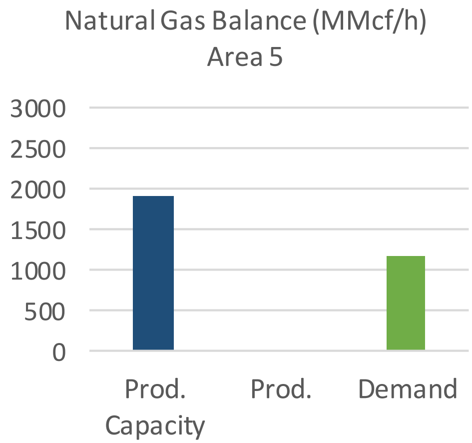












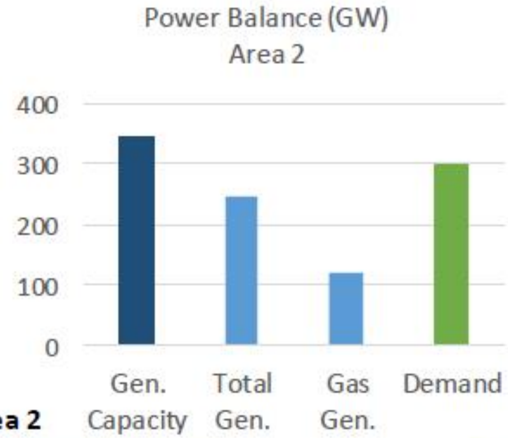
CAPACITY OF THE TRANSMISSION LINES (GW)

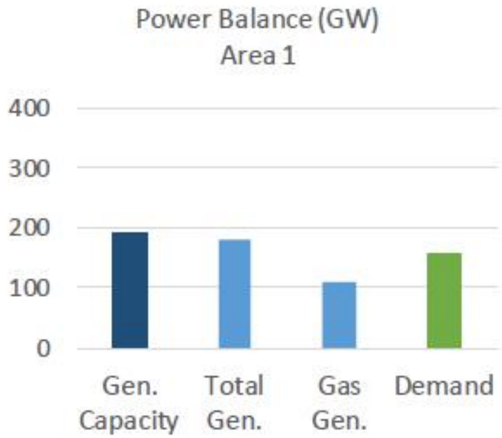
HIGH DEMAND

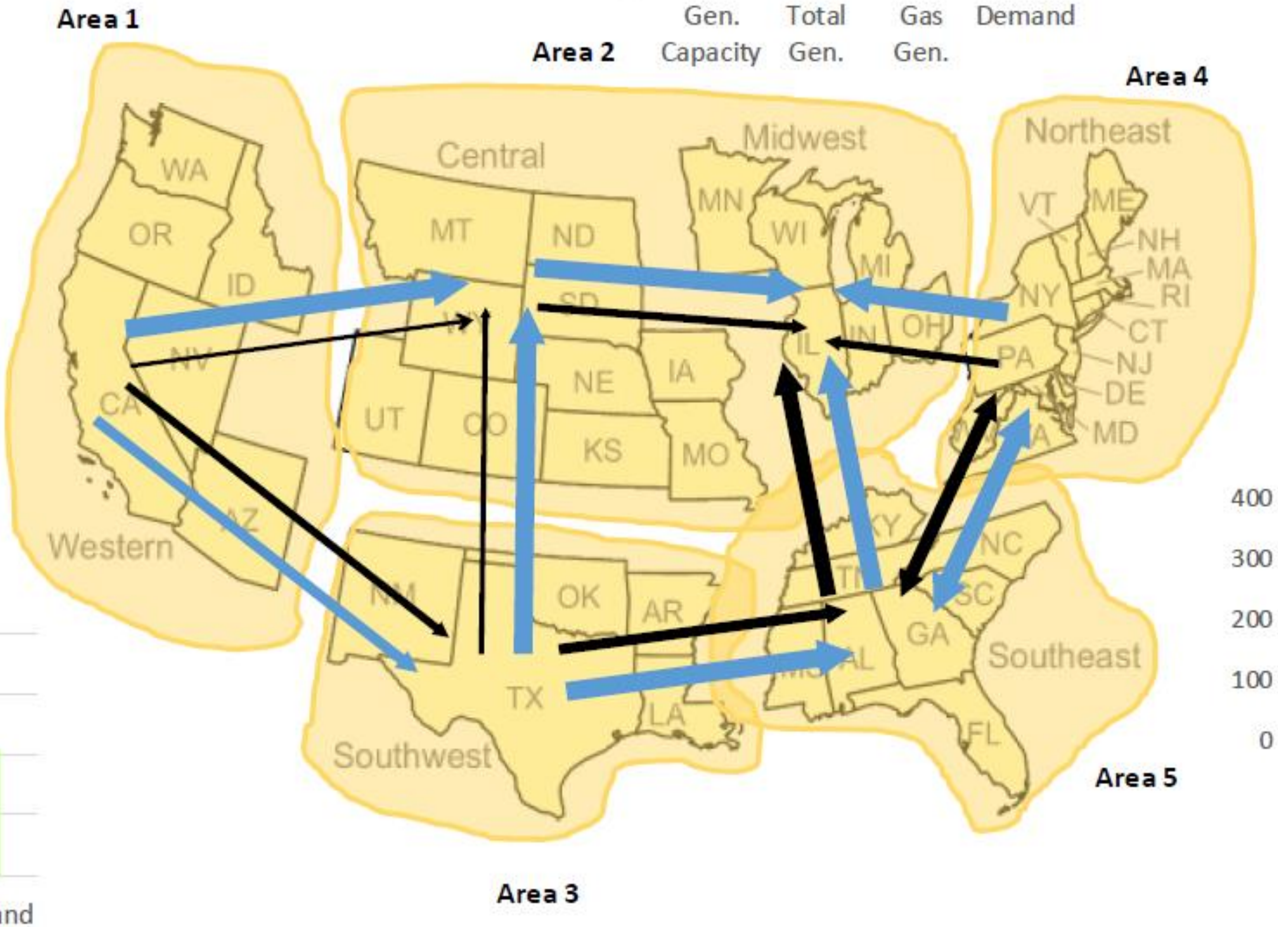
A bidirectional arrow means that the flows often change their direction for different time periods (different months, different load blocks, etc.)

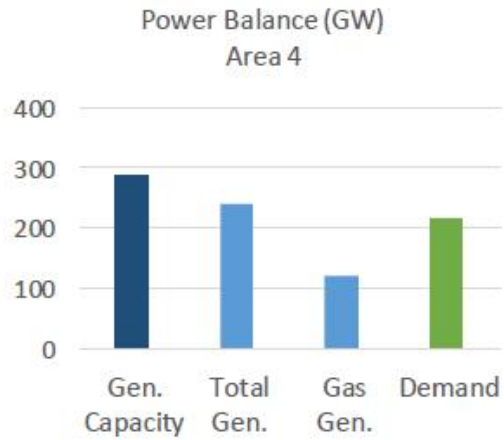
Existing Transmission Lines

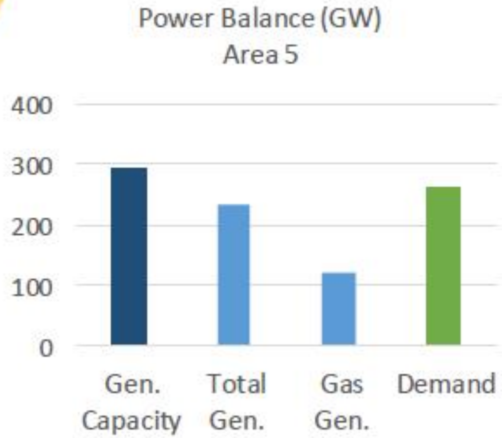
New Transmission Lines

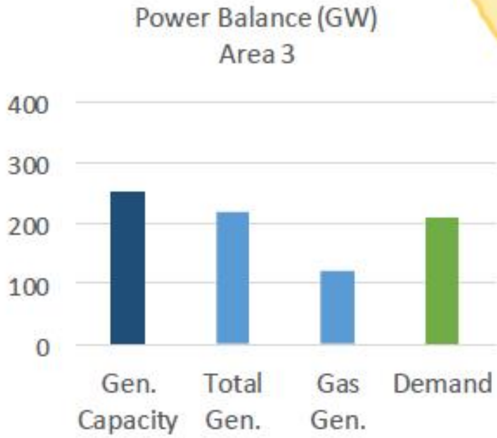












COMPARISON OF REGULATORY AUTHORITY

	Electricity	Natural Gas
FERC	• Regulates wholesale sales of electricity and transmission of electricity in interstate commerce	• Regulates natural gas transportation in interstate commerce (Pipelines)
	• Establishes rates (market-based or cost-of-service-based)	• Establishes rates (market-based or cost-of-service-based)
	• Oversees mandatory reliability standards for the bulk power system	
	• ***Does not*** site or approve electric generation, transmission, or distribution facilities - no "upstream" authority for generators or their fuel suppliers	**Siting and approval for pipeline, storage and LNG terminal construction, operation and abandonment**
NERC (& RRO's)	• Ensures reliability of bulk power system by establishing and enforcing standards	• No authority
ISO's/RTO's	• FERC-derived authority to operate efficient, reliable wholesale electric grid for transmission of electricity in interstate commerce	• No authority
State Commission	• Regulates retail sales of electricity	• Regulates retail sales of natural gas (LDCs)
	• Establishes retail rates	• Establishes retail rates
	• Siting and approval of electric generation, transmission, and distribution facilities	**Siting and approval for construction of new facilities that do not participate in interstate commerce** 6

The U.S. Department of Transportation (DOT) – Office of Pipeline and Hazardous Materials Safety Administration regulates the natural gas industry safety efforts.

This suggests that interregional gas transmission may be easier to build than interregional electric transmission.

Source: https://www.misoenergy.org/Library/Repository/Meeting%20Material/Stakeholder/ENGCTF/2013/20130214/20130214%20ENGCTF%20Item%2005%20Natural%20Gas%20101.pdf

Takeaways

1. Gas supply is up, due to unconventional gas availability; price is low.
2. Emergency capacity, misalignment, bumping receiving lots of attention to facilitate operational coordination.
3. High-gas future in electric may be risky; maintain wind growth.
4. Investment coordination is difficult analytically: good research area!
5. Procedural/regulatory coordination of investments may be most difficult of all because we have little experience in doing it.
6. Interregional electric lines are more difficult to build then interregional pipelines.

ADDITIONAL READING

1. "Electric & Natural Gas Coordinating Task Force Issue Summary Paper Misalignment of Natural Gas & Electric Operating Day and Scheduling," available at https://www.misoenergy.org/Library/Repository/Meeting%20Material/Stakeholder/MSC/2013/20131001/20131001%20MSC%20Item%2004b%20ENGCTF%20Misalignment%20of%20NG%20and%20EL.pdf
2. EIA's Proposed Definitions for Natural Gas Liquids, http://www.eia.gov/petroleum/workshop/ngl/pdf/definitions061413.pdf.
3. FERC reports on coordination between electric and natural gas: http://www.ferc.gov/industries/electric/indus-act/electric-coord.asp
4. American Gas Association Gas-Electric Integration Matters: http://www.aga.org/our-issues/RatesRegulatoryIssues/gas-and-electric-interdependency/aga-reports-studies/Pages/Default.aspx
5. PJM Gas/Electric Coordination: http://www.pjm.com/~/media/about-pjm/newsroom/fact-sheets/gas-electric-coordination-fact-sheet.ashx
6. MISO Electric and Natural Gas Coordination Task Force: https://www.misoenergy.org/STAKEHOLDERCENTER/COMMITTEESWORKGROUPSTASKFORCES/ENGCTF/Pages/home.aspx
7. AEP Electric/Gas Harmonization: https://www.aep.com/about/IssuesAndPositions/Generation/ElectricGasHarmonization.aspx
8. FERC Docket No. RM13-17-000; Order No 787: Communication of Operational Information Between Natural Gas Pipelines and Electric Transmission Operators; available at http://www.ferc.gov/CalendarFiles/20131115164637-RM13-17-000.pdf
9. FERC Docket No. RM14-2-000, Coordination of the Scheduling Processes of Interstate Natural Gas Pipelines and Public Utilities, March 20, 2014, Notice of Proposed Rulemaking, available at http://www.ferc.gov/whats-new/comm-meet/2014/032014/M-1.pdf.
10. A. Liu, Q. Zheng, J. Ho, V. Krishnan, B. Hobbs, M. Shahidehpour, and J. McCalley, "Co-optimization of Transmission and Other Supply Resources," NARUC Project No. 3316T5, prepared for the Eastern Interconnection States Planning Council (EISPC), Sep 1, 2013, available at http://www.naruc.org/grants/Documents/Co-optimization-White-paper_Final_rv1.pdf.
11. G. vsn Welie, Infrastructure Needs: Electricity-Natural Gas Interdependencies, April 21, 2014, available at http://www.iso-ne.com/pubs/pubcomm/pres_spchs/2014/van_welie_interdependencies_4-21-14.pdf.
12. R. Mukerji, "Gas-Electric Coodination: A NYISO Perspective," Sept 9, 2013, available at http://www.nyiso.com/public/webdocs/media_room/publications_presentations/NYISO_Presentations/NYISO_Presentations/Gas-Electric%20Coordination%20-%20A%20NYISO%20Perspective%20-%20R%20Mukerji_09-09-13.pdf.
13. SPP Gas-Electric Coordination Task Force, available at http://www.spp.org/committee_detail.asp?commID=123.
14. FERC Docket AD12-12-000, "Responses of the California Independent System Operator Corporation to Questions Regarding Electric and Natural Gas Industry Coordination and Communication, June 4, 2013, available at http://www.caiso.com/Documents/Jul2_2013-Responses-Questions-Electric-NaturalGasIndustryCoordination_AD12-12.pdf.

Additional Information

NATURAL GAS INDUSTRY ASSOCIATIONS

Natural Gas Supply Association (NGSA)
“Established in 1965 and headquartered in our nation’s capital, NGSA represents major integrated and large independent domestic producers of natural gas. The companies that comprise our membership produce and market roughly 40 percent of U.S. natural gas supply”. NGSA developed and maintain the website http://www.naturalgas.org/. Naturalgas.org is an educational website covering a variety of topics related to the natural gas industry.
http://www.ngsa.org/

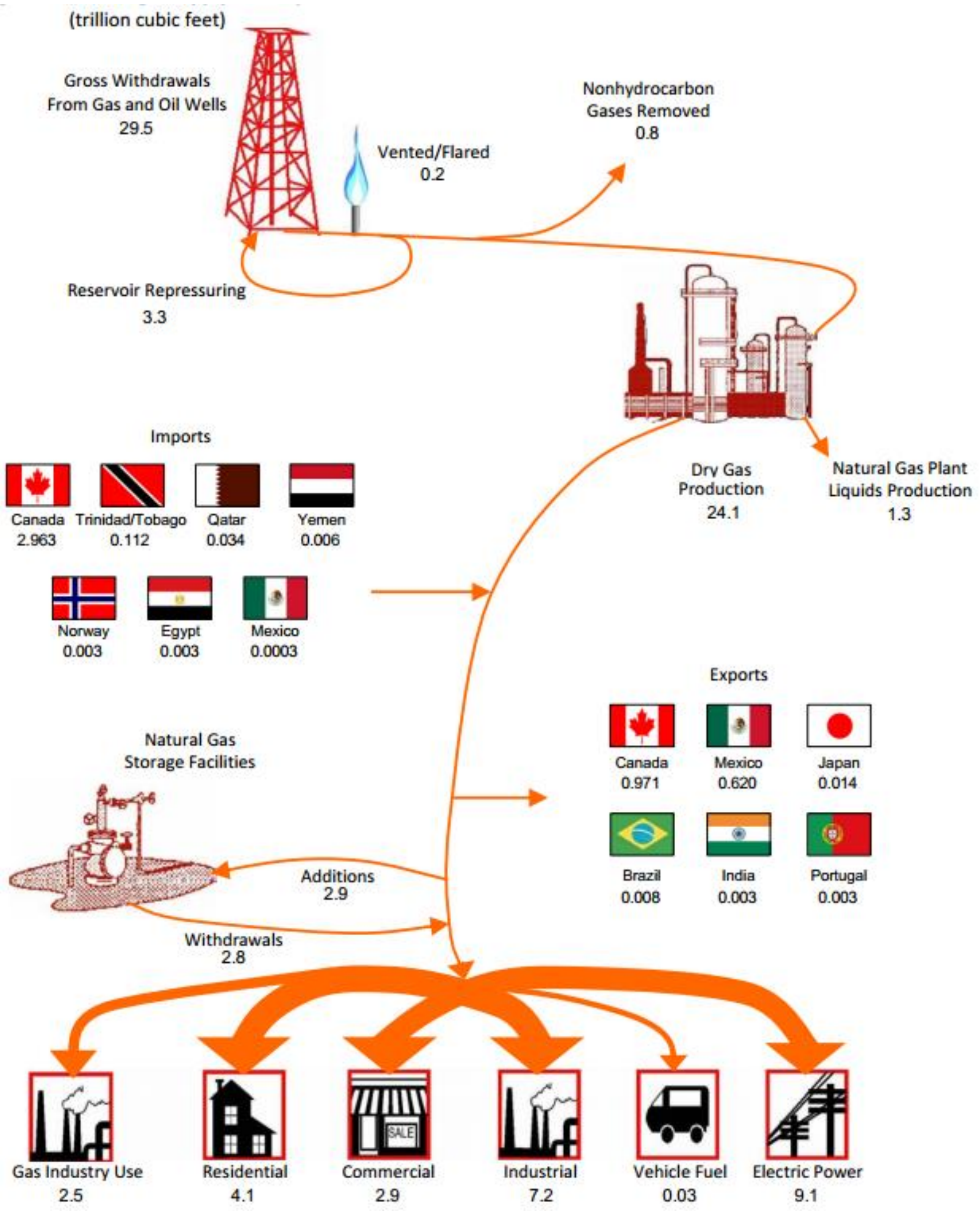
Gas Processors Association (GPA)
GPA serves the midstream energy industry and are an incorporated non-profit trade association that has served member companies since 1921. Our corporate members represent approximately 92% of all natural gas liquids produced in the United States and operate approximately 190,000 miles of domestic gas gathering lines.
https://www.gpaglobal.org/

Interstate Natural Gas Association of America (INGAA)
“The INGAA is a trade organization that advocates regulatory and legislative positions of importance to the natural gas pipeline industry in North America. It is comprised of 25 members, representing the vast majority of the interstate natural gas transmission pipeline companies in the U.S. and comparable companies in Canada”.
http://www.ingaa.org/

American Public Gas Association (APGA)
“Formed in 1961, APGA has over 700 members in 36 states and is the only not-for-profit trade organization that represents America's publicly owned natural gas local distribution companies (LDCs)”.
http://www.apga.org/i4a/pages/index.cfm?pageid=1

American Gas Association (AGA)
“Founded in 1918, AGA represents more than 200 local energy companies that deliver clean natural gas throughout the United States”.
http://www.aga.org/Pages/default.aspx

NATURAL GAS SUPPLY AND DISPOSITION IN THE U.S. 2012



Source: http://www.eia.gov/naturalgas/annual/pdf/nga12.pdf

TOP 10 US NATURAL GAS PRODUCTION COMPANIES - 2013

Rank	Company	NG Production (MMcf/day)
1	ExxonMobil	3,545
2	Chesapeake Energy	2,999
3	Anadarko	2,652
4	Devon Energy	1,942
5	Southwestern Energy Co	1,797
6	BP	1,539
7	ConocoPhillips	1,533
8	Encana	1,345
9	BHP Billiton	1,270
10	Chevron	1,246
	Total	**19,868**
	Part of all companies	**28.31%**

Source: http://www.ngsa.org

TOP 10 US INTERSTATE GAS PIPELINE COMPANIES - 2012

Rank	Company	Transmission mileage
1	Northern Natural Gas Co.	14,949
2	Tennessee Gas Pipeline Co.	13,780
3	El Paso Natural Gas Co.	10,234
4	Columbia Gas Transmission Corp.	9,708
5	Texas Eastern Transmission Corp.	9,563
6	Transcontinental Gas Pipe Line Corp.	9,378
7	Natural Gas Pipeline Co. of America	8,911
8	ANR Pipeline Co.	8,899
9	Southern Natural Gas Co.	7,079
10	Gulf South Pipeline Co. LP	6,484
	Total	**98,985**
	Part of all companies	**49.92%**

Source: Oil & Gas Journal. Volume 111 – Issue 9

UNITS

Pressure. The SI unit for pressure is the newton per square meter, which is called the Pascal (Pa). However, some other units of pressure used in the natural gas industry are:

V·T·E	Pascal	Bar	Standard atmosphere	Torr	Pounds per square inch
	(Pa)	(bar)	(atm)	(Torr)	(psi)
1 Pa	≡ 1 N/m^2	10^{-5}	9.8692×10^{-6}	7.5006×10^{-3}	1.450377×10^{-4}

Volume. Quantities of natural gas are usually measured in cubic feet.

Energy content. The energy content of a fuel (also referred as heating value) is the heat released when a known quantity of fuel is burned under specific conditions. The typical energy content of natural gas in the U.S. is roughly 1,027 BTU/cf depending on gas composition.

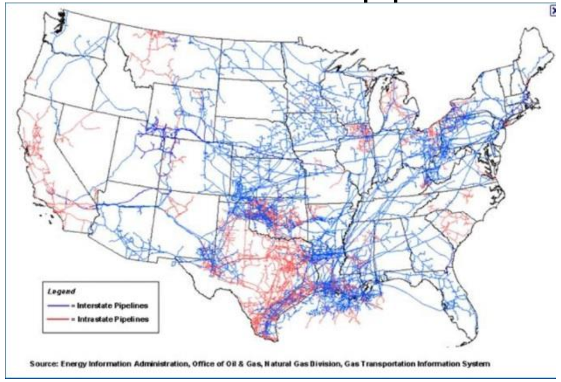
	Cubic feet	Energy content
	(cf)	(MMBTU)
1 MMcf	1,000,000	1,027
1 Bcf	1,000,000,000	1,027,000
1 Tcf	1,000,000,000,000	1,027,000,000

Other energy relations:
1 MWhr=3.413MMbtu (10^6btu);
1btu=1055joules
1 Quad=10^{15}BTUs

Flow. Natural gas flow can be measured in volumetric flow rates (MMcf/day which are often referred as MMCFD), or in mass flow rates (pounds/day). They are related by the gas' density.

PIPELINE NETWORK OPERATION

U.S. Pipeline Network
Over 150 different pipeline



Pipeline System
One company

OPERATION & METERING

- Inlet Station
- Compressor Station
- Intermediate Station
- Block Valve Station
- Outlet Station
- Regulator Stations

MAINTENANCE

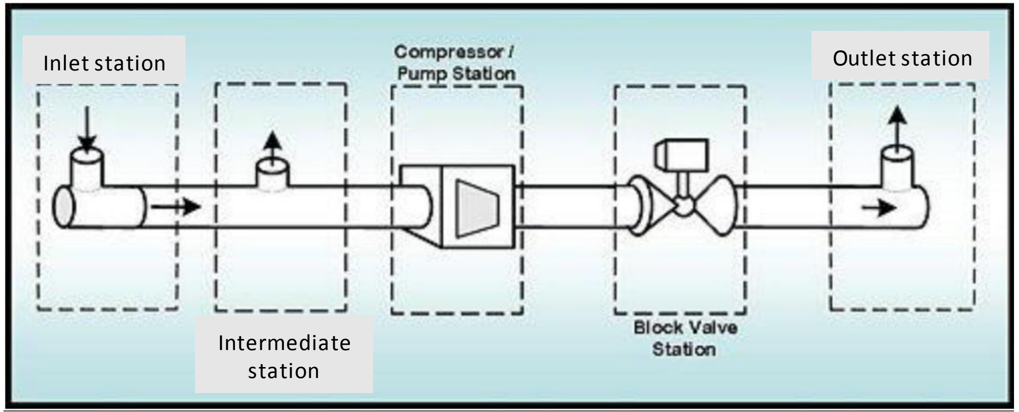
- Pigging Station

- Instrumentation (Flow, pressure, temperature, etc.)
- Data (Remote Terminal Units)
- Communication systems

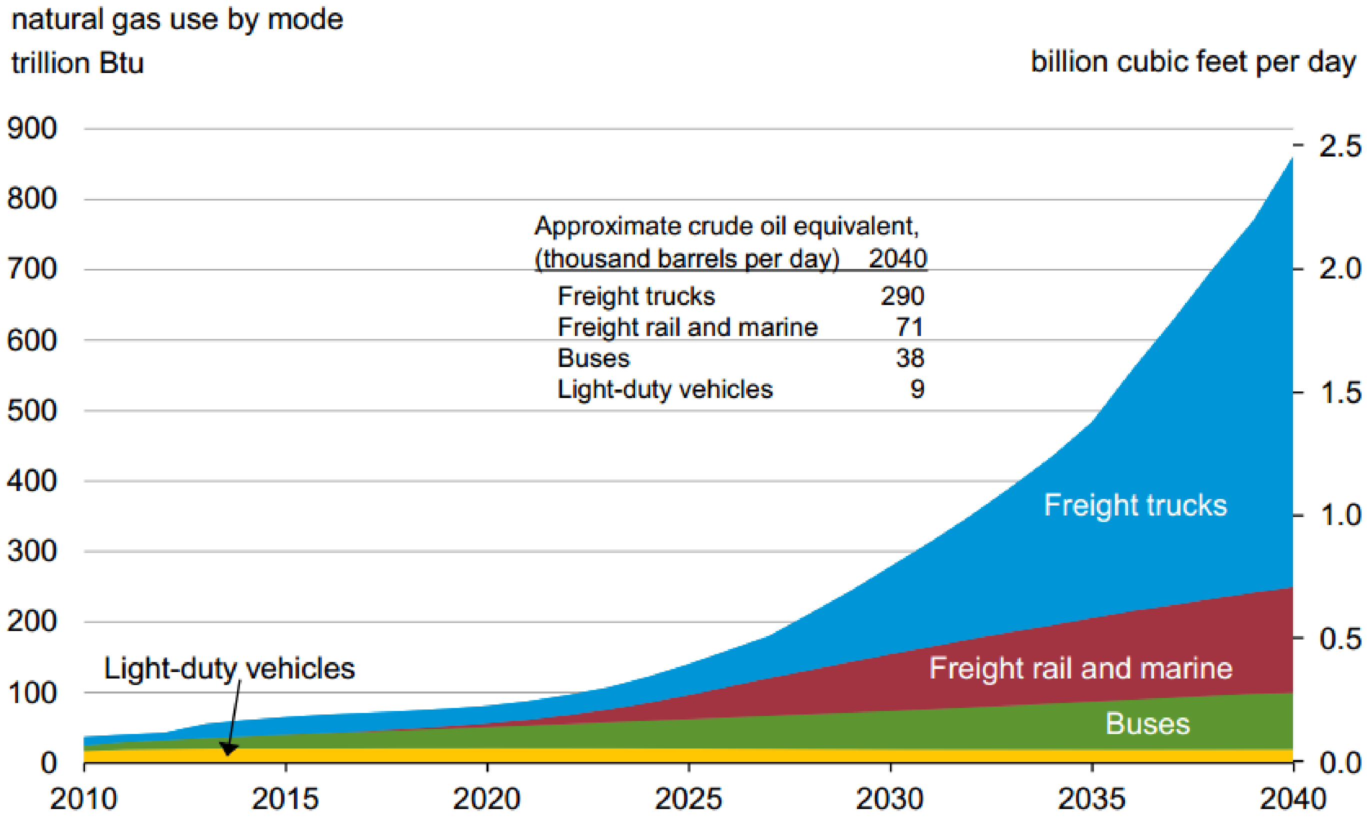
MONITORING & SUPERVISION

- SCADA system
- Control room
- CPM System (Computational Pipeline Monitoring)
- Aerial & Satellite surveillance
- Local supervision

- **Inlet Station - Where gas is injected into the line.**
- **Intermediate Station - Allows the pipeline operator to deliver part of the product.**
- **Compressor/Pump Station – To increase pipeline pressure.**
- **Block Valve Station - These are the first line of protection for pipelines. With these valves the operator can isolate a rupture/leak or any segment of the line for maintenance.**
- **Regulator Station - This is a special type of valve station, where the operator can release some of the pressure from the line. Regulators are usually located at the downhill side of a peak.**
- **Outlet Station - Where the gas is distributed to the consumer. It could be a tank terminal for liquid pipelines or a connection to a distribution network for gas pipelines.**



NATURAL GAS CONSUMPTION – Vehicular fuels



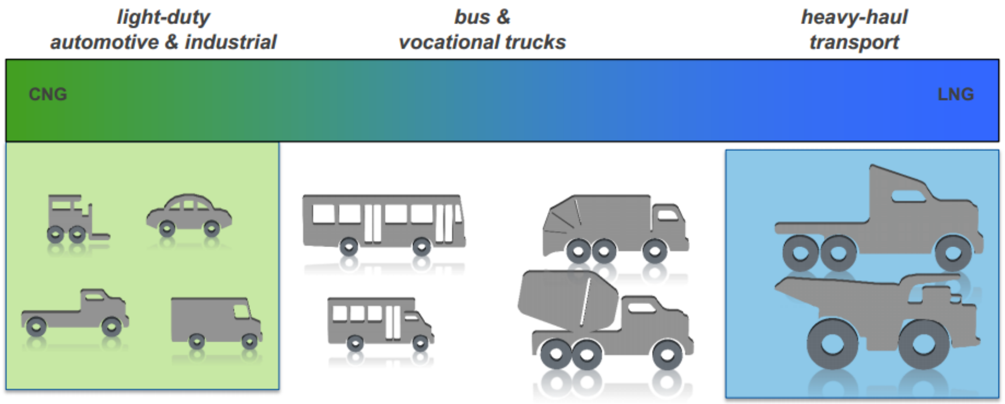
Source: EIA – Annual Energy Outlook 2014

The use of natural gas as a vehicle fuel represents just 0.16% and 2.69% of the total U.S. natural gas demand for years 2012 and 2040 respectively.

- Natural gas is less expensive than diesel or gasoline.

- Natural gas is used in the form of CNG or LNG to fuel cars and trucks.

CNG	LNG
NG in its gaseous form	NG in its liquid form
Stored at pressures between 3,000 to 3,600 psi	Stored at -260F at atmospheric pressures



Source: http://www.westport.com/file_library/files/webinar/2013-06-19_CNGandLNG.pdf

PIPELINE NETWORK MODELING

A pipeline network can be modeled as an undirected graph, with the vertices representing the inlet, intermediate and outlet stations and the edges representing the pipelines, and the compressor, regulator and block valves stations.

$$MG_W = d$$

Matrix equation for calculating the gas flows across the pipeline network. (M is the incidence matrix for the proposed graph, G_W is the vector of gas flows through the edges, and d is the vector of natural gas injections).

$$M^T \rho^2 = K G_W{}^2$$

Matrix representation for calculating the gas flows across a simplified pipeline network (it does not model compressor, regulator, and block valves stations) while enforcing Weymouth Equations. (K is a diagonal matrix of the pipeline constants, and ρ is the vector of pipelines pressures at the vertices).

$$M\left(G_W - G'_W\right) = d$$

$$M^T \rho^2 = K\left(G_W{}^2 - G'_W{}^2\right)$$

$$G_W, G'_W \geq 0$$

The previous set the equations can be modified for representing the pipeline network as a directed graph (G_W’ is the vector of gas flows through the edges in the opposite direction).

$$M^T \pi = K\left(G_W{}^2 - G'_W{}^2\right)$$

It is possible to introduce the change of variables $\pi = \rho^2$ for reducing the nonlinearities in the system of equations.

PIPELINE COMPONENT MODELING

$$\overbrace{\theta_{B_b ts} - \theta_{E_b ts}}^{\text{voltage phasor angles}} = X_b \overbrace{P_{L_{bts}}}^{\text{real power flow}}$$

DC Power Flow Equations - Steady state real power flow across circuits is determined by the difference in voltage phasor angles between the terminating buses.

The susceptance defines the transmission line characteristics

This constant value defines the pipeline characteristics

$$\underbrace{\rho^2_{B_d ts} - \rho^2_{E_d ts}}_{\text{pressures}} = K_d \underbrace{G^2_{W_{dts}}}_{\text{NG flow rate}}$$

Weymouth Equations - The squared value of the natural gas flow rate across a pipeline is determined by the difference of the squares of the pressures between the terminating buses.

MODEL 3 (MINLP, DCPF/Nonlinear Gas)

Minimize the Cost objective function

$$\underbrace{\sum_j \sum_k \sum_t \sum_s OperatCost^{G}_{jkt} P_{G_{jkts}} h_s}^{\text{Generation operational costs}} + \overbrace{\sum_j \sum_k \sum_t InvestCost^{G/U}_{jkt}\, Cap^{add}_{G_{jkt}}}^{\text{Generation investment costs}} + \overbrace{\sum_t \sum_{b \in L_C} InvestCost^{L}_{bt} Z_{bt}}^{\text{Transm. lines investment costs}}$$

$$+ \underbrace{\sum_j \sum_t \sum_s OperatCost^{P}_{jt} G_{P_{jts}} h_s}_{\text{Gas production operational costs}} + \underbrace{\sum_j \sum_t OperatCost^{S}_{jt} G_{S_{jt}}}_{\text{Storage operational costs}} + \underbrace{\sum_t \sum_{d \in W_C} InvestCost^{W}_{dt} Z_{dt}}_{\text{Pipelines investment costs}}$$

---

j: *denotes region* j

k: *denotes generation technology* k

t: *denotes period* t

s: *denotes load block* s

P_G: *denotes power generation level*

Cap^x_G: *if* $x = add\ (ret)$ *denotes generation capacity added (retired)*

G_P: *denotes natural gas production level*

G_S: *denotes natural gas storage capacity level*

Z: *indicates if line* b *(pipeline* d*) is installed in period* t

MODEL 3 (MINLP, DCPF/Nonlinear Gas)

Subject to the constraints

$$Cap_{G_{jkt}} - Cap_{G_{jk(t-1)}} = Cap_{G_{jkt}}^{add} - Cap_{G_{jkt}}^{ret} \dots \forall\, j,k,t$$

$$Cap_{G_{jkt}}^{ret} = Cap_{G_{jk(t-lifetime)}}^{add} \dots \forall\, j,k,t$$

$$Cap_{G_{jkt}}^{add} \le Cap_{G_{jkt}}^{add,max} \dots \forall\, j,k,t$$

Computes the total generation capacity from existing, added and retired capacity

$$P_{G_{jkts}} \le CC_{jkts} Cap_{G_{jkt}} \dots \forall\, j,k,t,s$$

Requires power generation level to be within unit capacity considering the capacity credit values.

$$\sum_s P_{G_{jkts}} h_s \le CF_{jkts} Cap_{G_{jkt}} \sum_s h_s \dots \forall\, j,k,t$$

Accounts for the tendency of each technology to produce over a time frame a certain fraction of the energy it would produce if it continuously operated at its capacity during that time frame.

$$\sum_k CC_{jkt(s=1)} Cap_{G_{jkt}} \ge (1+r) P_{D_{jt(s=1)}} \dots \forall\, j,t$$

Reserve constraint for the peak load

MODEL 3 (MINLP, DCPF/Nonlinear Gas)

$$\sum_{b:B_b=j} P'_{L_{bts}} - P_{L\,bts} + \sum_{b:E_b=j} P_{L\,bts} - P'_{L\,bts} = P_{D_{jts}} - \sum_{k} P_{G_{jkts}} \dots \forall\, j,t,s$$

Power balance for each load block

$$\theta_{B_b ts} - \theta_{E_b ts} = X_b\left(P_{L\,bts} - P'_{L\,bts}\right) \dots \forall\, b \in L_E, t, s$$

$$-(1-S_{bt})M \le \theta_{B_b ts} - \theta_{E_b ts} - X_b\left(P_{L\,bts} - P'_{L\,bts}\right) \le (1-S_{bt})M \dots \forall\, b \in L_C, t, s$$

Power DC flow equations for existing and candidate transmission lines

$$S_{bt} = \sum_{i=1}^{t} Z_{bi} \dots \forall\, b \in L_C, t$$

Allows to track the investments in the candidate transmission lines

$$P_{L\,bts} + P'_{L\,bts} \le P^{max}_{L_{bts}} \dots \forall\, b \in L_E, t, s$$

$$P_{L\,bts} + P'_{L\,bts} \le S_{bt} P^{max}_{L_{bts}} \dots \forall\, b \in L_C, t, s$$

Represent capacity limits for existing and candidate transmission lines

---

θ: *denotes the angle variable*

S: *indicates if transmission line b (pipeline d) has been installed until period t*

M: *denotes a large constant value*

P_L: *denotes the power transmitted through line b in a defined direction*

P'_L: *denotes the power transmitted through line b in an opposite direction*

MODEL 3 (MINLP, DCPF/Nonlinear Gas)

$$\sum_{d:B_d=j} G'_{W_{dts}} - G_{W_{dts}} + \sum_{d:E_d=j} G_{W_{dts}} - G'_{W_{dts}} = G_{D_{jts}} - G_{P_{jts}} + G_{I_{jts}} - G_{Y_{jts}} \ldots \forall j,t,s$$

Gas flow balance for each load block

$$G_{S_{jt}} \sum_s h_s = G_{S_{j(t-1)}} \sum_s h_s + \sum_s \left(G_{I_{jts}} - G_{Y_{jts}}\right) h_s \ldots \forall j,t$$

Storage balance for each time period

$$\pi_{B_d ts} - \pi_{E_d ts} = K_d \left(G^2_{W_{dts}} - G'^2_{W_{dts}}\right) \ldots \forall d \in W_E, t, s$$

$$-(1 - S_{dt})M \le \pi_{B_d ts} - \pi_{E_d ts} - K_d \left(G^2_{W_{dts}} - G'^2_{W_{dts}}\right) \le (1 - S_{dt})M \ldots \forall d \in W_C, t, s$$

Weymouth equations for existing and candidate pipelines

$$S_{dt} = \sum_{i=1}^{t} Z_{di} \ldots \forall d \in W_C, t$$

Allows to track the investments in the candidate pipelines

$$G_{W_{dts}} + G'_{W_{dts}} \le G^{max}_{W_{dts}} \ldots \forall d \in W_E, t, s$$

$$G_{W_{dts}} + G'_{W_{dts}} \le S_{dt} G^{max}_{W_{dts}} \ldots \forall d \in W_C, t, s$$

Represent capacity limits for existing and candidate pipelines

---

G_I: *denotes natural gas storage injections* $\quad$ G_Y: *denotes natural gas storage withdraws*

G_W: *denotes the natural gas transmitted through pipeline d in a defined direction*

G'_W: *denotes the natural gas transmitted through pipeline d in an opposite direction*

π: *denotes the squared pressure variable*

MODEL 3 (MINLP, DCPF/Nonlinear Gas)

$$Cap_{G_{jkt}}^{add}, P_{G_{jkts}}, P_{L_{bts}}, P'_{L\,bts}, G_{W\,dts}, G'_{W\,dts} \geq 0 \ldots \forall\, b, d, j, k, t, s$$

Imposes non-negativity on some of the problem variables

$$-pi \leq \theta_{j,t,s} \leq pi \ldots \forall\, j, t, s$$

$$\pi_{j,t,s}^{min} \leq \pi_{j,t,s} \leq \pi_{j,t,s}^{max} \ldots \forall\, j, t, s$$

$$G_{P_{jt}}^{min} \leq G_{P_{jts}} \leq G_{P_{jt}}^{max} \ldots \forall\, j, t, s$$

$$G_{S_{jt}}^{min} \leq G_{S_{jt}} \leq G_{S_{jt}}^{max} \ldots \forall\, j, t$$

$$G_{I_{jt}}^{min} \leq G_{I_{jts}} \leq G_{I_{jt}}^{max} \ldots \forall\, j, t, s$$

$$G_{Y_{jt}}^{min} \leq G_{Y_{jts}} \leq G_{Y_{jt}}^{max} \ldots \forall\, j, t, s$$

Imposes lower and upper bounds on some of the problem variables

Binary variables: $S_{b,t}, Z_{b,t}, S_{d,t}, Z_{d,t}$

Binary variables required in the disjunctive model for both transmission systems

NATURAL GAS EXPANSION PLANNING PROCESS – INTERSTATE PIPELINES

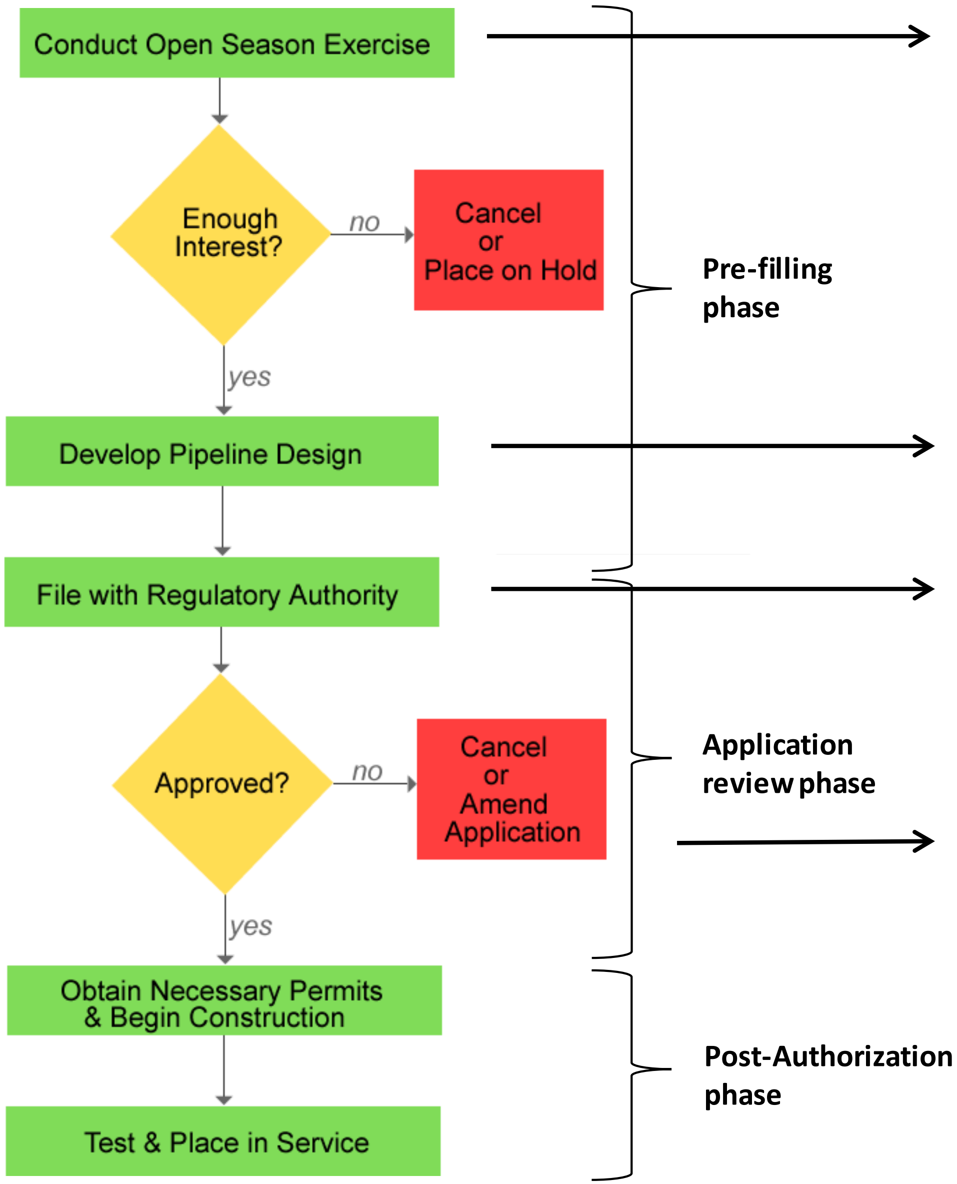
The natural gas industry has a market driven transportation development mechanism.

"The planning process for a new natural gas pipeline and storage infrastructure is based on an underpinning of contracts for firm service entitlements for the contracting party… Within this model, no capacity is constructed specifically to serve interruptible service requirements"

Source: NERC – Special Reliability Assessment Phase II May 2013

Pre-filing Phase

- FERC staff work with applicant and stakeholders before the filing of an application.
- Voluntary for pipelines, required for LNG facilities.
- For projects requiring an Environmental Impact Statement (EIS), or an Environmental Assessment (EA)
- Early identification and resolution of environmental issues
- Goal of "no surprises" when application is filled



Non-binding agreements (firm service) for a portion of the capacity rights to determine the market interest for the project for a minimum of 10 years.

- Upgrading and expanding facilities (compressors)
- Looping
- Installing a lateral or extension off the existing mainline
- Building an entirely new pipeline

NEPA prefilling review process or
Traditional application review process

Section 7 (c) of the Natural Gas Act of 1938 grants FERC the authority to issue a certificate of public convenience and necessity to natural gas companies upon demonstrating that an interstate pipeline is in "public" interest.

Source: http://www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/ngpipeline/develop.html