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

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

~260 US marketers

~1200 US LDCs

>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

>160 US pipeline companies with >300k miles of pipe
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
- Trapped in coal deposits
  - Coalbed methane
- Trapped in rock formations
  - Shale gas
  - Tight gas
- Trapped in rock formations
  - Conventional gas

NG from conventional geological formations

Similar chemical compositions but different geological characteristics of their reservoirs

Sea floor and below for deep waters and shallow artic seas
- Gas hydrates

Gas trapped in rock formations

Sources:

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 cm² 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, m² are used. One darcy is equal to 0.98692E-12 m²
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).

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: EIA – Annual Energy Outlook 2014 Reference Case

Source: http://www.eia.gov/pressroom/presentations/sieminski_01222014.pdf
NATURAL GAS PRODUCTION & PROCESSING

1. Raw NG
   - Non-Associated NG From Gas Wells
     - "Semi Dry" NG
   - Associated NG From Oil Wells
     - Crude Oil
     - Wet NG
   - Non-Associated NG From Condensate Wells
     - "Less Wet" NG
       - "Semi Dry" NG
     - Lease Condensate
     - Wastewater
   - Lease separator facility

2. Dry Quality NG
3. NG Plant Liquids
4. Other components
   - Ethane (Chemical industry)
   - Propane (Propane industry)
   - Butane (Gasoline additive)
   - Pentanes & other heavy hydrocarbons
   - Hydrogen sulfide
   - Carbon dioxide
   - Mercaptans
   - Nitrogen
   - Mercury
   - Water Vapor

Processing plant
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
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.

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.

LNG TERMINALS IN U.S. PROPOSED

EXPORT!

Export Terminal
PROPOSED TO FERC
1. Freeport, TX: 1.8 Bcf/d (Freeport LNG Dev/Freeport LNG Expansion/FLNG Liquefaction) (CP12-509)
2. Corpus Christi, TX: 5.1 Bcf/d (Cheniere – Corpus Christi LNG) (CP12-507)
3. Coos Bay, OR: 0.9 Bcf/d (Jordan Cove Energy Project) (CP13-483)
4. Lake Charles, LA: 2.2 Bcf/d (Southern Union - Trunkline LNG) (CP14-120)
5. Hackberry, LA: 1.7 Bcf/d (Sempra – Cameron LNG) (CP13-25)
6. Cove Point, MD: 0.82 Bcf/d (Dominion – Cove Point LNG) (CP13-113)
7. Astoria, OR: 1.25 Bcf/d (Oregon LNG) (CP09-6)
8. Lavaca Bay, TX: 1.38 Bcf/d (Excelerate Liquefaction) (CP14-71 & 72)
9. Elba Island, GA: 0.35 Bcf/d (Southern LNG Company) (CP14-103)
10. Sabine Pass, LA: 1.40 Bcf/d (Sabine Pass Liquefaction) (CP13-552)
11. Lake Charles, LA: 1.07 Bcf/d (Magnolia LNG) (CP14-347)
13. Sabine Pass, TX: 2.1 Bcf/d (ExxonMobil – Golden Pass) (PF13-14)
14. Pascagoula, MS: 1.5 Bcf/d (Gulf LNG Liquefaction) (PF13-4)

PROPOSED CANADIAN SITES IDENTIFIED BY PROJECT SPONSORS
15. Kitimat, BC: 1.28 Bcf/d (Apache Canada Ltd.)
16. Douglas Island, BC: 0.23 Bcf/d (BC LNG Export Cooperative)
17. Kitimat, BC: 3.23 Bcf/d (LNG Canada)

Import Terminal
PROPOSED TO FERC
1. Robinston, ME: 0.5 Bcf/d (Kestrel Energy - Downeast LNG)
2. Astoria, OR: 0.5 Bcf/d (Oregon LNG)
3. Corpus Christi, TX: 0.4 Bcf/d (Cheniere – Corpus Christi LNG)

POTENTIAL U.S. SITES IDENTIFIED BY PROJECT SPONSORS
4. Offshore New York: 0.4 Bcf/d (Liberty Natural – Port Ambrose)

US Jurisdiction
- FERC
- MARAD/USCG

As of May 21, 2014

* Filed Certificate Application

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.

Above illustrates the two ways that LNG is moved from squares on the map to triangles.
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.
Hydraulic Fracturing
Hydraulic Fracturing & potential impacts

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

Water Acquisition
- Change in the quantity of water available for drinking.
- Change in drinking water quality
- Release to surface and ground water through on-site spills and/or leaks

Chemical Mixing
- 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.

Well Injection
- Release to surface or ground water through spills or leakage from on-site storage

Flowback and Produced Water
- 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

Wastewater Treatment and Waste Disposal

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

"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
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.

Source: U.S. Energy Information Administration

http://www.eia.gov/dnav/ng/hist/rngwhhdd.htm
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.
Change in US Electric Energy Portfolio

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

Growth in Capacity: All

Additions to electricity generation capacity, 1985-2040

U.S. electricity generation capacity additions
gigawatts

Source: EIA Form 860 & EIA, Annual Energy Outlook 2013
Growth in capacity: gas & wind

How much do we have?

**gas**

- Current US natural gas production: 24 Tcf/yr
- Technical recoverable dry gas: 1698 Tcf, R/P: 71 years
- Technical recoverable dry shale gas: 637 Tcf, R/P: 27 years

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

**wind**

Annual wind energy potential (TWhr or $10^{12}$ Whr)

Total onshore energy potential is 62 PWhr which is over 2.1 x 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)

What are the risks?
**Levelized cost of energy**

\[
LCOE = \frac{\text{Levelized Annual Revenue Requirement}}{\text{Average Annual Energy Production}}
\]

(\text{Unsubsidized})

<table>
<thead>
<tr>
<th>Technology</th>
<th>Production Energy</th>
<th>Annual Average</th>
<th>Revenue</th>
<th>Annual Levelized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar PV—Crystalline Rooftop</td>
<td>$68$</td>
<td>$91$</td>
<td>$104$</td>
<td>$140$</td>
</tr>
<tr>
<td>Solar PV—Crystalline Utility Scale</td>
<td>$72$</td>
<td>$80$</td>
<td>$89$</td>
<td>$99$</td>
</tr>
<tr>
<td>Solar PV—Thin-film Utility Scale</td>
<td>$109$</td>
<td>$125$</td>
<td>$104$</td>
<td>$206$</td>
</tr>
<tr>
<td>Solar Thermal</td>
<td>$102$</td>
<td>$135$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel Cell</td>
<td>$89$</td>
<td>$142$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Microturbine</td>
<td>$87$</td>
<td>$136$</td>
<td></td>
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<tr>
<td>Geothermal</td>
<td>$87$</td>
<td>$136$</td>
<td></td>
<td></td>
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<tr>
<td>Biomass Direct</td>
<td>$0$</td>
<td>$0$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind</td>
<td>$45$</td>
<td>$98$</td>
<td>$158$</td>
<td></td>
</tr>
<tr>
<td>Energy Efficiency</td>
<td>$0$</td>
<td>$0$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Battery Storage</td>
<td></td>
<td></td>
<td>$218$</td>
<td>$329$</td>
</tr>
<tr>
<td>Diesel Generator</td>
<td></td>
<td></td>
<td>$207$</td>
<td>$332$</td>
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<tr>
<td>Gas Peaking IGCC</td>
<td></td>
<td></td>
<td>$141$</td>
<td>$184$</td>
</tr>
<tr>
<td>Nuclear</td>
<td></td>
<td></td>
<td>$86$</td>
<td>$115$</td>
</tr>
<tr>
<td>Coal</td>
<td></td>
<td></td>
<td>$127$</td>
<td>$145$</td>
</tr>
<tr>
<td>Gas Combined Cycle</td>
<td>$94$</td>
<td>$97$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Lazard's levelized cost of energy analysis - Version 7.0, August 2013, available**

## Gas and wind: overall comparison (yellow is winner)

<table>
<thead>
<tr>
<th></th>
<th>Wind</th>
<th>Natural Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall cost (see last slide)</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Fuel production - land</td>
<td>None</td>
<td>Some</td>
</tr>
<tr>
<td>Fuel production - water</td>
<td>None</td>
<td>Much</td>
</tr>
<tr>
<td>Fuel production – GHG emissions</td>
<td>None</td>
<td>Some (methane)</td>
</tr>
<tr>
<td>Fuel transport - land</td>
<td>None</td>
<td>Some</td>
</tr>
<tr>
<td>Fuel transport – public resistance</td>
<td>None</td>
<td>Some</td>
</tr>
<tr>
<td>Power plant - land</td>
<td>Some</td>
<td>Some</td>
</tr>
<tr>
<td>Power plant - water</td>
<td>None</td>
<td>Much</td>
</tr>
<tr>
<td>Power plant – CO$_2$ emissions</td>
<td>None</td>
<td>Some</td>
</tr>
<tr>
<td>Power plant - other</td>
<td>Bats and birds</td>
<td>None</td>
</tr>
<tr>
<td>Electric transmission - land</td>
<td>Much</td>
<td>Some</td>
</tr>
<tr>
<td>Electric transmission – public resistance</td>
<td>Much</td>
<td>Some</td>
</tr>
<tr>
<td>Future risk (see next slide)</td>
<td>Little</td>
<td>Much</td>
</tr>
</tbody>
</table>
### Risks of heavy gas portfolio:
1. Gas price goes up due to **gas demand increase** (pwr plnts, trnsprt, exports) or **gas supply decrease**: (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

### Risks of heavy wind portfolio:
1. Climate change reduces wind speeds
2. Major bat/bird impact
3. LCOE does not decrease
4. No new transmission
Gas-electric investment coordination

- Gas well & storage investment
- Electric Xmission investment
- Non-gas generation investment
- Gas pwr plant location
- Gas pwr plant investment
- Non-electric gas demand
- Gas price
- Gas Xmission investment

Electric demand
Co-optimization of electric generation, electric transmission, and natural gas pipeline
**NATURAL GAS CHARACTERISTICS**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Content (MMBTU/MMcf)</td>
<td>1,027</td>
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</tbody>
</table>

**PIPELINE CHARACTERISTICS**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (inch)</td>
<td>42</td>
</tr>
<tr>
<td>Transmission Capacity (MMcf/day)</td>
<td>1,800.0</td>
</tr>
<tr>
<td>Transmission Capacity (MMcf/hour)</td>
<td>75.00</td>
</tr>
</tbody>
</table>

**COMPRESSOR STATION CHARACTERISTICS**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance between stations (miles)</td>
<td>50</td>
</tr>
<tr>
<td>Power (HP per station)</td>
<td>25,000</td>
</tr>
</tbody>
</table>

**PIPELINE INVESTMENT COSTS**

<table>
<thead>
<tr>
<th>Cost</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipeline Investment Cost (*) ($ per inch - mile)</td>
<td>155,000</td>
</tr>
<tr>
<td>Pipeline Investment Cost ($ per mile)</td>
<td>6,510,000</td>
</tr>
</tbody>
</table>

**COMPRESSOR STATION COSTS**

<table>
<thead>
<tr>
<th>Cost</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor Station Inv. Cost (*) ($ per HP)</td>
<td>2,600</td>
</tr>
<tr>
<td>Compressor Station Inv. Cost ($ per mile)</td>
<td>1,300,000</td>
</tr>
</tbody>
</table>

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

**PIEpline System Investment Costs**

<table>
<thead>
<tr>
<th>Cost</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipeline System Investment Cost ($ per mile)</td>
<td>7,810,000</td>
</tr>
<tr>
<td>Pipeline System Investment Cost ($ per (MMcf/hr x mile))</td>
<td>104,133</td>
</tr>
<tr>
<td>Pipeline System Investment Cost ($ per (MMBTU/hr x mile))</td>
<td>101.40</td>
</tr>
</tbody>
</table>

**CONVENTIONAL COMBINED CYCLE PLANT CHARACTERISTICS**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Rate (MMBTU/GWh)</td>
<td>7,196</td>
</tr>
</tbody>
</table>

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.

**TRANSMISSION LINES INVESTMENT COST**

<table>
<thead>
<tr>
<th>Cost</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission Line Investment Cost ($ per GW - mile)</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Transmission Line Investment Cost ($ per (MMBTU/h x mile))</td>
<td>139.0</td>
</tr>
</tbody>
</table>

Gas-electric investment growth


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.


2030 Market Outlook, Bloomberg New Energy Finance, http://bnef.folioshack.com/document/v71ve0krs8e0/1fp9ha
PIPET LINE FLOW MODEL

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

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

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

SET OF NONLINEAR ALGEBRAIC EQUATIONS

ACCURATE MODEL

APPROXIMATE MODEL

Weymouth Equation
\[
\rho_i^2 - \rho_j^2 = K_k G_{W_i} \left| G_{W_i} \right|
\]

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)

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

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

Turbulent flows in hydraulically smooth pipes

Turbulent flows in rough pipes

Panhandle A Equation
AGA Partially Turbulent Equation
White Equation
Panhandle B Equation
AGA Partially Turbulent Equation

AGA Partially Turbulent Equation

Panhandle A Equation
White Equation
Panhandle B Equation
AGA Partially Turbulent Equation
LINEARIZING WEYMOUTH EQUATIONS USING A TAYLOR SERIES EXPANSION REPRESENTATION

- Existing pipelines

\[ K_d \left( G_{W_d}^2 - G_{W_d}'^2 \right) = \rho_{B_d}^2 - \rho_{E_d}^2 \]

\[-(1 - S_d)M \leq \rho_{B_d}^2 - \rho_{E_d}^2 - K_d \left( G_{W_d}^2 - G_{W_d}'^2 \right) \leq (1 - S_d)M \]

- Candidate pipelines

\[ K_d' \left( G_{W_d}^2 - G_{W_d}'^2 \right) = c_{B_d} \rho_{B_d} - c_{E_d} \rho_{E_d} \]

\[-(1 - S_d)M \leq c_{B_d} \rho_{B_d} - c_{E_d} \rho_{E_d} - K_d' \left( G_{W_d}^2 - G_{W_d}'^2 \right) \leq (1 - S_d)M \]

\[ c_{B_d} = \sqrt{\frac{\pi_{B_d}^{(0)}}{\pi_{B_d}^{(0)} - \pi_{E_d}^{(0)}}} \quad c_{E_d} = \sqrt{\frac{\pi_{E_d}^{(0)}}{\pi_{B_d}^{(0)} - \pi_{E_d}^{(0)}}} \quad K_d' = \sqrt{K_d} \]

\[ \pi_{B_d}^{(0)} = \left( \rho_{B_d}^{(0)} \right)^2 \quad \pi_{E_d}^{(0)} = \left( \rho_{E_d}^{(0)} \right)^2 \]

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

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
**MODEL 2 (MILP, DCPF/Linear Gas)**

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

**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

<table>
<thead>
<tr>
<th>Power system security and reliability constraints</th>
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<tr>
<td>Electric Generating Units reserves</td>
</tr>
<tr>
<td>Generation capacity constraints</td>
</tr>
<tr>
<td>Balance (additions and retirements)</td>
</tr>
<tr>
<td>Lower and upper bounds</td>
</tr>
</tbody>
</table>

**GAS SYSTEM CONSTRAINTS**
- NG Wells Production constraints
  - Bounds on the production levels
- Transmission network constraints
  - Node gas balance equations
  - Linearized gas flow – pressure equations
  - Pipelines capacity bounds
- NG Storage constraints
  - Lower and upper storage levels (storage, injection, and withdrawal).
  - Energy balance constraints

**Transmission lines investment constraints using a Disjunctive Model**

**Pipelines investment constraints using a Disjunctive Model**

**INTEGERS**

**INTEGERS**
**MODEL 3 (MINLP, DCPF/Nonlinear Gas)**

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

**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

**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

- Transmission lines investment constraints using a Disjunctive Model
  - INTEGERS

- Pipelines investment constraints using a Disjunctive Model
  - INTEGERS
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.
A bidirectional arrow means that the flows often change their direction for different time periods (different months, different load blocks, etc.)
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.)
### COMPARISON OF REGULATORY AUTHORITY

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


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.
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 than interregional pipelines.


3. FERC reports on coordination between electric and natural gas: http://www.ferc.gov/industries/electric/indus-act/electric-coord.asp


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


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

TOP 10 US NATURAL GAS PRODUCTION COMPANIES - 2013

<table>
<thead>
<tr>
<th>Rank</th>
<th>Company</th>
<th>NG Production (MMcf/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ExxonMobil</td>
<td>3,545</td>
</tr>
<tr>
<td>2</td>
<td>Chesapeake Energy</td>
<td>2,999</td>
</tr>
<tr>
<td>3</td>
<td>Anadarko</td>
<td>2,652</td>
</tr>
<tr>
<td>4</td>
<td>Devon Energy</td>
<td>1,942</td>
</tr>
<tr>
<td>5</td>
<td>Southwestern Energy Co</td>
<td>1,797</td>
</tr>
<tr>
<td>6</td>
<td>BP</td>
<td>1,539</td>
</tr>
<tr>
<td>7</td>
<td>ConocoPhillips</td>
<td>1,533</td>
</tr>
<tr>
<td>8</td>
<td>Encana</td>
<td>1,345</td>
</tr>
<tr>
<td>9</td>
<td>BHP Billiton</td>
<td>1,270</td>
</tr>
<tr>
<td>10</td>
<td>Chevron</td>
<td>1,246</td>
</tr>
</tbody>
</table>

Total: 19,868
Part of all companies: 28.31%

Source: http://www.ngsa.org

TOP 10 US INTERSTATE GAS PIPELINE COMPANIES - 2012

<table>
<thead>
<tr>
<th>Rank</th>
<th>Company</th>
<th>Transmission mileage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Northern Natural Gas Co.</td>
<td>14,949</td>
</tr>
<tr>
<td>2</td>
<td>Tennessee Gas Pipeline Co.</td>
<td>13,780</td>
</tr>
<tr>
<td>3</td>
<td>El Paso Natural Gas Co.</td>
<td>10,234</td>
</tr>
<tr>
<td>4</td>
<td>Columbia Gas Transmission Corp.</td>
<td>9,708</td>
</tr>
<tr>
<td>5</td>
<td>Texas Eastern Transmission Corp.</td>
<td>9,563</td>
</tr>
<tr>
<td>6</td>
<td>Transcontinental Gas Pipe Line Corp.</td>
<td>9,378</td>
</tr>
<tr>
<td>7</td>
<td>Natural Gas Pipeline Co. of America</td>
<td>8,911</td>
</tr>
<tr>
<td>8</td>
<td>ANR Pipeline Co.</td>
<td>8,899</td>
</tr>
<tr>
<td>9</td>
<td>Southern Natural Gas Co.</td>
<td>7,079</td>
</tr>
<tr>
<td>10</td>
<td>Gulf South Pipeline Co. LP</td>
<td>6,484</td>
</tr>
</tbody>
</table>

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:

<table>
<thead>
<tr>
<th>Y-T-E</th>
<th>Pascal (Pa)</th>
<th>Bar (bar)</th>
<th>Standard atmosphere (atm)</th>
<th>Torr (Torr)</th>
<th>Pounds per square inch (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Pa</td>
<td>$1 \text{ N/m}^2$</td>
<td>$10^{-5}$</td>
<td>$9.8692 \times 10^{-5}$</td>
<td>$7.5006 \times 10^{-3}$</td>
<td>$1.450377 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

**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.

<table>
<thead>
<tr>
<th>Cubic feet (cf)</th>
<th>Energy content (MMBTU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 MMcf</td>
<td>1,000,000</td>
</tr>
<tr>
<td>1 Bcf</td>
<td>1,000,000,000</td>
</tr>
<tr>
<td>1 Tcf</td>
<td>1,000,000,000,000</td>
</tr>
</tbody>
</table>

Other energy relations:
1 MWhr = 3.413 MMBtu ($10^6$ btu);
1 btu = 1055 joules
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 companies

---

**OPERATION & METERING**
- Inlet Station
- Intermediate Station
- Outlet Station
- Compressor Station
- Block Valve Station
- Regulator Stations

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

---

**MAINTENANCE**
- Pigging Station

---

**OPERATION & METERING**
- Control room
- SCADA system
- CPM System
- Aerial & Satellite surveillance

**MONITORING & SUPERVISION**
- Computational Pipeline Monitoring
- 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 is less expensive than diesel or gasoline.

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

<table>
<thead>
<tr>
<th>CNG</th>
<th>LNG</th>
</tr>
</thead>
<tbody>
<tr>
<td>NG in its gaseous form</td>
<td>NG in its liquid form</td>
</tr>
<tr>
<td>Stored at pressures between 3,000 to 3,600 psi</td>
<td>Stored at -260F at atmospheric pressures</td>
</tr>
</tbody>
</table>

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.

Source: EIA – Annual Energy Outlook 2014

PIPEDLINE 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).

\[ M^T \rho^2 = KG_w^2 \]

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 \( \rho \) is the vector of pipelines pressures at the vertices).

\[ M \left( G_w - G'_w \right) = d \]

\[ M^T \rho^2 = K \left( G_w^2 - G'_w^2 \right) \]

\[ G_w, G'_w \geq 0 \]

\[ M^T \pi = K \left( G_w^2 - G'_w^2 \right) \]

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).

It is possible to introduce the change of variables \( \pi = \rho^2 \) for reducing the nonlinearities in the system of equations.
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 susceptibility defines the transmission line characteristics

This constant value defines the pipeline characteristics

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

\[
\text{Generation operational costs:} \quad \sum_{j} \sum_{k} \sum_{t} \sum_{s} \text{OperatCost}^G_{jkt} P_{Gjkt} h_s + \sum_{j} \sum_{k} \sum_{t} \sum_{s} \text{OperatCost}^P_{jts} G_{Pjts} h_s + \sum_{j} \sum_{t} \sum_{s} \text{OperatCost}^S_{jts} G_{Stj} h_s
\]

\[
\text{Generation investment costs:} \quad \sum_{j} \sum_{k} \sum_{t} \sum_{s} \text{InvestCost}^G_{jkt} \text{Cap}_{Gjkt}^{\text{add}} + \sum_{j} \sum_{k} \sum_{t} \text{InvestCost}^G_{jkt} \text{Cap}_{Gjkt}^{\text{ret}} + \sum_{t} \sum_{b \in L_C} \text{InvestCost}^L_{bt} Z_{bt}
\]

\[
\text{Transm. lines investment costs:} \quad \sum_{t} \sum_{d \in W_C} \text{InvestCost}^W_{dt} Z_{dt}
\]

\[
\text{Gas production operational costs:} \quad + \sum_{j} \sum_{k} \sum_{t} \sum_{s} \text{OperatCost}^G_{jkt} P_{Gjkt} h_s + \sum_{j} \sum_{t} \sum_{s} \text{OperatCost}^P_{jts} G_{Pjts} h_s + \sum_{j} \sum_{t} \sum_{s} \text{OperatCost}^S_{jts} G_{Stj} h_s + \sum_{t} \sum_{d \in W_C} \text{InvestCost}^W_{dt} Z_{dt}
\]

\[
\text{Storage operational costs:} \quad \sum_{j} \sum_{k} \sum_{t} \sum_{s} \text{OperatCost}^G_{jkt} P_{Gjkt} h_s + \sum_{j} \sum_{t} \sum_{s} \text{OperatCost}^P_{jts} G_{Pjts} h_s + \sum_{j} \sum_{t} \sum_{s} \text{OperatCost}^S_{jts} G_{Stj} h_s + \sum_{t} \sum_{d \in W_C} \text{InvestCost}^W_{dt} Z_{dt}
\]

\[
\text{Pipelines investment costs:} \quad \sum_{t} \sum_{b \in L_C} \text{InvestCost}^L_{bt} Z_{bt}
\]

- \( j \): denotes region \( j \)
- \( k \): denotes generation technology \( k \)
- \( t \): denotes period \( t \)
- \( s \): denotes load block \( s \)
- \( P_G \): denotes power generation level
- \( \text{Cap}_G^x \): if \( x = \text{add} \) (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

\[ \text{Cap}_{G_{jkt}} - \text{Cap}_{G_{jkt}(t-1)} = \text{Cap}^{add}_{G_{jkt}} - \text{Cap}^{ret}_{G_{jkt}} \quad \forall \ j, k, t \]

\[ \text{Cap}^{ret}_{G_{jkt}} = \text{Cap}^{add}_{G_{jkt}(t-\text{lifetime})} \quad \forall \ j, k, t \]

\[ \text{Cap}^{add}_{G_{jkt}} \leq \text{Cap}^{add,max}_{G_{jkt}} \quad \forall \ j, k, t \]

\[ P_{G_{jkts}} \leq CC_{jkts} \text{Cap}_{G_{jkt}} \quad \forall \ j, k, t, s \]

\[ \sum_s P_{G_{jkts}} h_s \leq CF_{jkts} \text{Cap}_{G_{jkt}} \sum_s h_s \quad \forall \ j, k, t \]

\[ \sum_k CC_{jkt(s=1)} \text{Cap}_{G_{jkt}} \geq (1 + r)P_{D_{jt(s=1)}} \quad \forall \ j, t \]

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

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

- 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.

- Reserve constraint for the peak load
MODEL 3 (MINLP, DCPF/Nonlinear Gas)

\[
\sum_{b:B_b=j} P'_{L_{bts}} - P_{L_{bts}} + \sum_{b:E_b=j} P_{L_{bts}} - P'_{L_{bts}} = P_{D_{jts}} - \sum_k P_{G_{jkt}} \quad \forall j, t, s
\]

\[
\theta_{B_{bts}} - \theta_{E_{bts}} = X_b (P_{L_{bts}} - P'_{L_{bts}}) \quad \forall b \in L_E, t, s
\]

\[-(1 - S_{bt})M \leq \theta_{B_{bts}} - \theta_{E_{bts}} - X_b (P_{L_{bts}} - P'_{L_{bts}}) \leq (1 - S_{bt})M \quad \forall b \in L_C, t, s\]

\[
S_{bt} = \sum_{i=1}^{t} Z_{bi} \quad \forall b \in L_C, t
\]

\[
P_{L_{bts}} + P'_{L_{bts}} \leq P_{L_{bts}}^{max} \quad \forall b \in L_E, t, s
\]

\[
P_{L_{bts}} + P'_{L_{bts}} \leq S_{bt} P_{L_{bts}}^{max} \quad \forall b \in L_C, t, s
\]

\[\theta: \text{denotes the angle variable}\]
\[S: \text{indicates if transmission line } b \text{ (pipeline } d) \text{ has been installed until period } t\]
\[M: \text{denotes a large constant value}\]
\[P_L: \text{denotes the power transmitted through line } b \text{ in a defined direction}\]
\[P'_L: \text{denotes the power transmitted through line } b \text{ in an opposite direction}\]
MODEL 3 (MINLP, DCPF/Nonlinear Gas)

\[
\sum_{d:B_d=j} G'_W_{dts} - G_W_{dts} + \sum_{d:E_d=j} G_W_{dts} - G'_W_{dts} = G_{D_{jts}} - G_{P_{jts}} + G_{I_{jts}} - G_{Y_{jts}} \quad \forall \ j, t, s
\]

\[
G_{S_{jts}} \sum s h_s = G_{S_{j(t-1)}} \sum s h_s + \sum s (G_{I_{jts}} - G_{Y_{jts}}) h_s \quad \forall \ j, t
\]

\[
\pi_{B_{dts}} - \pi_{E_{dts}} = K_d \left( G^2_{W_{dts}} - G^2_{W_{dts}} \right) \quad \forall \ d \in W_E, t, s
\]

\[-(1 - S_{dt})M \leq \pi_{B_{dts}} - \pi_{E_{dts}} - K_d \left( G^2_{W_{dts}} - G^2_{W_{dts}} \right) \leq (1 - S_{dt})M \quad \forall \ d \in W_C, t, s
\]

\[
S_{dt} = \sum_{i=1}^{t} Z_{di} \quad \forall \ d \in W_C, t
\]

\[
G_{W_{dts}} + G'_{W_{dts}} \leq G^\text{max}_{W_{dts}} \quad \forall \ d \in W_E, t, s
\]

\[
G_{W_{dts}} + G'_{W_{dts}} \leq S_{dt} G^\text{max}_{W_{dts}} \quad \forall \ d \in W_C, t, s
\]

\(G_I\): denotes natural gas storage injections  \(G_Y\): 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
\(\pi\): denotes the squared pressure variable
MODEL 3 (MINLP, DCPF/Nonlinear Gas)

\[ \text{Cap}_{G_{jkt}}^{\text{add}}, P_{G_{jkt}^s}, P_{L_{bts}}, P_{L'_{bts}}, G_{W_{dts}}, G'_{W_{dts}} \geq 0 \quad \forall \ b, d, j, k, t, s \]

Imposes non-negativity on some of the problem variables

\[ -p_i \leq \theta_{j,t,s} \leq p_i \quad \forall \ j, t, s \]

\[ \pi_{j,t,s}^{\text{min}} \leq \pi_{j,t,s} \leq \pi_{j,t,s}^{\text{max}} \quad \forall \ j, t, s \]

\[ G_{P_{jt}}^{\text{min}} \leq G_{P_{jt}^s} \leq G_{P_{jt}}^{\text{max}} \quad \forall \ j, t, s \]

\[ G_{S_{jt}}^{\text{min}} \leq G_{S_{jt}^s} \leq G_{S_{jt}}^{\text{max}} \quad \forall \ j, t \]

\[ G_{l_{jt}}^{\text{min}} \leq G_{l_{jt}^s} \leq G_{l_{jt}}^{\text{max}} \quad \forall \ j, t, s \]

\[ G_{Y_{jt}}^{\text{min}} \leq G_{Y_{jt}^s} \leq G_{Y_{jt}}^{\text{max}} \quad \forall \ j, t, s \]

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
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

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