A Nash-Cournot Equilibrium Model for the North American Natural Gas Sector*

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My Background

North American Market

Equilibrium Model

Numerical Results

Future Work

Outline of Presentation

- My Background
- North American Market Background
- Equilibrium Model
- Numerical Results
- Future Work and References

Overview of Research

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- **Research: Main Topics**
  - Mathematical modeling in engineering-economic systems using optimization and equilibrium analysis usually involving some infrastructural elements
    - Models of energy markets and risk (natural gas and electricity)
    - Transportation/traffic flow
    - “Smart Growth” land development
    - Wastewater treatment
    - Wireless telecommunications networks
  - Development of algorithms for solving equilibria in energy & transportation systems
  - Development of general purpose algorithms for equilibrium models (using the nonlinear complementarity format)
  - Operations research areas: Multiobjective optimization, nonlinear programming, complementarity theory, statistics, integer programming

From well-head to burner-tip

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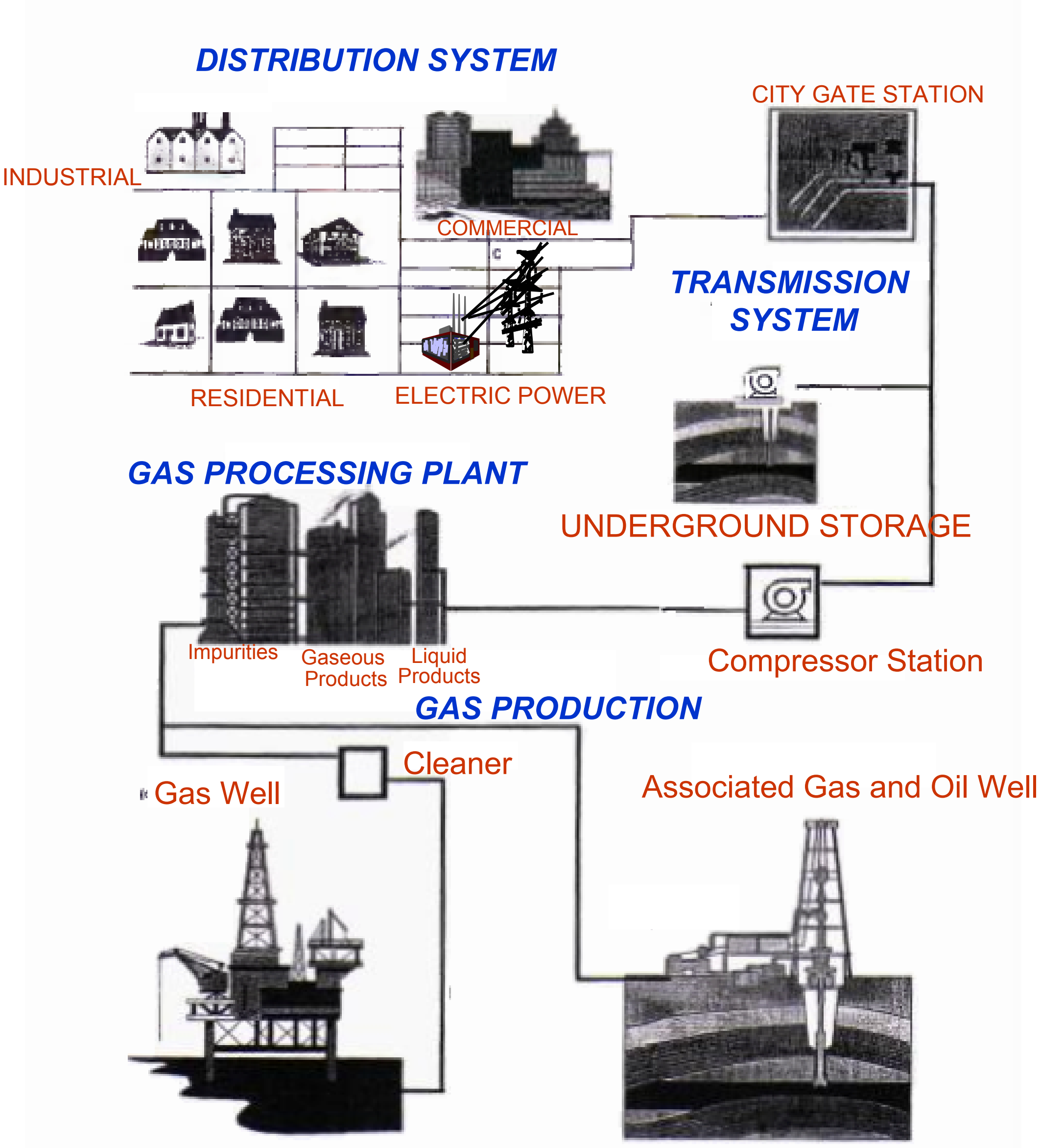

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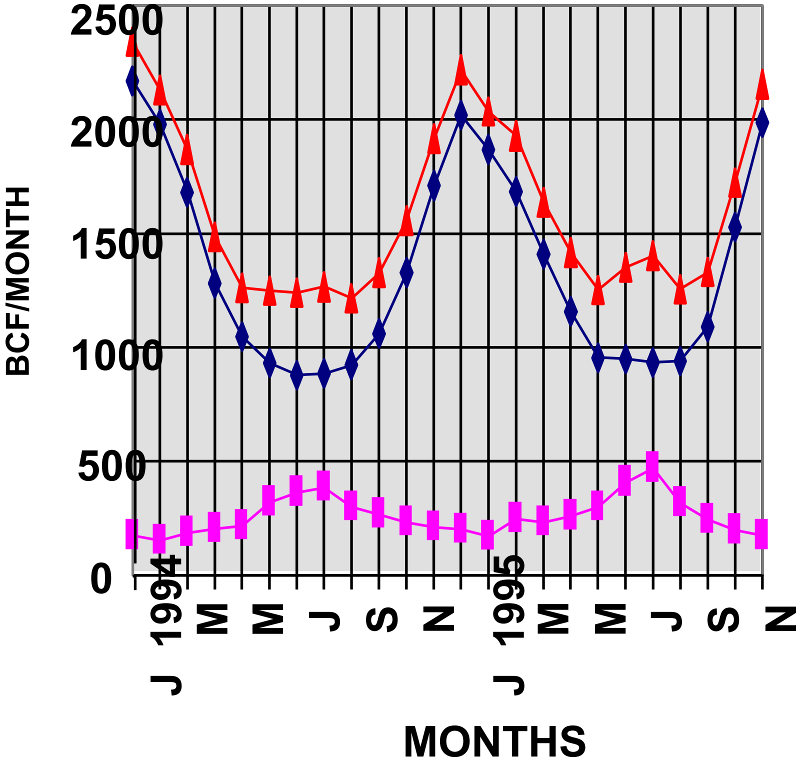
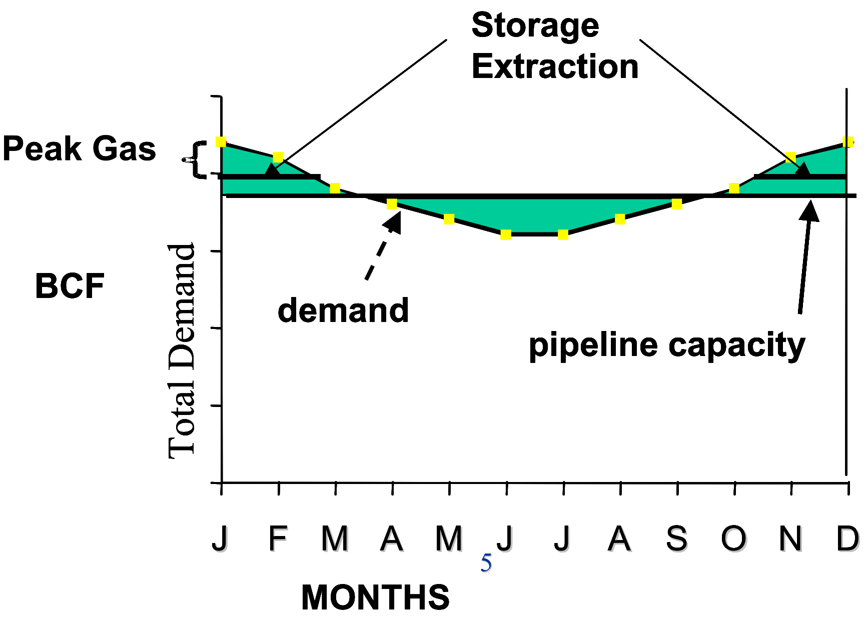
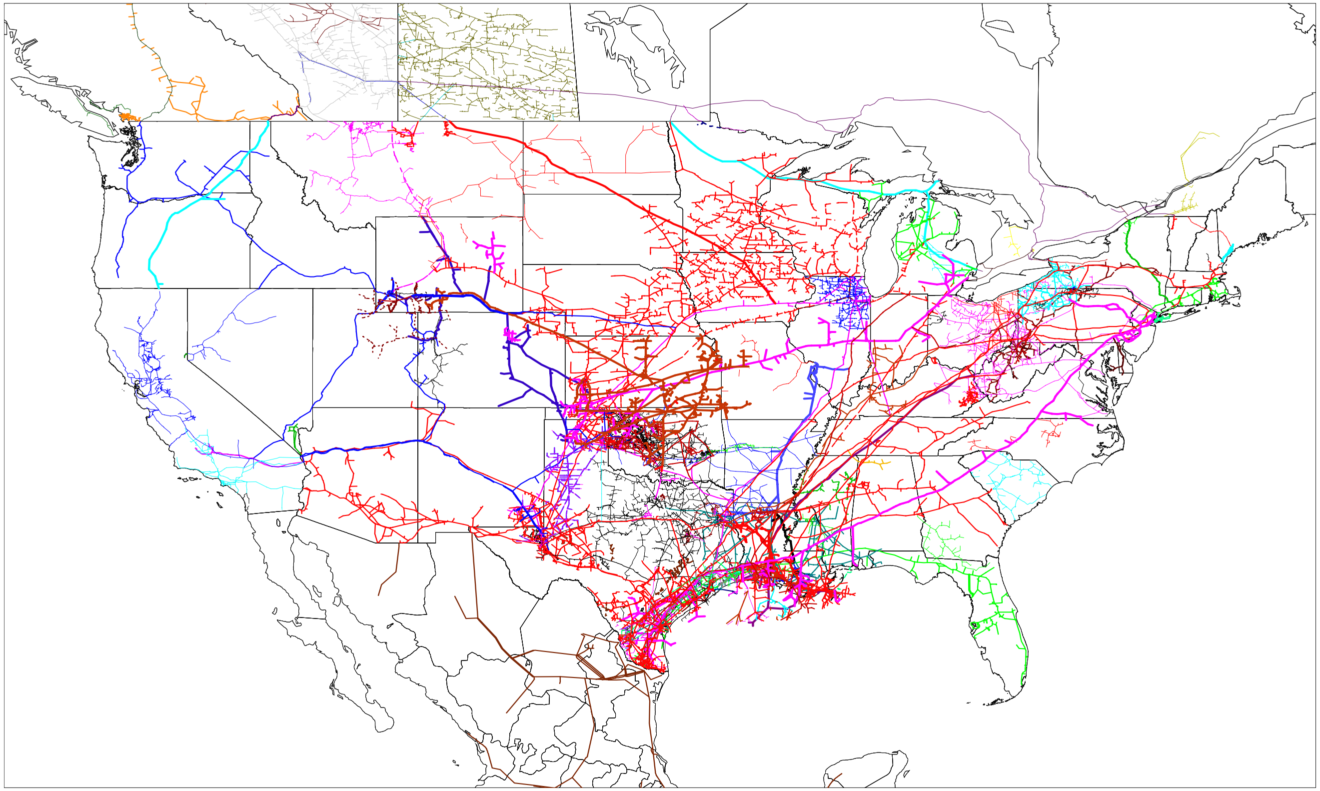


- **Seasonality in demand**
- **Pipeline, storage, peak gas**



- Pipelines
- 110 Interstate Pipelines, (51 classified as majors) with 190,000+ miles of Transmission Lines



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- Key events (US) (Chambers, Sturm)
- Before 1985
  - regulated interstate gas pipelines provided a bundled service that included
    - transportation
    - transportation-related services (e.g., storage)
    - the natural gas itself
  - Customers paid the cost of gas based on long-term contracts between the pipelines and unaffiliated gas producers
  - Customers paid on a “pass-through” basis, i.e., no return on the commodity allowed for the pipelines (unlike electric power)
  - Thus, pipelines made no profit on the purchase and sale of gas

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- Key events (US)
- Deregulatory FERC Orders 436 (1985), 500 (1989), 636 (1992) 888, 889 (1996)
  - Unbundling of services by interstate pipelines
  - Natural gas buyer can choose to buy gas from a supplier at one location, transport it along a pipeline a short distance (lower transportation rate), and receive the volumes
  - Promoting wholesale competition through open access, non-discriminatory transmission services by public utilities
  - Recovery of stranded costs by public utilities and transmitting utilities
  - Standards of conduct developed for pipelines and marketer affiliates

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- Key events (US)
- This new marketplace may permit certain abuses of market power
  - Interstate pipelines have a natural monopoly but highly regulated by FERC
  - Production is more or less a perfectly competitive market due to the large volume of producers
  - Marketer/shippers are unregulated by FERC maybe they have some market power?
- Why straightforward system optimization will not work
- Need for a game-theoretic format (e.g., Nash-Cournot) for some players

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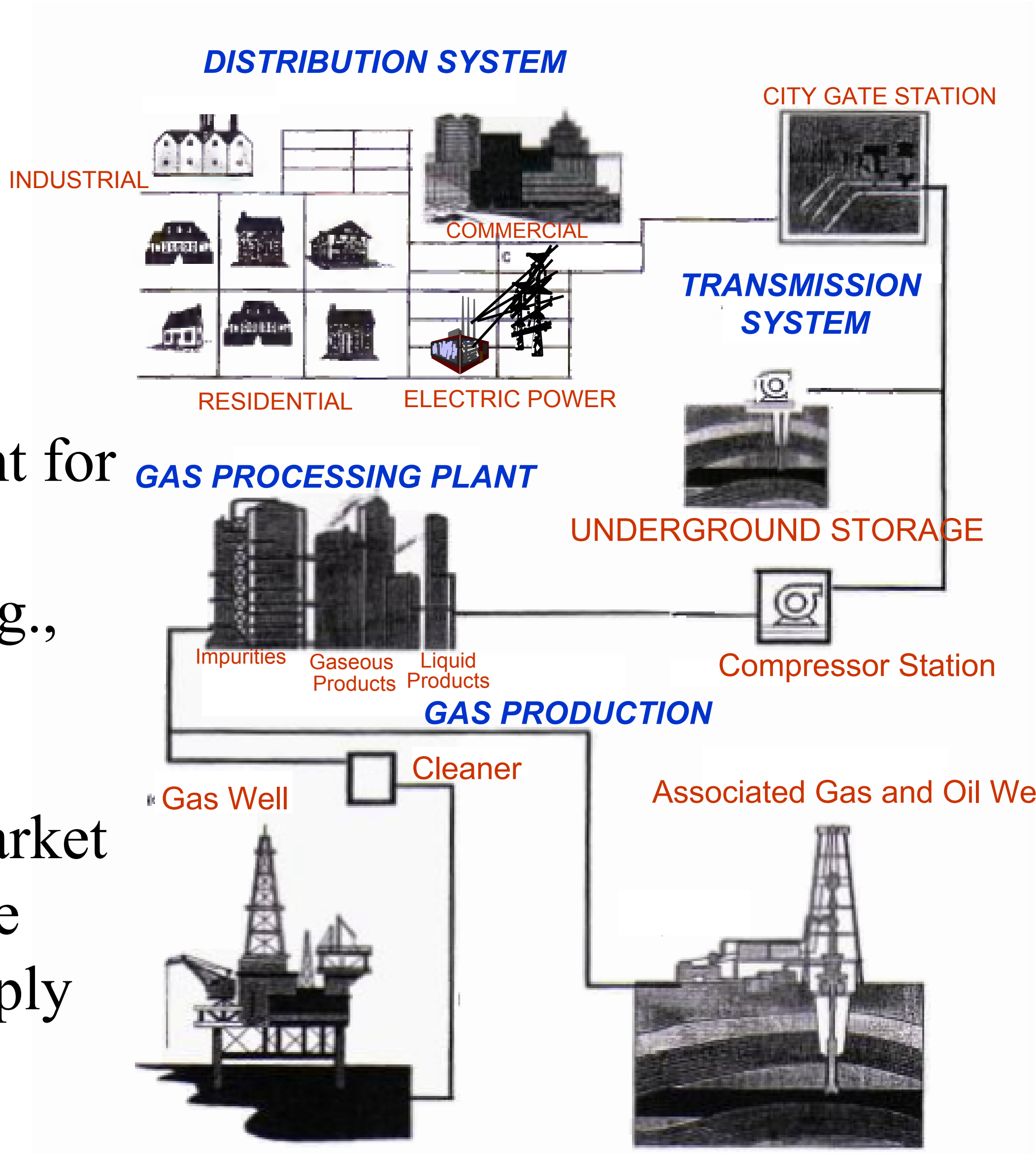
- Want to account for imperfect competition (e.g., oligopoly) to measure the influence of market power along the natural gas supply chain



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- Develop short term model to characterize the new natural gas industry (no new capacity)
  - **Pipeline companies**
    - Maximize net revenues: regulated rate revenues + congestion revenues subject to capacity bounds
  - **Production companies**
    - Maximize net profits subject to drilling restrictions
    - Perfect competition in the production market (reasonable for North America), price-takers
  - **Storage reservoir operators**
    - Maximize net profits subject to extraction, injection, and volumetric restrictions
    - Injection and extraction in different seasons
    - Storage reservoir operators use “seasonal arbitrage”
    - Perfect competition in the storage market, price takers for production and transportation

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- **Marketers/shippers**
  - Maximize net profits
  - Nash-Cournot players in the “marketer market”, thus marketers can exert market power via inverse demand functions
  - Price-takers in the storage, production, peak gas, and transportation markets
- **Peak gas suppliers**
  - Maximize net profits subject to peak supply capacity restrictions
  - Perfect competition in the peak supply market
  - Peak supply only in the high demand season, substitute for storage and pipeline gas
- **Consumers**
- Residential, commercial, industrial, electric power sectors
- Inverse demand functions as part of the marketer problems

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- Market clearing
  - Total supply = total demand in various markets
- Use multiple seasons
  - Season 1 (low demand), April-October, days$_1$=214
  - Season 2 (high demand), November-March, excluding January, days$_2$=120
  - Season 3, (very high or peak demand), e.g., January, days$_3$=31

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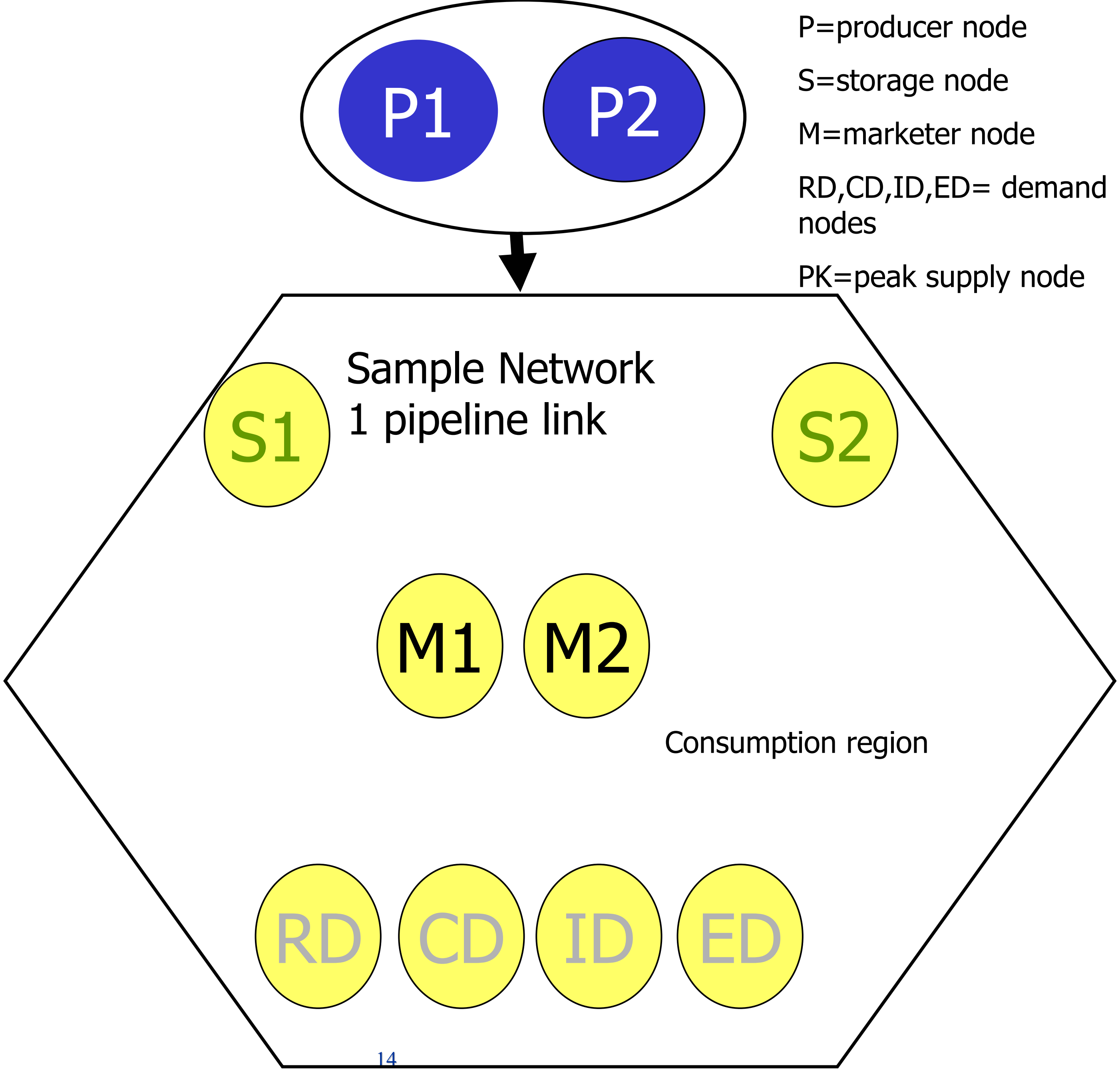

P=producer node

S=storage node

M=marketer node

RD,CD,ID,ED= demand nodes

PK=peak supply node

Sample Network
1 pipeline link

Consumption region

Sample Network
Low Demand Season

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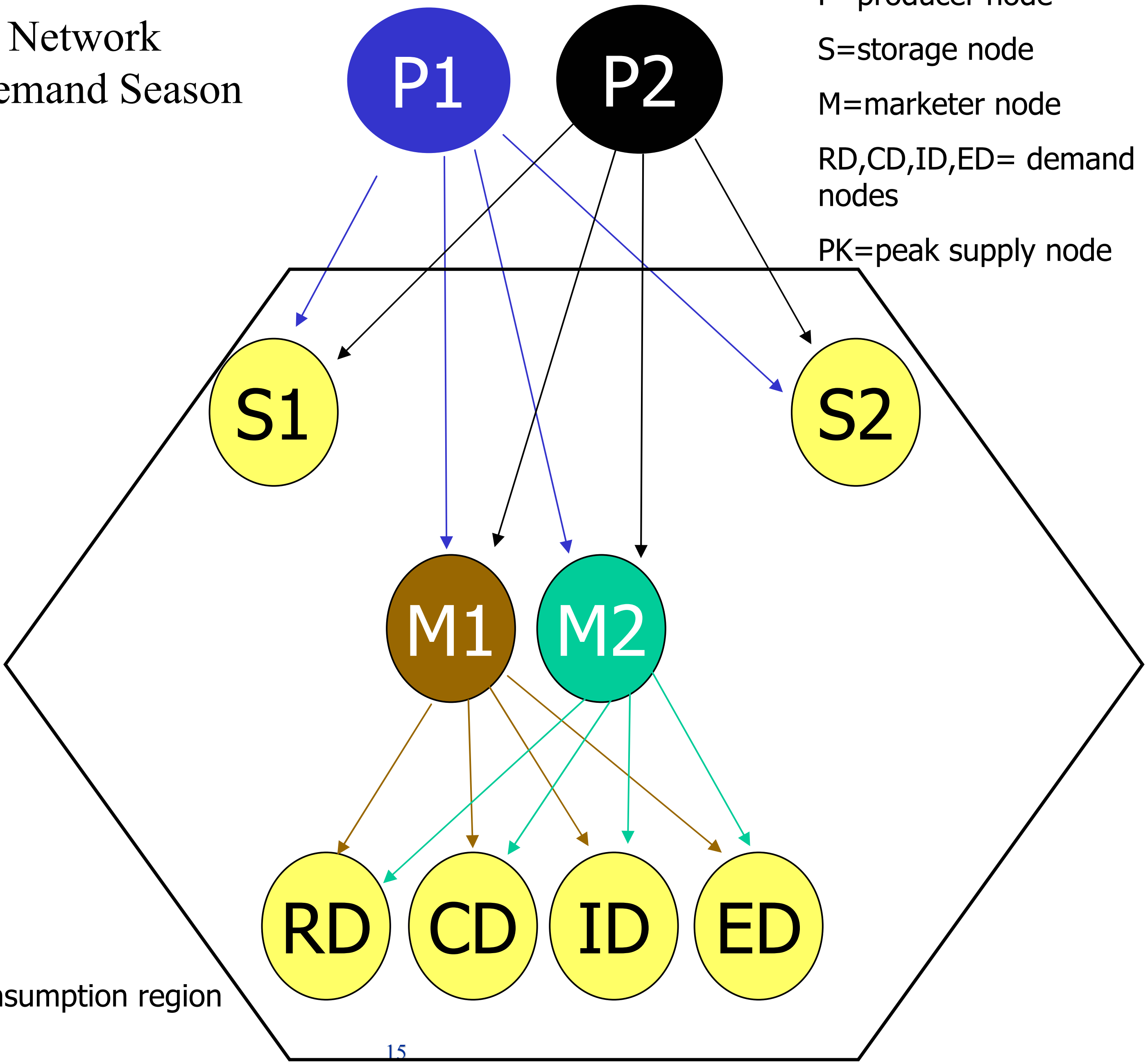

P=producer node

S=storage node

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Sample Network
High Demand Season

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M=marketer node

RD,CD,ID,ED= demand nodes

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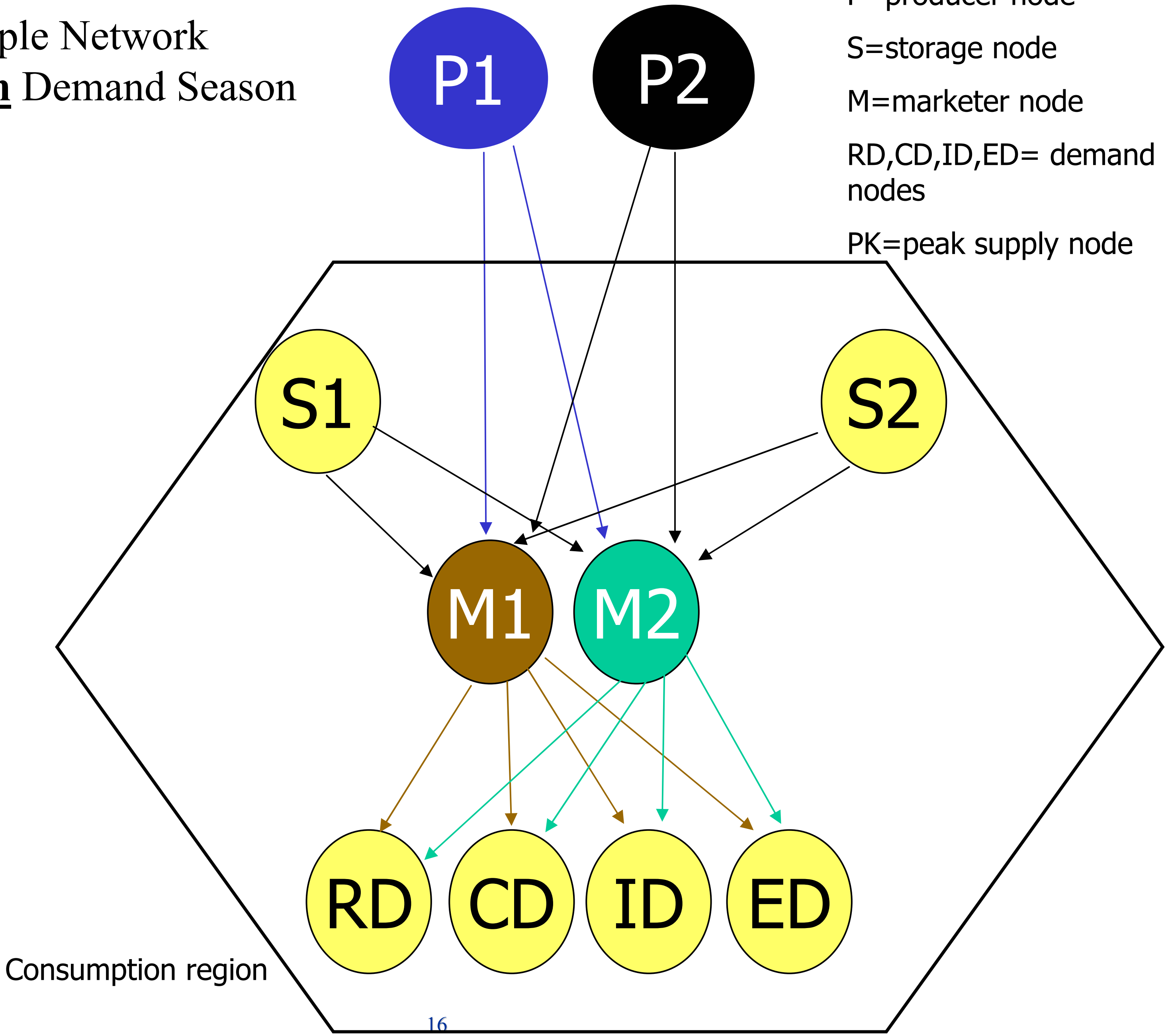

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Sample Network
<u>**Very High**</u>
Demand Season

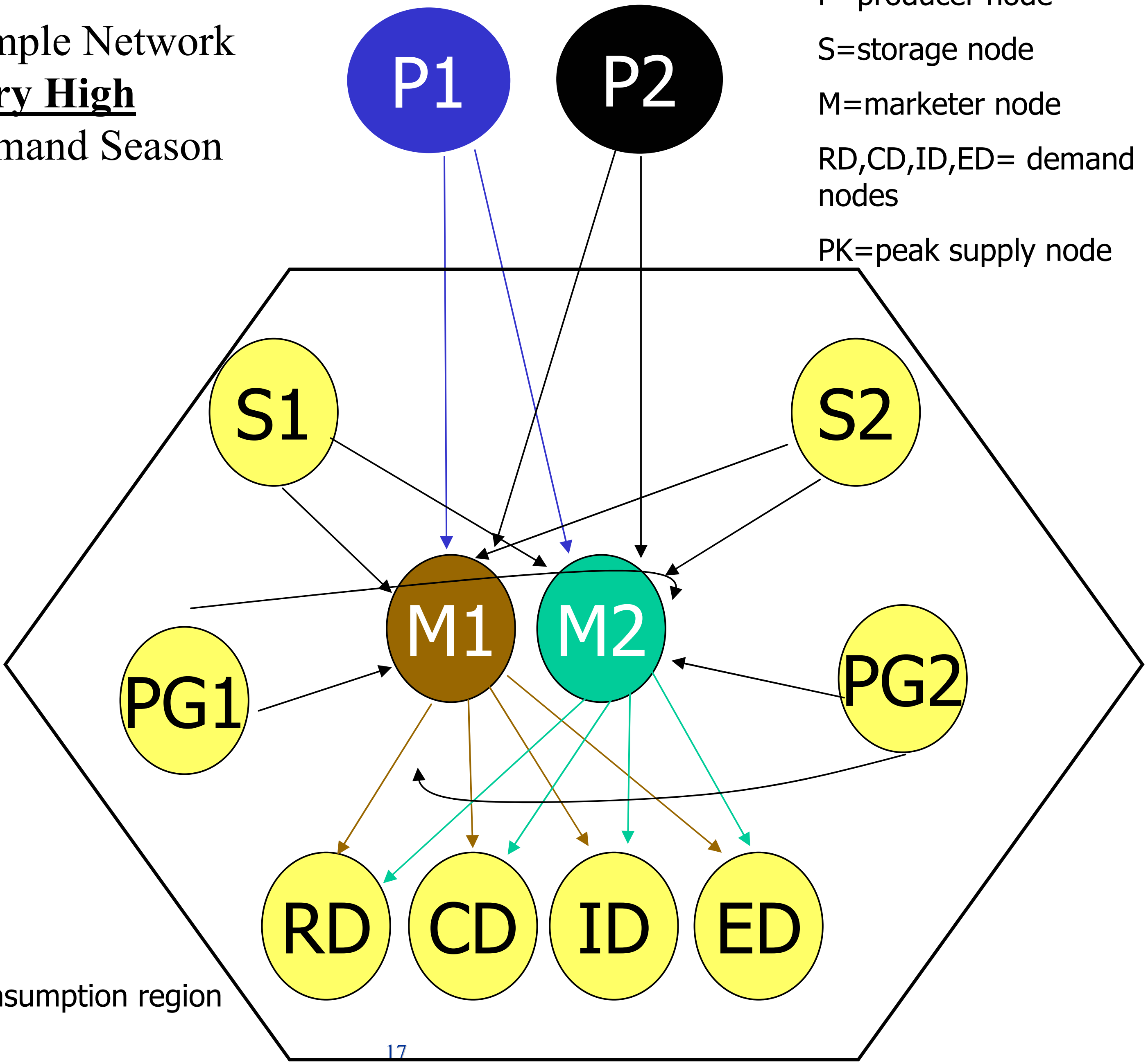
P=producer node

S=storage node

M=marketer node

RD,CD,ID,ED= demand nodes

PK=peak supply node



Consumption region

Pipeline Aggregation 1: Regional Aggregation

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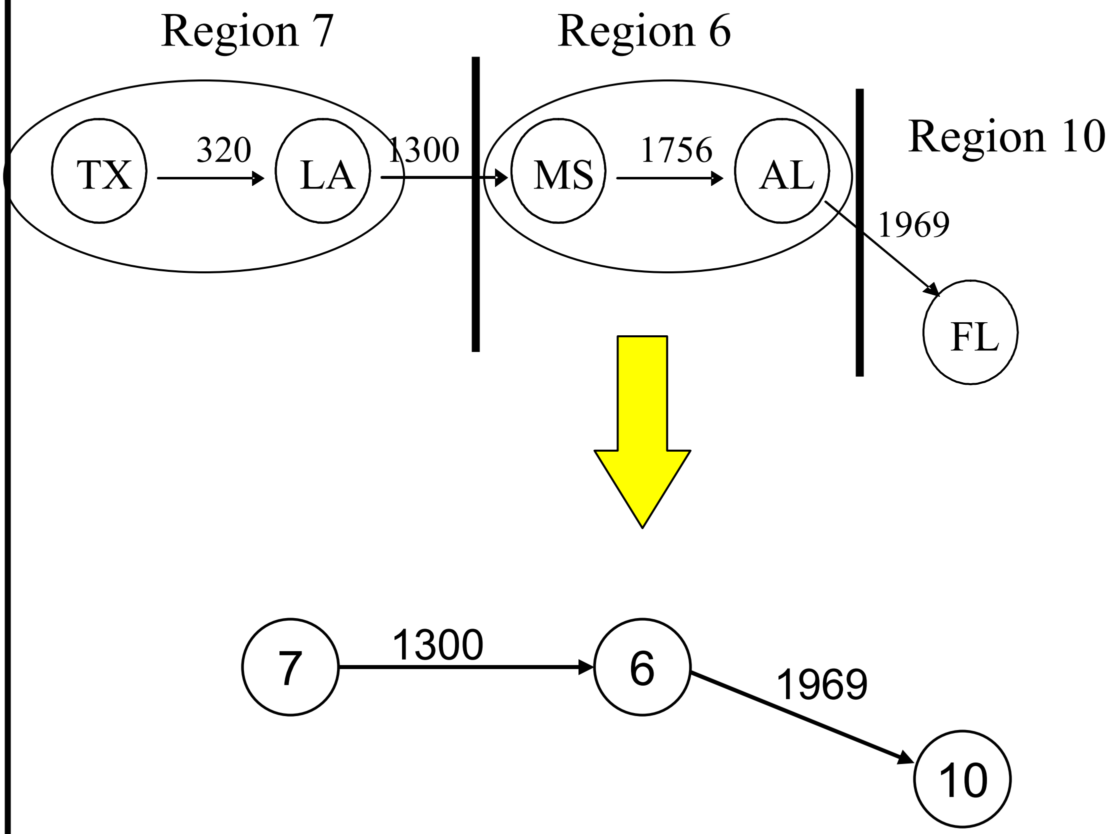

Pipeline Aggregation 2: Pipeline Combination

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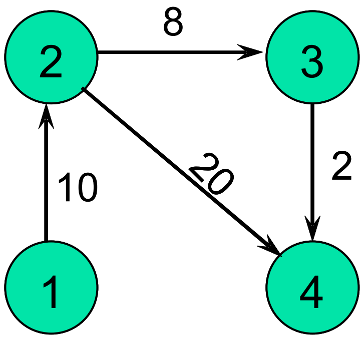
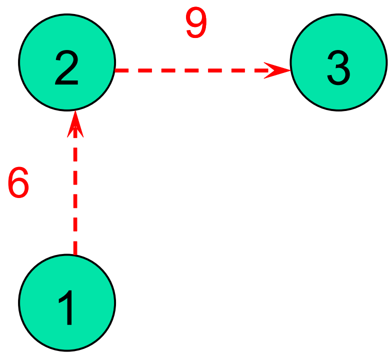
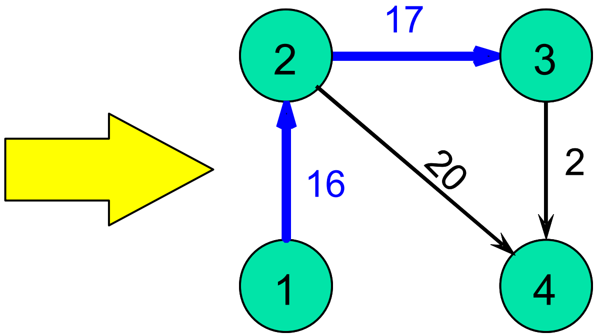


pipelines 1 (Solid)

+



pipelines 2 (dashed)



Aggregated pipelines

Pipeline Aggregation 3: Link Capacity Constraints

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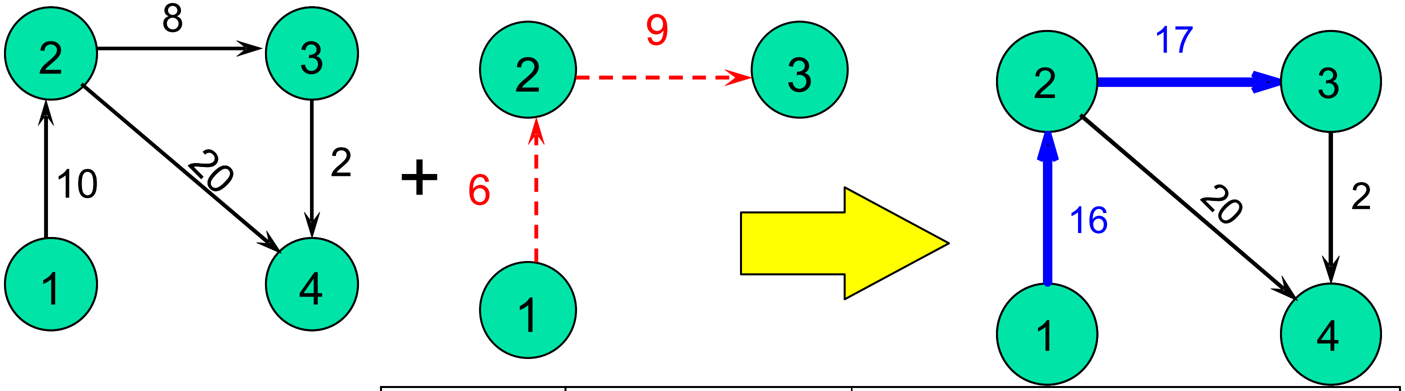

OD Pair	Path Flows	Pipelines Used
1. (1,2)	1. 1->2	both
2. (1,3)	2. 1->2->3	both
3. (1,4)	3. 1->2->4	1->2 both, 2->4 solid
	4. 1->2->3->4	1->2 both, 2->3 both, 3->4 solid
4. (2,3)	5. 2->3	2->3 both
5. (2,4)	6. 2->4	2->4 solid
	7. 2->3->4	2->3 both, 3->4 solid
6. (3,4)	8. 3->4	3->4 solid

Denoting f_i as the path flow for $i = 1\ldots8$, the following constraints are needed

$$\begin{pmatrix} f_1 + f_2 + f_3 + f_4 \\ f_2 + f_4 + f_5 + f_7 \\ f_3 + f_6 \\ f_4 + f_7 + f_8 \end{pmatrix} \le \begin{pmatrix} 16 \\ 17 \\ 20 \\ 2 \end{pmatrix} \begin{matrix} arc\,1,2 \\ arc\,2,3 \\ arc\,2,4 \\ arc\,3,4 \end{matrix}$$

Pipeline Aggregation 4: Additional Restriction

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- Assume that gas cannot go back and forth between the two different pipelines, the flow on paths would have to stay on the same pipeline.
- Additional constraints are needed to capture pipeline specific information.

Pipeline Aggregation 5: Additional Restriction 1

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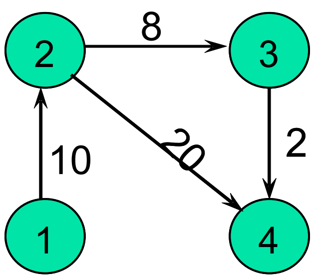
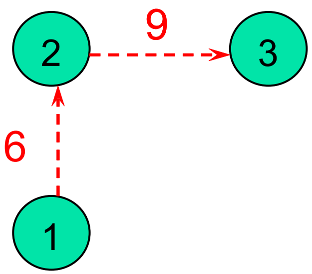
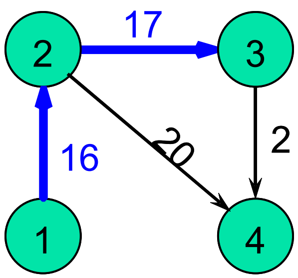
- f_2 : flow 1->2->3 use both pipelines
- For pipeline 1: $f_{2\text{-}1} \leq min\ (10,8)$
- For pipeline 2: $f_{2\text{-}2} \leq min\ (6,9)$
- Hence, $f_2 \leq 14$ instead of $f_2 \leq 16$







Pipeline Aggregation 5: Additional Restriction 2

- f_3 (flow 1->2->4) and f_4 (flow 1->2->3->4) would stay in pipeline 1 and use the arc (1,2) of pipeline 1 in common
- So $f_3 + f_4 \le 10$ would be used to enforce this condition

Pipeline Operator's Problem (Linear Program)

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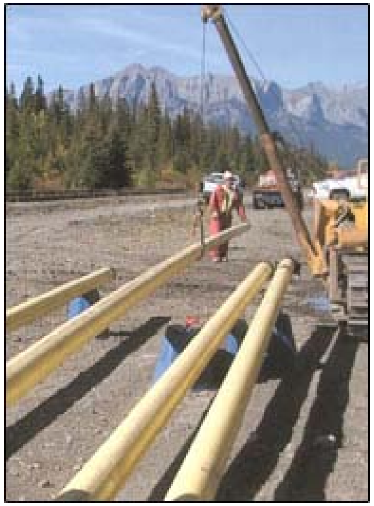


- Maximize congestion revenues s.t.
  - bounds on capacity
  - post-processor for regulated revenues
  - Other constraints that are pipeline-specific (not shown here)

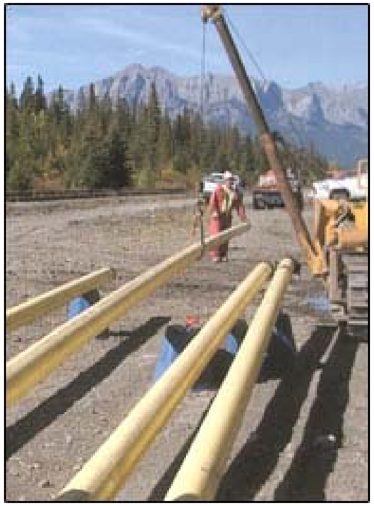
$$\text{Max} \sum_{y \in Y} \sum_{s=1}^{3} days_s \tau_{asy} f_{asy}$$

s.t.

$$f_{asy} \leq \bar{f}_a \quad (\rho_{asy}) \qquad \forall s, y$$

$$0 \leq f_{asy} \qquad \forall s, y$$

Pipeline Operator's Problem (Linear Program)



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- KKT conditions are both necessary and sufficient for optimality
- These conditions are

$$0 \le -days_s \tau_{asy} + \rho_{asy} \perp f_{asy} \ge 0 \qquad \forall s, y$$

$$0 \le \bar{f}_a - f_{asy} \perp \rho_{asy} \ge 0 \qquad \forall s, y$$

Producer's Problem (Convex Program)

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- Maximize production revenues less production costs
  s.t.
  - bounds on production rates
  - bounds on volume of gas produced

$$\text{Max} \sum_{y \in Y} \sum_{s=1}^{3} days_s \pi_{nsy} q_{csy} - days_s c_c^{pr}(q_{csy})$$

s.t.

$$q_{csy} \le \bar{q}_c \qquad (\lambda_{csy}) \quad \forall s, y$$

$$\sum_{y \in Y} \sum_{s=1}^{3} days_s q_{csy} \le prod_c \qquad (\mu_c)$$

$$0 \le q_{csy} \qquad \forall s, y$$

Producer's Problem (Convex Program)

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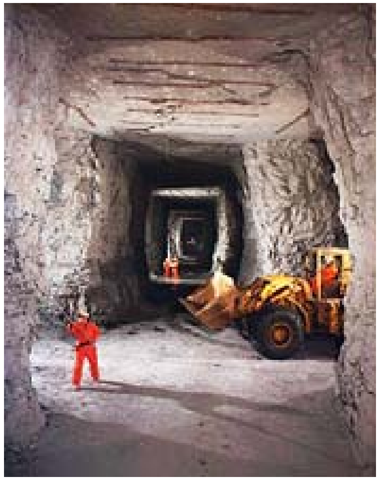
- If cost function is convex, KKT conditions are both necessary and sufficient for optimality
- Necessity since polyhedral constraints
- These conditions are

$$0 \le -days_s \pi_{nsy} + days_s c_c^{pr}(q_{csy})' + \lambda_{csy} + days_s \mu_c \perp q_{csy} \ge 0 \ \forall s, y$$

$$0 \le \bar{q}_c - q_{csy} \perp \lambda_{csy} \ge 0 \qquad \forall s, y$$

$$0 \le prod_c - \sum_{y \in Y} \sum_{s=1}^{3} days_s q_{csy} \perp \mu_c \ge 0$$

Storage Reservoir Operator's Problem (Convex Program)



- Maximize net revenues from marketers less injection, long-distance transportation and congestion costs
  s.t.
  - volumetric bound on working gas
  - maximum extraction rate bound
  - maximum injection rate bound
  - annual injection-extraction balancing
  - nonnegativity of injection and extraction

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Storage Reservoir Operator's Problem (Convex Program)

- If cost function is convex, KKT conditions are both necessary and sufficient for optimality
- Necessity since polyhedral constraints

Max

$$\sum_{y\in Y}\left[days_2\gamma_{n2y}x_{r2y} + days_3\gamma_{n3y}x_{r3y} - days_1 c_r^{st}\left(\sum_{a\in A(n)} g_{ary}\right) - \sum_{a\in A(n)} days_1\left(\tau_{a1y} + \tau_{a1y}^{reg} + \pi_{n_2(a)1y}\right)g_{ary}\right]$$

s.t.

$$days_2 x_{r2y} + days_3 x_{r3y} - days_1 \sum_{a\in A(n)} g_{ary}\left(1-loss_a\right)\left(1-loss_r\right) = 0 \quad (\delta_{ry}) \quad \forall y$$

$$x_{rsy} \le \bar{x}_r \quad (\omega_{rsy}) \quad s = 2,3, \forall y$$

$$\sum_{a\in A(n)} g_{ary} \le \bar{g}_r \quad \left(\xi_{ry}\right) \quad \forall y$$

$$\sum_{s=2,3} days_s x_{rsy} \le \bar{k}_r \quad \left(\zeta_{ry}\right) \quad \forall y$$

$$0 \le g_{ary} \forall a \in A(n), x_{r2y}, x_{r3y} \quad \forall y$$

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Marketer/Shipper's Problem (Convex Program)

- Maximize net demand sector revenues less, local delivered costs from storage and peak supply, long-distance cost from producers, congestion costs (inverse demand equations by sectors used)
  s.t.
  - pipeline gas consistency
  - storage gas consistency
  - nonnegativity of gas supplies (pipeline, storage, peak)

Marketer/Shipper’s Problem (Convex Program)

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- If revenue functions concave, KKT conditions are both necessary and sufficient for optimality
- Necessity since polyhedral constraints

$$
\begin{aligned}
&Max \sum_{y\in Y}\sum_{k\in K} \Big[days_1 \theta^k_{n1y}\left(h^k_{m1y}+h^{k*}_{-m1y}\right)h^k_{m1y} + days_2\theta^k_{n2y}\left(h^k_{m2y}+h^{k*}_{-m2y}+u^k_{m2y}+u^{k*}_{-m2y}\right)\left(h^k_{m2y}+u^k_{m2y}\right)+ \\
&days_3\theta^k_{n3y}\left(h^k_{m3y}+h^{k*}_{-m3y}+u^k_{m3y}+u^{k*}_{-m3y}+v^k_{my}+v^{k*}_{-my}\right)\left(h^k_{m3y}+u^k_{m3y}+v^k_{my}\right)\Big] \\
&-\sum_{y\in Y}\left[\left(\sum_{s=1}^{3}\sum_{a\in A(n)} days_s\left(\tau_{asy}+\tau^{reg}_{asy}+\pi_{n_2(a)sy}\right)h_{amsy}\right)+days_2\gamma_{n2y}u_{m2y}+days_3\gamma_{n3y}u_{m3y}+days_3\beta_{ny}v_{my}\right]
\end{aligned}
$$

s.t.

$$\sum_{k\in K} days_s h^k_{msy} - \sum_{a\in A(n)} days_s(1-loss_a)h_{amsy} = 0 \qquad (\alpha_{msy}) \ \forall s,y$$

$$\sum_{k\in K} days_s u^k_{msy} - days_s u_{msy} = 0 \qquad (\phi_{msy}) \ \forall s=2,3,\forall y$$

$$\sum_{k\in K} days_3 v^k_{my} - days_3 v_{my} = 0 \qquad (\varphi_{my}) \qquad \forall y$$

$$0 \le h^k_{msy} \qquad \forall k,s,y$$

$$0 \le h_{amsy} \qquad \forall a\in A(n),s,y$$

$$0 \le u^k_{msy} \qquad \forall k,s=2,3,y$$

$$0 \le u_{msy} \qquad \forall s=2,3,y$$

$$0 \le v^k_{my} \ , \ 0 \le v_{my} \qquad \forall y$$

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Peak Gas Operator's Problem (Convex Program)

- Maximize net revenues from marketers less peak gas costs
  s.t.
  - maximum peak gas supply upper bound
  - nonnegative peak gas supply and deliveries

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Peak Gas Operator’s Problem (Convex Program)

$$\text{Max} \sum_{y \in Y} days_3(\beta_{ny} w_{py} - c_p^{pg}(w_{py}))$$

s.t.

$$w_{py} \le \overline{w}_p \quad (\sigma_{py}) \qquad \forall y$$

$$0 \le w_{py} \qquad \forall y$$

Resulting Nonlinear Complementarity Problem

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- Apply Karush-Kuhn-Tucker Optimality conditions for the optimization problems faced by the
  - Pipeline operators, producers, storage operators, marketers, peak gas suppliers
  - Market clearing conditions
  - Existence & uniqueness results for mixed NCP version as well as model formulation discussion
    - S. A. Gabriel, S. Kiet, J. Zhuang. (2003) "A Competitive Equilibrium Model for the Natural Gas Market Based on a Mixed Complementarity Formulation," *forthcoming, Operations Research.*
  - For numerical study, convex, quadratic cost functions+ Linear demand equations → mixed linear complementarity problem
    - S. A. Gabriel, J.-F. Zhuang, S. Kiet. (2004) "A Nash-Cournot Model for the North American Natural Gas Market," IAEE Conference Proceedings, Zurich, Switzerland.
    - S.A. Gabriel, J.-F. Zhuang, S. Kiet. (2004) "A Large-Scale Linear Complementarity Model of the North American Natural Gas Market," in review.

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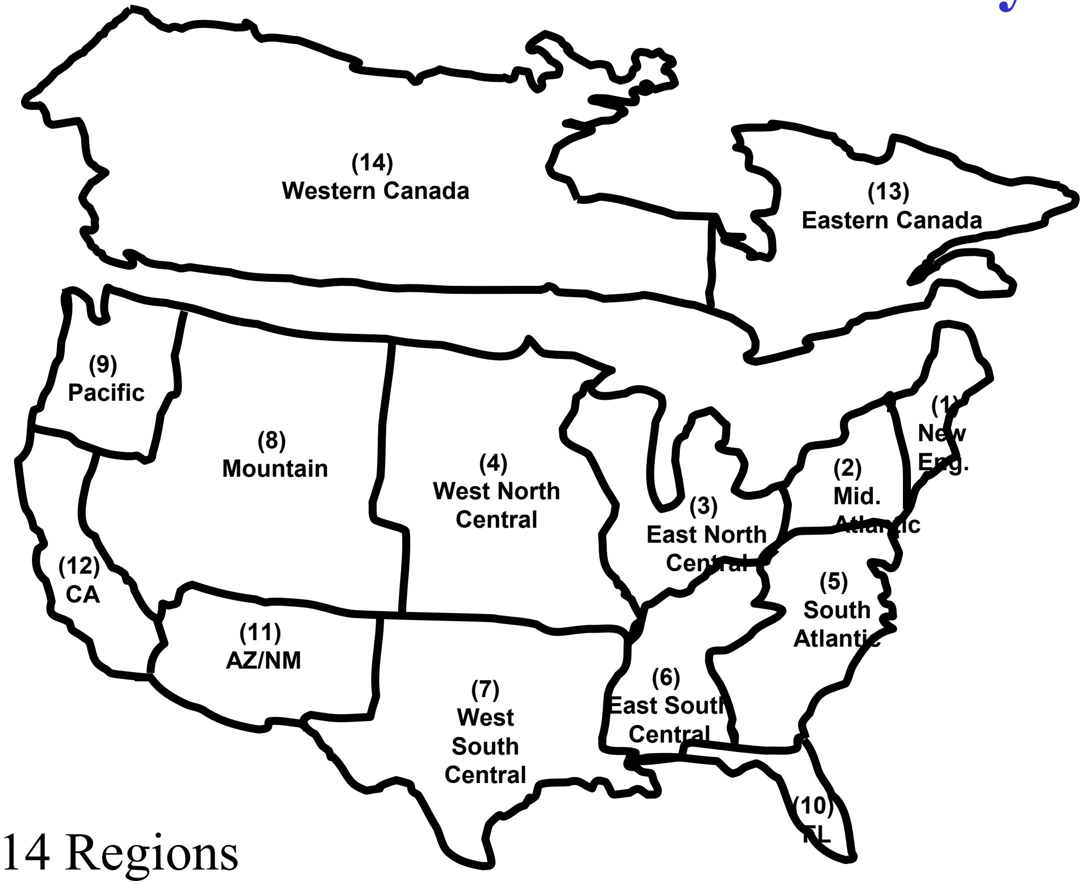
North American Numerical Study



- Total 14 Regions
- US portion based on US DOE natural gas regions

1 New England	2 Mid Atlantic	3 E. North Central	4 W. North Central	5 South Atlantic	6 E. South Central	7 W. South Central	8 Mountain	9 Pacific	10 Florida	11 AZ/NM	12 CA
CT	NJ	IL	IA	DE	AL	AR	CO	OR	FL	AZ	CA
ME	NY	IN	KS	DC	KY	LA	ID	WA		NM	
MA	PA	MI	MN	GA	MS	OK	MT				
NH		OH	MO	MD	TN	TX	NV				
RI		WI	NE	NC			UT				
VT			ND	SC			WY				
			SD	VA							
				WV							

National Petroleum Council (NPC) Study

http://www.npc.org/

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- Investigations of the ongoing and future operations
- Requirements of the U.S. oil and gas industries
- Statistical studies descriptive of these industries
- Delineations of the U.S. oil and gas resource base
- Comprehensive analyses of the domestic energy
- Supply/Demand Situation
- Examine other evolving market conditions that may affect the potential for natural gas demand, supplies and delivery through 2025
- The current policy direction - unaltered - will likely lead to difficult conditions in the natural gas market, but industries, government, and consumers will react
- Therefore, this study assumes action beyond the status quo

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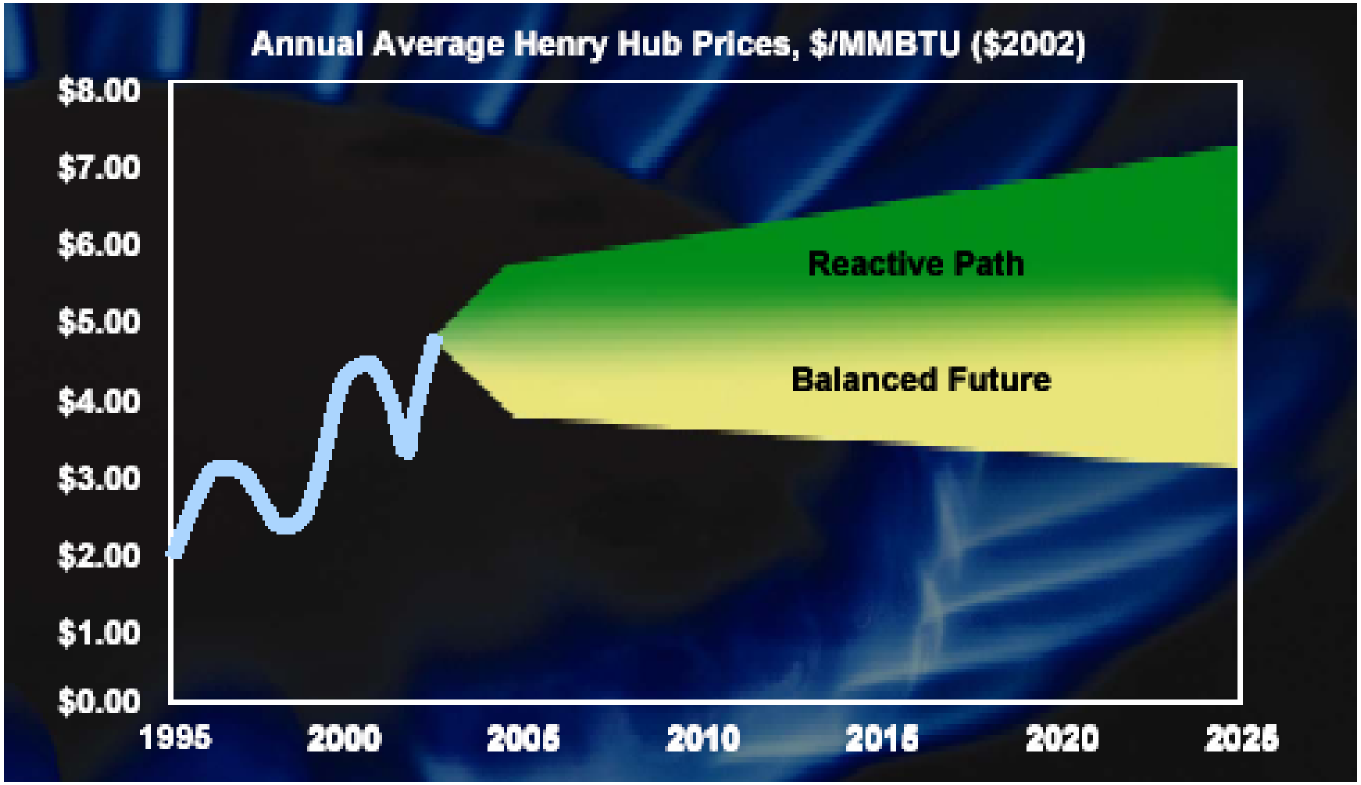
NPC Study

Two Paths Beyond Status Quo

1. Reactive Path Scenario	2. Balanced Future Scenario
Public Policies Remain in Conflict, Encouraging Consumption while Inhibiting Supply … Resulting in Higher Prices and Volatility.	Public policies aligned: alternate fuels and new natural gas supply sources compete to ensure lowest consumer cost.

NPC Study Potential Price Ranges



Sources: NPC 2003

NPC Study Interpretation

Summary of Demand and Supply Annual Percentage Changes for Each Case

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	Demand Sectors Growth or Decline				Supply Growth	
Reactive Path	**Res.**	**Com.**	**Ind.**	**Elec. Power**	**Prod.**	**LNG**
	0.75%	**0.81%**	**-1.00%**	**1.90%**	**0.80%**	**25.99%**
Balanced Future	**Res.**	**Com.**	**Ind.**	**Elec. Power**	**Prod.**	**LNG**
	0.51%	**0.89%**	**-0.74%**	**1.70%**	**0.93%**	**28.49%**

**** Demand percentage changes are actual figures from the NPC study, supply values are estimated based on graphs.***

- Base Cases, 2002: Nash-Cournot and Perfectly Competitive Marketers
- Balanced Future Cases, 2008: Nash-Cournot & Perfectly Competitive Marketers
- Reactive Path Cases, 2008: Nash-Cournot & Perfectly Competitive Marketers

Market Participants by Region

My Background

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Region	Production	Storage	Marketers	Peak Gas
1. New England	*No*	*No*	**2**	Yes
2. Mid Atlantic	Yes	Yes	**2**	Yes
3. East North Central	Yes	Yes	**2**	Yes
4. West North Central	Yes	Yes	**2**	Yes
5. South Atlantic	Yes	Yes	**2**	Yes
6. East South Central	Yes	Yes	**2**	Yes
7. West South Central	Yes	Yes	**2**	Yes
8. Mountain	Yes	Yes	**2**	Yes
9. Pacific	Yes	Yes	**2**	Yes
10. Florida	Yes	*No*	**2**	*No*
11. Arizona/New Mexico	Yes	Yes	**2**	*No*
12. California	Yes	Yes	**2**	Yes
13. Eastern Canada	Yes	Yes	**2**	Yes
14. Western Canada	Yes	Yes	**2**	Yes

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Model Calibration Accuracy

- Investigations of the calibration dataset used
  - Gas Demand Quantity for all 4 sectors
  - Gas Price (Production, City Gate and End User)
  - Capacity (Pipeline, Production, Storage, and Peak Gas)
  - Transportation Costs
  - Sources of Calibration Information Used (Yr. 2002):
  - Energy Information Administration (EIA) of the U.S. Department of Energy (DOE)
  - Natural Resources Canada (NRCAN)

Calibration Accuracy for Base Case 2002*

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Calibration Price Accuracy Table:

Region	Production	City Gate	Res. Demand	Comm. Demand	Ind. Demand	Power Demand
USA	7.49 %	1.50 %	0.10 %	0.62 %	0.44 %	2.47 %
Canada	10.49 %	N/A	N/A	N/A	N/A	N/A

Calibration Quantity Accuracy Table:

Region	Production	Res. Demand	Comm. Demand	Ind. Demand	Power Demand
USA	4.66 %	-0.55 %	-0.62 %	-0.90 %	-0.63 %
Canada	-2.22 %	0.72 %	0.22%	0.14 %	0.69 %

* Calibration Accuracy Based on Comparison Between Base Case and EIA & NRCAN Data

Supply and Demand Functions Used

Function	Function Forms	Example
Producer Costs **(Producer *c* for season *s* and year *y*)**	Quadratic	$\alpha_0 + \alpha_1 x + \frac{1}{2}\alpha_2 x^2$
Storage Operator Costs **(Operator *r* for season *s* and year *y*)**	Quadratic	$\beta_0 + \beta_1 x + \frac{1}{2}\beta_2 x^2$
Peak Gas Operator Costs **(Operator *p* for season *s* and year *y*)**	Quadratic	$\gamma_0 + \gamma_1 x + \frac{1}{2}\gamma_2 x^2$
Inverse Demand **(Sector *k* for season *s* and year *y*)**	Linear	$A - B\theta$

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Computational Statistics

- Computational and Modeling Aspects
  - LCP with 4298 variables all together
  - Solver: GAMS/PATH
  - Computer: 2.80 GHz Intel® Pentium® 4 Processor and 1.0GB of memory
  - Typical solution times for each case
  - About 25 seconds to read the input from an EXCEL file
  - 10 to 100 seconds for GAMS/PATH to solve the model depending on the parameter settings and cases solved
  - About 8 seconds to write the output to another EXCEL file
  - About 3-4 months to calibrate the Base Case!

Base Case- Nash Cournot (NC) vs. Base Case Perfect Competition (PC)

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		BC-NC	BC - PC	% diff.
Producers	Wellhead Prices ($/Mcf)	$ 3.49	$ 4.39	-20.62%
	Production (MMcf)	21,449,980	22,410,085	-4.28%
	Profits (1000$)	40,999,255	64,320,640	-36.26%
Storage Operators	Gas Prices ($/Mcf)	$ 3.96	$ 5.08	-22.05%
	Extraction (MMcf)	1,806,400	2,854,332	-36.71%
	Profits (1000$)	70,325	159,069	-55.79%
Peak Gas Operators	Gas Prices ($/Mcf)	$ 4.22	$ 5.20	-18.85%
	Supply(MMcf)	241,644	241,644	0.00%
	Profits (1000$)	673,754	908,682	-25.85%
Marketers	Profits (1000$)	39,050,713	0	n/a
End-user Prices	RD	$ 7.98	$ 5.22	52.70%
	CD	$ 6.79	$ 5.18	30.99%
	ID	$ 4.54	$ 4.46	1.76%
	ED	$ 3.88	$ 4.11	-5.66%
Consumption (MMcf)	RD	5,070,051	6,752,150	-24.91%
	CD	3,359,012	4,326,044	-22.35%
	ID	7,791,256	7,666,899	1.62%
	ED	5,332,594	3,744,228	42.42%
Pipeline	Regulated Income (1000$)	8,477,208.21	9,395,139.17	-9.77%
	Congestion Income (1000$)	7,896,513.94	6,611,806.11	19.43%

Balanced Future Nash Cournot (NC) vs. Balanced Future Perfect Competition (PC)

My Background

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		BF-NC	BF - PC	% diff.
Producers	Wellhead Prices ($/Mcf)	$ 3.60	$ 4.45	-19.10%
	Production (MMcf)	21,596,952	22,834,094	-5.42%
	Profits (1000$)	42,648,106	64,262,676	-33.63%
Storage Operators	Gas Prices ($/Mcf)	$ 4.03	$ 5.10	-20.98%
	Extraction (MMcf)	1,532,182	2,478,187	-38.17%
	Profits (1000$)	48,105	152,930	-68.54%
Peak Gas Operators	Gas Prices ($/Mcf)	$ 3.57	$ 4.72	-24.36%
	Supply(MMcf)	1,076,855	1165085.298	-7.57%
	Profits (1000$)	1,514,677	2,827,067	-46.42%
Marketers	Profits (1000$)	42,832,340	0	n/a
End-user Prices	RD	$ 8.06	$ 5.26	53.39%
	CD	$ 7.03	$ 5.22	34.60%
	ID	$ 4.56	$ 4.52	0.97%
	ED	$ 4.19	$ 4.20	-0.15%
Consumption (MMcf)	RD	5,330,381	7,169,293	-25.65%
	CD	3,712,096	4,871,733	-23.80%
	ID	6,351,427	5,438,908	16.78%
	ED	7,138,690	6,358,119	12.28%
Pipeline	Regulated Income (1000$)	8,504,341.30	9,594,763.95	-11.36%
	Congestion Income (1000$)	9,120,153.98	9,030,300.89	1.00%

Base Case, Balanced Future, and Reactive Path Nash Cournot Cases

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		Base Case	Balanced Future	Reactive Path
Producers	Wellhead Prices ($/Mcf)	$ 3.49	3.21%	3.50%
	Production (MMcf)	21,449,980	0.69%	0.66%
	Profits (1000$)	40,999,255	4.02%	4.46%
Storage Operators	Gas Prices ($/Mcf)	$ 3.96	1.77%	1.77%
	Extraction (MMcf)	1,806,400	-15.18%	-13.87%
	Profits (1000$)	70,325	-31.60%	-25.52%
Peak Gas Operators	Gas Prices ($/Mcf)	$ 4.22	-15.40%	-12.09%
	Supply(MMcf)	241,644	345.64%	311.45%
	Profits (1000$)	673,754	124.81%	136.36%
Marketers	Profits (1000$)	39,050,713	9.68%	10.88%
End-user Prices	RD	$ 7.98	1.11%	2.55%
	CD	$ 6.79	3.48%	3.32%
	ID	$ 4.54	0.52%	0.04%
	ED	$ 3.88	8.15%	9.26%
Consumption (MMcf)	RD	5,070,051	5.13%	7.78%
	CD	3,359,012	10.51%	9.11%
	ID	7,791,256	-18.48%	-23.90%
	ED	5,332,594	33.87%	38.50%
Pipeline	Regulated Income (1000$)	8,477,208.21	0.32%	0.55%
	Congestion Income (1000$)	7,896,513.94	15.50%	16.35%

Case Comparison, % diff. with Base Case

Balanced Future and Reactive Path Cases Not Much Different for ID, ED

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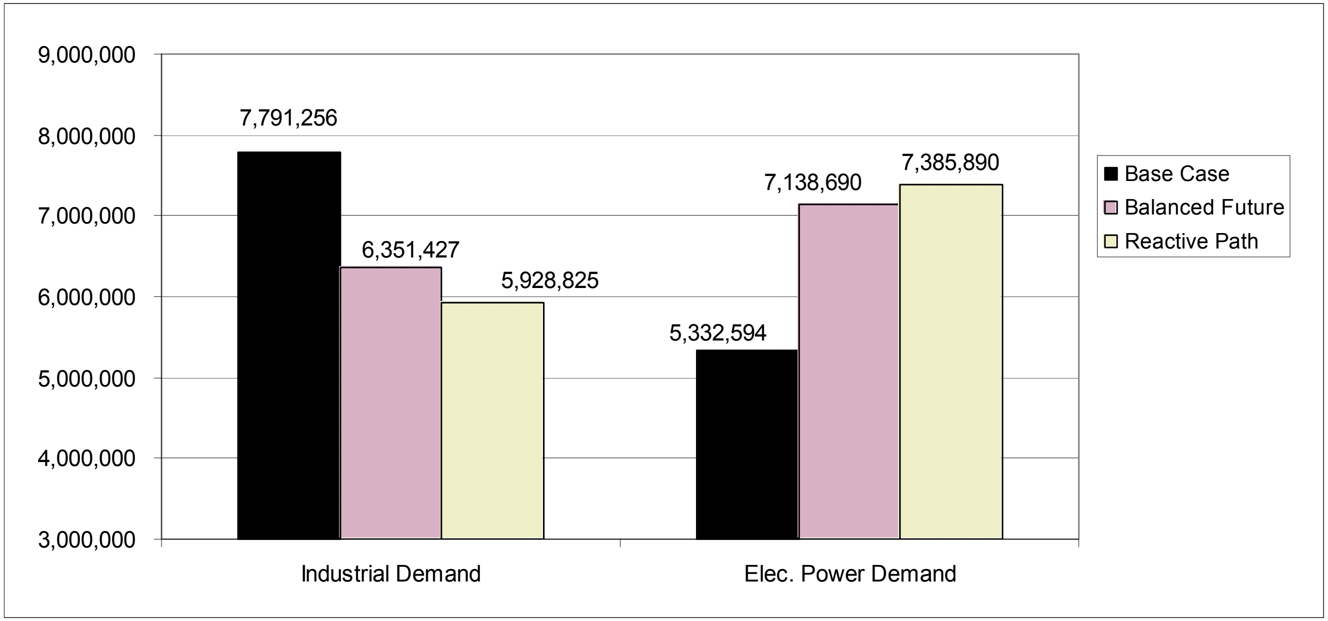

Comparison of Industrial and Electric Power Demand (MMcf)

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Future Work

Future Work and References

- Adding stochasticity to the market player problems
  - Model formulation and solution **(Denver 2004 INFORMS meeting, marketers have chance constraints, ongoing work to consider recourse with the spot market)**
  - Mathematical analysis including existence & uniqueness results **(some improvements for deterministic case, stochastic case ongoing)**
  - Decomposition methods (e.g., Benders, Dantzig-Wolfe)
- Using micro-level approach for demand and/or supply functions
  - Certain modules are “black boxes”, hard to generate data
  - US DOE NEMS model, ICF Consulting’s GSAM model

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Future Work and References

- **Related Papers: North American market**
  - S.A. Gabriel, S. Kiet, J.-F. Zhuang. (2003) “A Mixed Complementarity-Based Equilibrium Model of Natural Gas Markets,” forthcoming, *Operations Research*
  - S. A. Gabriel, J.-F. Zhuang, S. Kiet. (2004) "A Nash-Cournot Model for the North American Natural Gas Market," IAEE Conference Proceedings, Zurich, Switzerland.
  - S.A. Gabriel, J.-F. Zhuang, S. Kiet. (2004) “A Large-Scale Linear Complementarity Model of the North American Natural Gas Market,” in review
- **Related Papers: European market**
  - M.G. Boots, F.A.M Rijkers, and B.F. Hobbs. (2004) “Modelling the role of trading companies in the downstream European gas market: a successive oligopoly approach,” *The Energy Journal*, 25, July 2004.
  - F. van Oostvoorn. (2003) “Long-term gas supply security in an enlarged Europe: Final Report ENGAGED Project,” www.ecn.nl/library/reports/2003/c03122.html
  - R. Egging and S.A. Gabriel. (2004) “Examining Market Power in the European Natural Gas Market ,” in review
  - S.A. Gabriel, Y. Smeers. (2004) “Complementarity Problems in Restructured Gas Markets,” in review