Natural Gas Market Modeling

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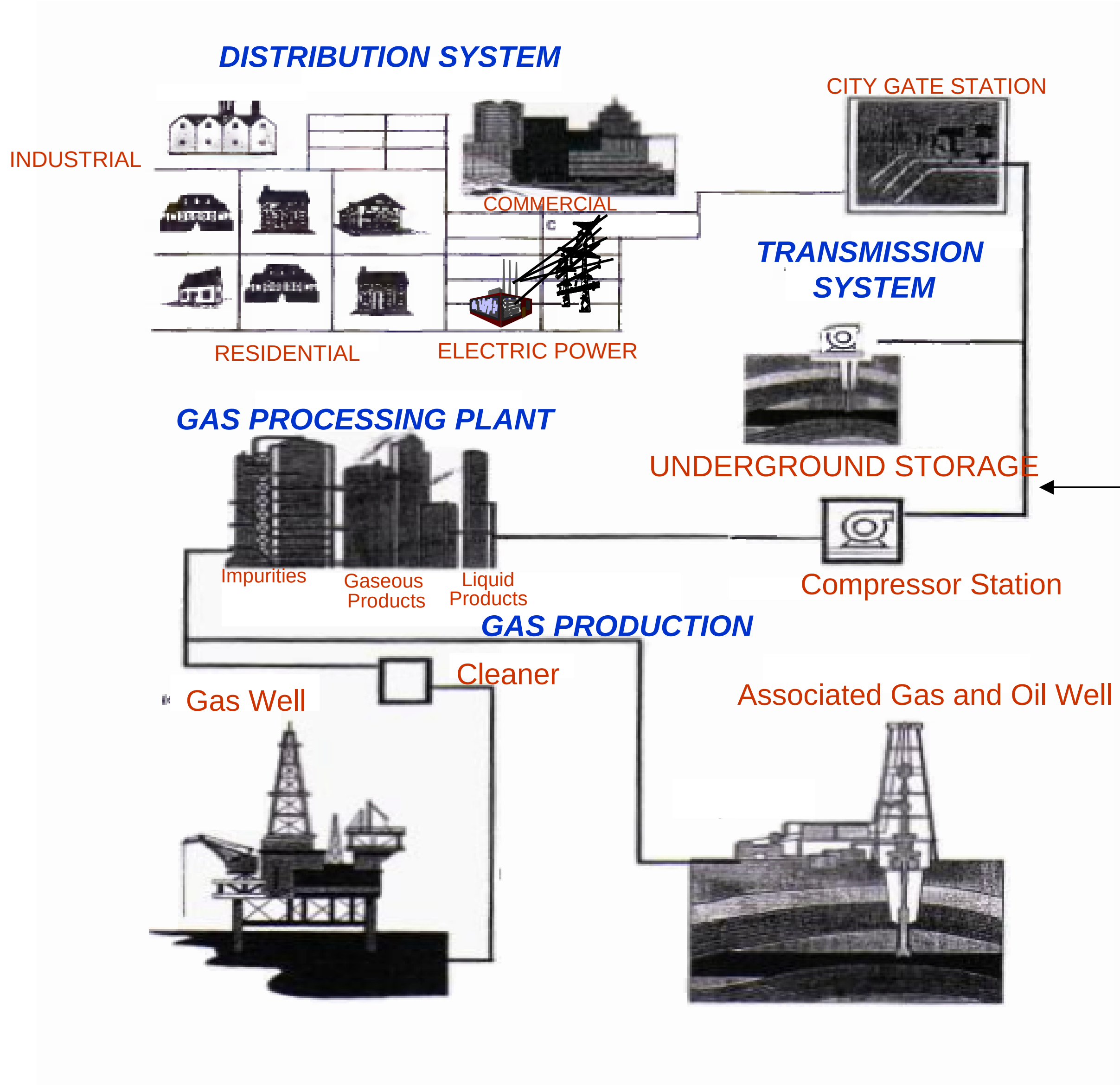
Outline

- **Overview of Recent World Natural Gas Market Events**
  - Industry Background
  - Summary of Energy Market Forum (EMF-23) and DOE meetings
  - Natural Gas Markets in the Headlines
- **A Stochastic Complementarity Modeling Approach (Zhuang and Gabriel)**
  - A Stochastic-Natural Gas Equilibrium Model (S-NGEM)
  - Selected Numerical Results
  - Conclusions & Future Research
  - Relevant Recent Works

Complementarity Modeling and Natural Gas Markets (Gabriel et al.)

1. Gabriel, Kiet and Zhuang (2005), A Mixed Complementarity-Based Equilibrium Model of Natural Gas Markets, *Operations Research, 53(5), 799-818*.
2. Gabriel, Zhuang and Kiet (2005), A Large-Scale Complementarity Model of the North American Natural Gas Market, *Energy Economics*, 27, 639-665.
3. Gabriel, Zhuang and Kiet (2004), A Nash-Cournot Model for the North American Natural Gas Market, *IAEE Conference Proceedings*, Zurich, Switzerland, September.
4. R. Egging and Gabriel (2006, Examining Market Power in the European Natural Gas Market, *Energy Policy*, in press.
5. Gabriel and Smeers (2006), Complemenatarity Problems in Restructured Natural Gas Markets, *Recent Advances in Optimization. Lecture Notes in Economics and Mathematical Systems, Edited by A. Seeger,* Vol. 563, Springer-Verlag Berlin Heidelberg, 343-373.
6. Zhuang and Gabriel (2006), A Complementarity Model for Solving Stochastic Natural Gas Market Equilibria *in review*.

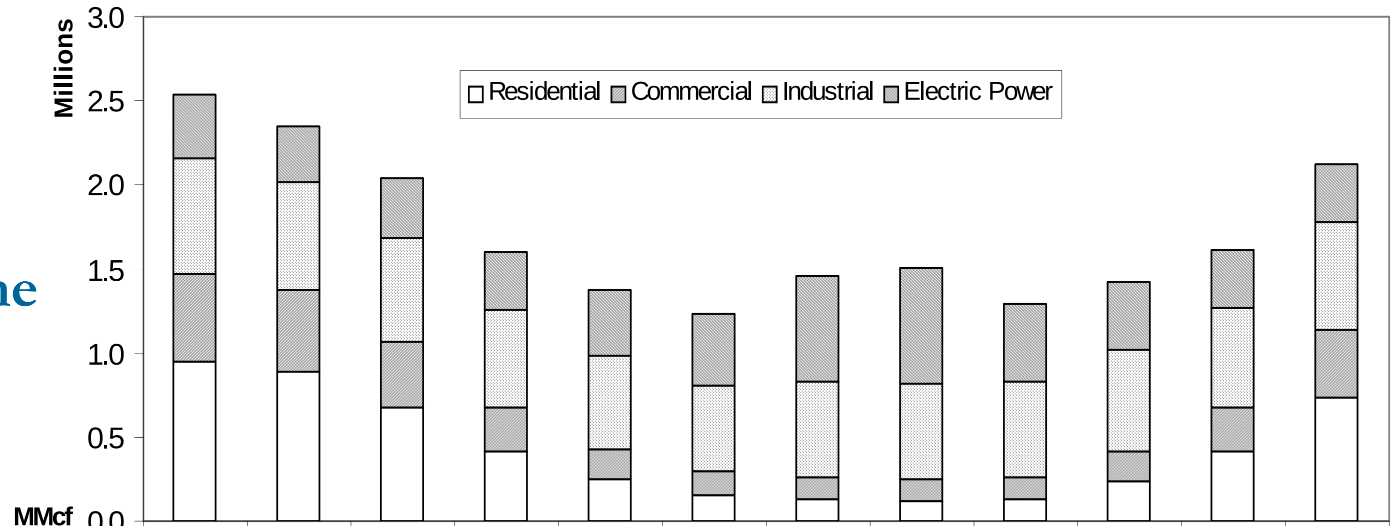
Industry Background



From well-head to burner-tip

Seasonal Demand Aspects

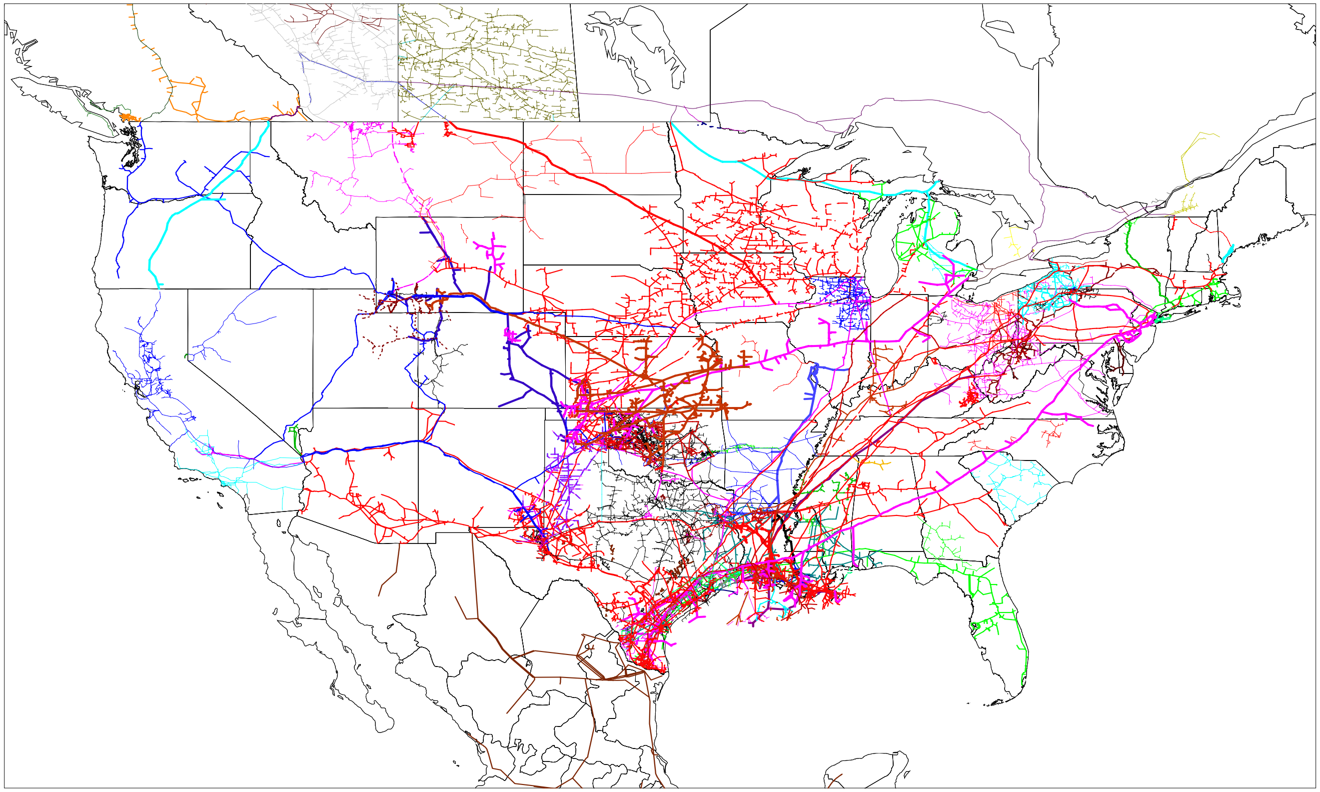
- Strong seasonal demand
- Graphic for the US Market (2003)



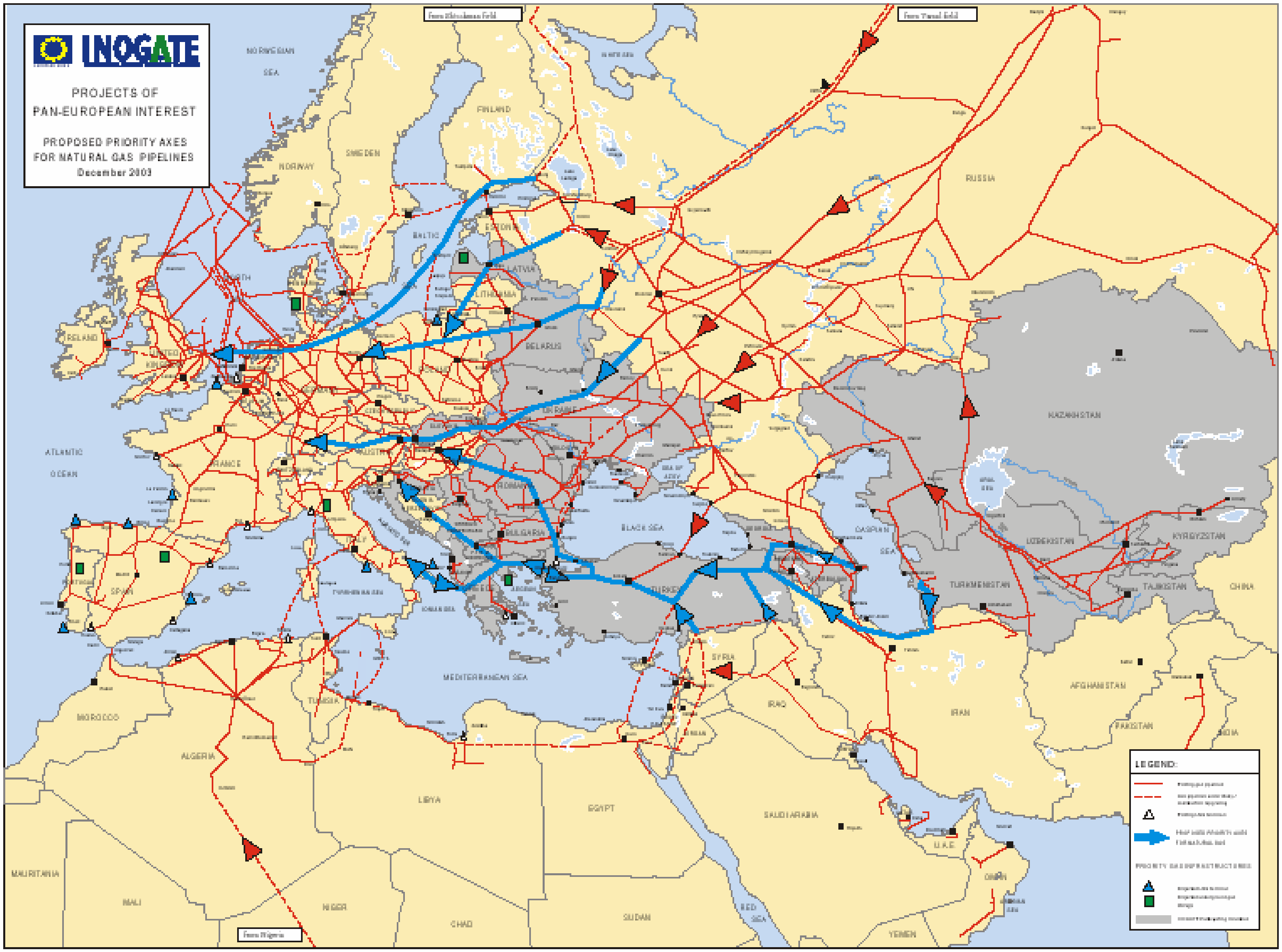
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Electric Power	382,443	334,698	361,243	352,164	394,021	435,598	630,270	683,513	468,510	408,817	348,129	335,810
Industrial	686,025	640,202	615,171	574,328	556,416	508,348	572,719	577,497	561,221	601,231	595,609	650,261
Commercial	522,463	487,178	390,806	263,067	181,047	137,575	132,219	130,824	136,613	181,260	259,504	394,103
Residential	945,744	884,233	674,581	414,062	247,501	157,262	126,386	115,784	128,579	231,574	413,718	738,775

Transportation and Distribution

- Pipelines in the US

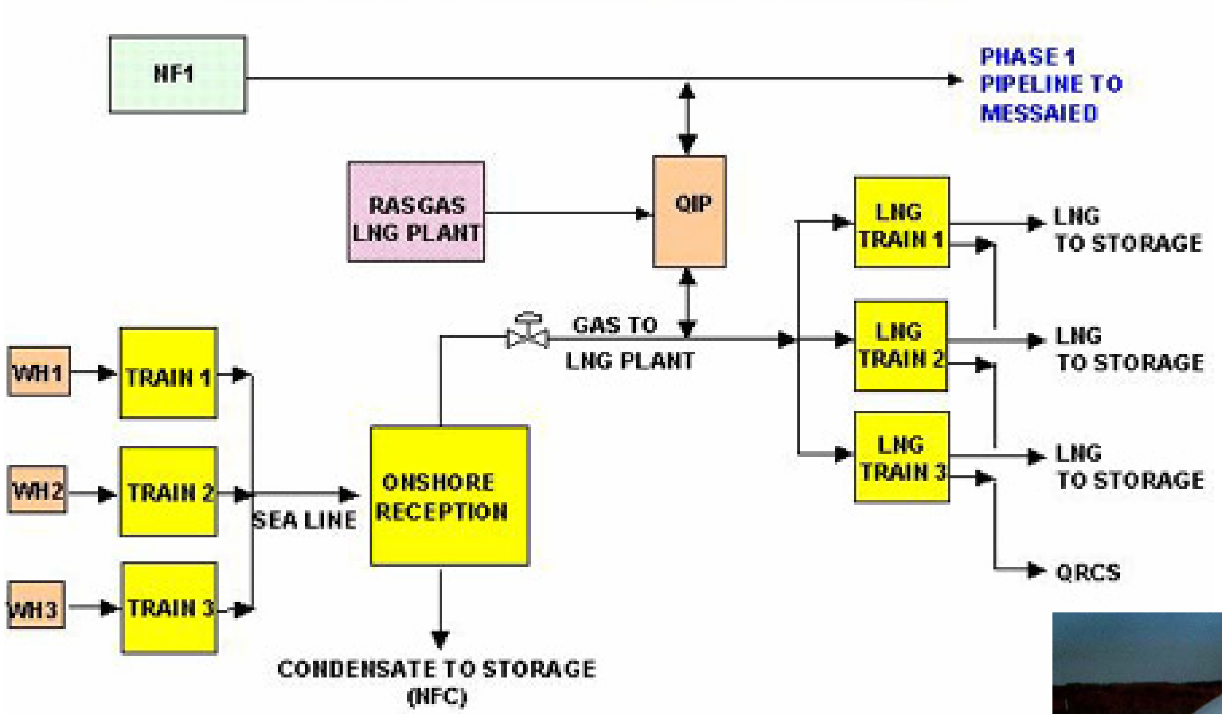


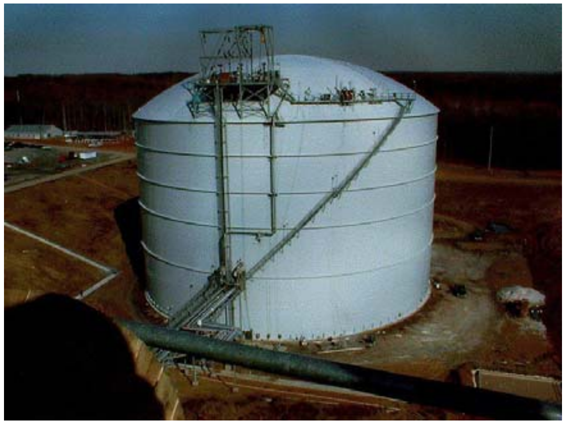
- Source: http://www.inogate.org/html/maps/mapsgas.htm



LNG degasification process in Qatargas

Source: http://www.qatargas.com.qa/lng/lng-process.htm





LNG Storage Tank

LNG transportation and distribution

Security escort for LNG tanker

LNG Ship Unloading at Terminal

Picture source: http://www.ferc.gov/for-citizens/lng.asp

Industry Background

- Deregulation results (US)
  - Price determination
    - In regulated market, the price of the gas was regulated by government. Gas was traded under long-term contracts.
    - In the deregulated market, the price of the gas is determined by market itself.
    - Spot market contracts are used to maintain flexibility to take advantage of market imbalance conditions caused by uncertain factors.
  - More agents competing noncooperatively and independently
    - Gas sales, transportation and storage were unbundled from interstate natural gas pipelines by FERC Order 636 issued in April 1992, which also converted interstate gas pipelines to open access transporters.
  - Roles played by policy makers
    - Policy makers focus on the competition control instead of price control.

Summary of Energy Modeling Forum (EMF23) and DOE Natural Gas/Fossil Fuel Meetings

- Rising importance of LNG vs. pipelines
  - Increased demand (e.g., China) and increased importance of natural gas
    - Environmental reasons
    - Price reasons
- World Markets as opposed to previously just continental ones
  - When should Russia send gas east to S. Korea/Japan/N. America or west to Europe?
  - Trinidad gas to N. America or Europe (can decide "on the fly")
- Importance of Russian influence
  - Constrained Russian exports, constrained Russian imports to EU (scenarios to run)
- Gas Cartel?
  - Russia, Qatar, Iran (scenarios to run)
- Strategic, Game Theory Models Vs. Cost-Minimization Ones
- Scenario Analysis vs. Stochastic Equilibrium Models
- Modeling investment decisions in the context of market equilibria
- Tracking individual supply projects and/or building up supply curves

Natural Gas in the Headlines of the New York Times Dec/Jan

- Natural Gas and Geo-Politics-Russia
  - "Dispute Over Natural Gas Prices in Ukraine," NYT 12/16/05
  - "Putin Offers 3-Month Extension of Ukraine's Gas Subsidy," NYT 12/31/05
  - "Russia Cuts Off Gas to Ukraine in Cost Dispute," NYT 1/2/06
  - "Russia Restores Most of Gas Cut to Ukraine Line," NYT 1/3/06
  - "A Dispute Underscoreds the New Power of Gas," NYT 1/3/06
  - "Russian and Ukraine Reach Compromise on Natural Gas," NYT 1/5/06
  - "Envoys Say Gas Crisis Hurt West's Relations with Russia," NYT 1/5/06
  - "Ukraine Concedes it Took Gas From Pipeline but Says it Had the Contractual Right, "NYT 1/3/06
  - "Gas Halt May Produce Big Ripples in European Policy," NYT 1/3/06
  - "Ex-Premier of Ukraine Attacks Gas-Price Deal," NYT 1/7/06
  - "Europe Comes to Terms with Need for Russian Gas," NYT 1/8/06
  - "Ukraine is Increasingly Dependent on Gas from Turkmenistan," NYT 1/10/06
  - "Gazprom Builds Wealth for Itself, but Anxiety for Others," NYT 1/13/06"

Natural Gas in the Headlines of the New York Times Dec/Jan

- Natural Gas and Geo-Politics-Georgia and Qatar
  - "Qatar Finds A Currency of Its Own," NYT, 12/22/05
  - "Explosions in Southern Russia Sever Gas Lines to Georgia," NYT 1/23/06
  - "Georgia Reopens Old Gas Line to East Post-Blast Storage," NYT 1/24/06
  - "Russia Gas Line Explosions Scare Europe," NYT 1/26/06
  - "Georgia, Short of Gas, Is Hit With a Blackout," NYT 1/27/06

From "Russia Cuts Off Gas to Ukraine in Cost Dispute," NYT 1/2/06

Min. gas price/1000 m^3	Problems with Russia
Ukraine, $220	Orange Revolution, aspires to join NATO & EU
Moldova, $160	Russia supports separatists; aspires to join EU
Estonia, $120	NATO member; has border disputes with Russia
Latvia, $120	NATO member
Lithuania, $120	NATO member
Armenia, $110	None
Azerbaijan, $110	Is building rival oil and gas pipelines
Georgia, $110	Rose Revolution; Russia supports separatists
Belarus, $47	None

Natural Gas in the Headlines of the New York Times Dec/Jan

- Other Natural Gas Issues
  - Natural Gas for Diesel Fuel:
    - "A New Old Way to Make Diesel", NYT 1/18/06, Qatar
  - Price Questions on Gas Rights:
    - "As Profits Soar, Companies Pay U.S. Less for Gas Rights Energy Giants Report Different Sales Prices to Investors and Federal Government," NYT 1/23/06
    - "Data Sought on Royalties Paid for Gas," NYT 1/24/06

Gas Industry Modeling Activities N. America and European Union Models)

- Operational models (e.g., storage, production)
- Some large-scale equilibrium models

	European Natural Gas Market	Deregulated North American Natural Gas Market
Deterministic Models	• GASTALE (Gas Market System for Trade Analysis in a Liberalising Europe), an oligopolistic model of production and trade, 2000s	• NGTDM (Natural Gas Transmission and Distribution Module) and OGSM (Oil and Gas Supply Module) in NEMS (National Energy Modeling System), 1990s • GSAM (Gas Systems Analysis Model), late 1990s
Stochastic Models	• A stochastic dynamic Nash-Cournot model by Haurie et al., 1987 • A stochastic Stackelberg Cournot model by DeWolf and Smeers, 1997	

Complementarity Modeling Methodology (Zhuang and Gabriel)

- NCP/VI: Nonlinear Complementarity Problem/Variational Inequality Problem
  - Market equilibrium with certain players strategic (e.g., US: marketers, EU: producers)
- Stochastic NCP/VI
- Stochastic programming is the framework for modeling optimization problems that involve uncertainty.
  - Recourse method used to formulate the stochasticity faced by each agent.

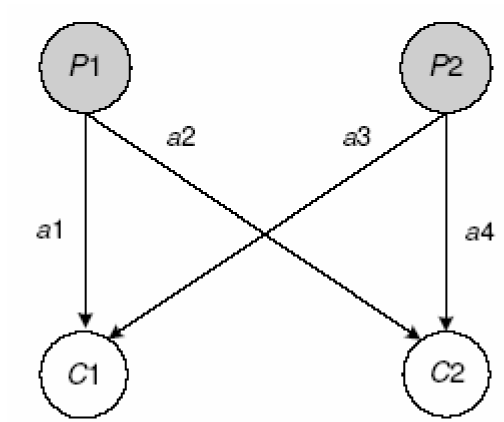
Market Composition

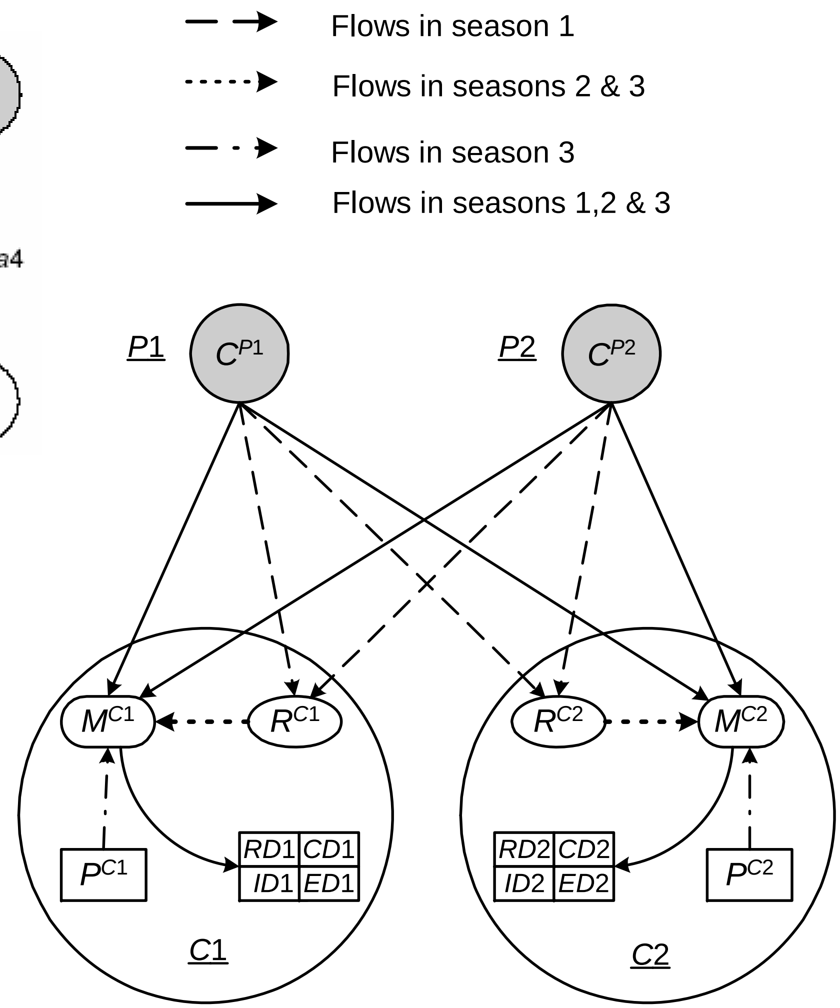
- Market players
  - Producers
  - Pipeline operators
  - Storage operators
  - Peak gas operators
  - Marketers/shippers (only strategic players)
  - Consumers
    - Residential
    - Commercial
    - Industrial
    - Electric power

Market Network

- Production regions
  - Producers
- Consumption regions
  - Storage operators
  - Peak gas operators
  - Marketers
  - Consumers
- Pipeline arcs connecting production and consumption regions
- Note: no intermediate regions modeled

Market Network





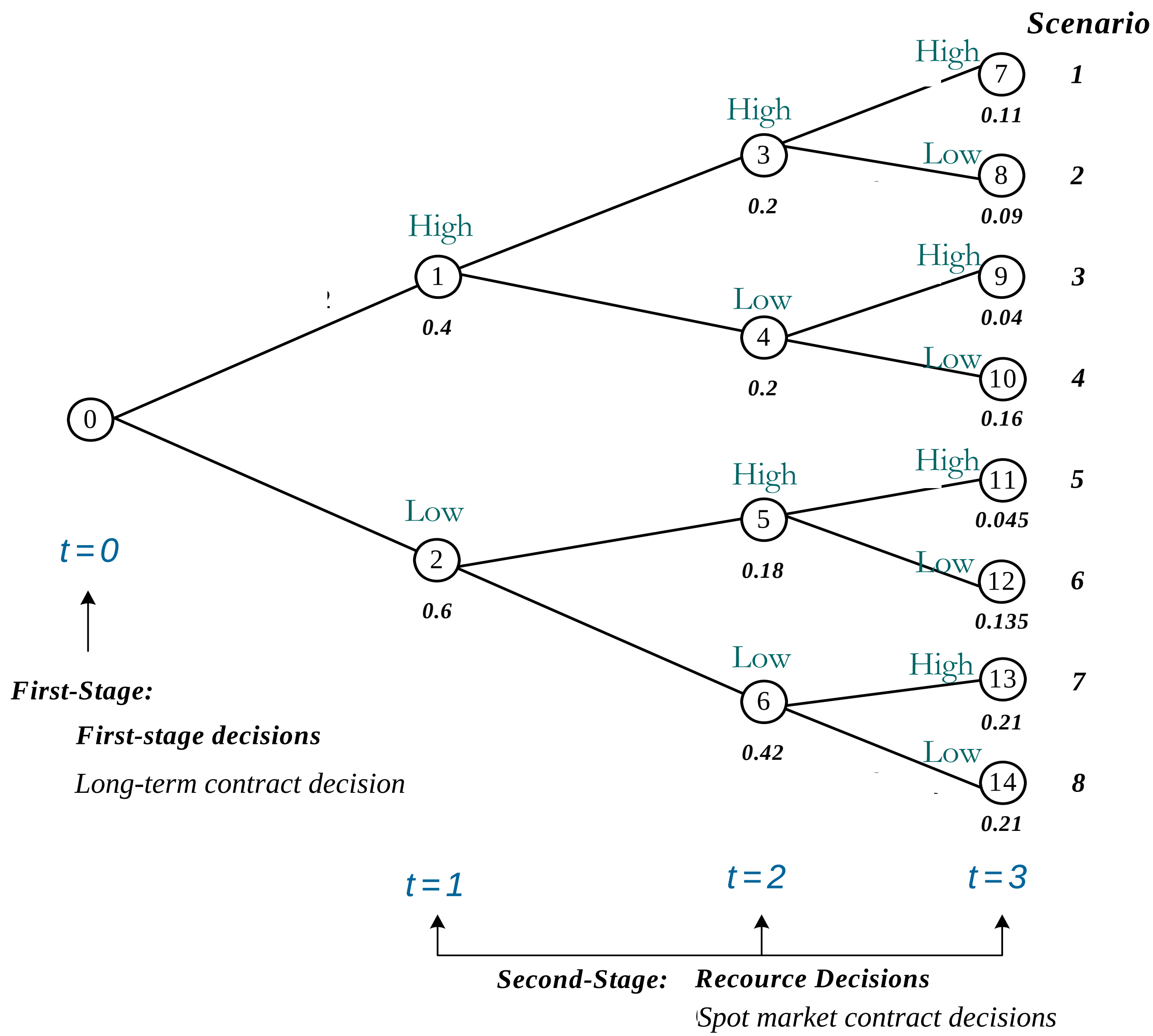
Seasonality

- Season 1 (low demand season)
  - April – October
- Season 2 (high demand season)
  - November, December, February, March
- Season 3 (peak demand season)
  - January

Recourse Method

- Two-stage recourse program
  - First-stage: first-stage decision before the realization of the uncertainty
  - Random event occurs
  - Second-stage: recourse decision to compensate for any adverse effects that might have been experienced as a result of the first-stage decision
  - Maximize/minimize the profit/cost of the first-stage decision plus the expected profit/cost of the recourse decision.
- Multistage recourse program
  - when the decision problem involves a sequence of decisions that react to outcomes that evolve over time

Scenario Tree of Demand



Model S-NGEM

- Long-term contract decision: first-stage decision
  - Supply assurance
  - Firm service
  - Reservation charges
- Spot market contract decision: recourse decision
  - Flexibility to secure gas at lower price
  - Swing service and baseload service

Players

- Consumers
  - Residential and commercial sectors
    - Represented by stochastic demand functions as part of the marketer's problem
    - No long-term contract
  - Industrial and electric power sectors
    - Predetermined demand
    - Mostly long-term contract demand
- Regulated Players
  - Pipeline Operator
    - Regulated by FERC
    - Maximize the <u>expected</u> congestion fees of the pipeline subject to the pipeline capacity

Players

- Non-strategic players
  - Producers, storage operators and peak gas operators
    - Price-takers in their own market and in other markets
    - Aware of the uncertain demand implicitly via the market-clearing conditions
    - Maximize the <u>expected</u> profits subject to engineering restrictions, production capacity and material balance constraints.

Players

- Strategic players
  - Marketers
    - Nash-Cournot players for the residential and commercial sectors
    - Price-takers in the production, storage, peak gas, and transportation markets.
    - The only players aware of consumers' uncertain behaviors via the demand functions in their objective functions.
    - Maximize <u>expected</u> profits subject to gas volume balancing restrictions

Model Structure

- Model S-NGEM
  - Optimization problems for all players except consumers
    - Maximize   <u>Expected</u> profits
    - subject to   Engineering and other constraints
  - System Constraints
    - Market-clearing conditions for both the long-term and spot markets
- Model S-NGEM is an instance of a Mixed Nonlinear Complementarity Problem (MiCP).
  - Assumptions:
    - Convex, continuously differentiable cost functions
    - Concave revenue functions
    - Positive marginal costs in the positive orthant

Theoretical Results

- A price relationship for the long-term and spot market contracts.
  - Take the producer as an example,

For a production node $n \in PN$, *given* q^0_{csy} *and* $q^1_{csy,i^{s,y}}$, *if there exists some producer* $c \in C^n$ *such that*

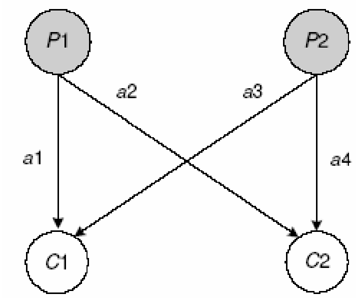
Conditions	Conclusions		
(a)	$\pi^0_{n^c(c)sy}$	$\geq$	$\sum_{i^{s,y} \in I^{s,y}} \eta(i^{s,y}) \pi^1_{n^c(c)sy,i^{s,y}}$
(b)	$\pi^0_{n^c(c)sy}$	$\leq$	$\sum_{i^{s,y} \in I^{s,y}} \eta(i^{s,y}) \pi^1_{n^c(c)sy,i^{s,y}}$
(a) + (b)	$\pi^0_{n^c(c)sy}$	$=$	$\sum_{i^{s,y} \in I^{s,y}} \eta(i^{s,y}) \pi^1_{n^c(c)sy,i^{s,y}}$

(a) if the long-term production rate $q^0_{csy} > 0$,

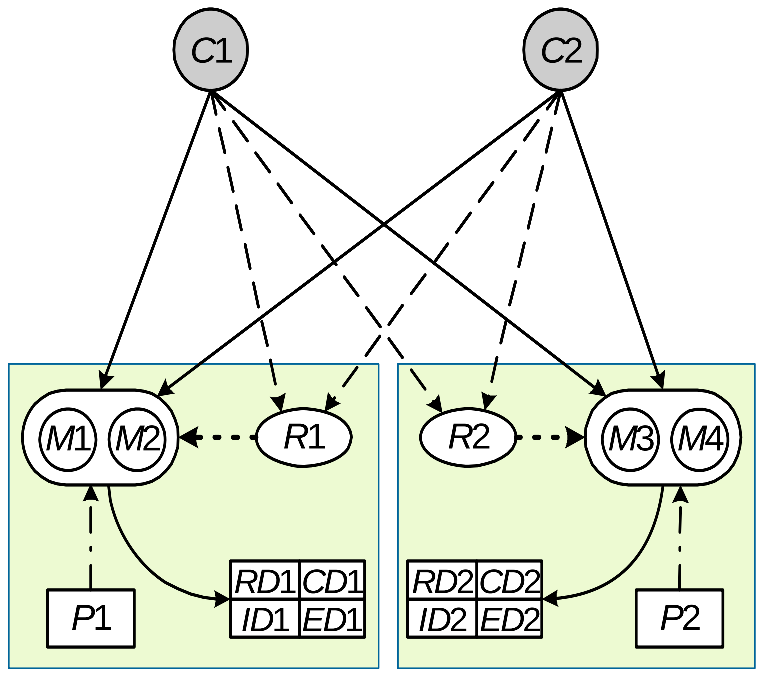
(b) if the spot market production rate $q^1_{csy,i^{s,y}} > 0, \forall i^{s,y} \in I^{s,y}$,

  - Similar relationship established for pipeline operators, peak gas operators and storage operators.

Sample Network



- Example network:
  - Two production nodes
    - One producer at each production node
  - Two consumption nodes, each consumption node has
    - One storage operator
    - One peak gas operator
    - Two marketers
    - Four demand sectors
    - Four pipelines connecting these four nodes



- Time horizon: One year with three seasons

Data Set

- Deterministic Parameters
  - Capacities for all players
  - Cost functions for all players
  - Long-term demand for $ID1$, $ID2$, $ED1$ and $ED2$
- Stochastic Parameters
  - Spot market demand for $ID1$, $ID2$, $ED1$ and $ED2$
  - Coefficients of the demand functions for $RD1$, $RD2$, $CD1$ and $CD2$
  - Random demand at the two consumption nodes were assumed independent.

Computation

- Linear complementarity problem (LCP) of 6,186 variables
  - 142 first-stage variables
  - 6,044 recourse variables
- GAMS/PATH as the solver
- CPU time: from 5 to 20 seconds on a PC computer with a 2.26GHz Intel® Pentium®4 Processor and 1.0GB of memory

Case Studies

- Base Case
- Case 1: low demand, low price scenario
- Case 2: high demand, high price scenario
- Case 3: perfect competition scenario

Expected Profits and Surplus

Participants	Base Case	Case 1	Case 2	Case 3
$C1$	1,191.8	1,081.8/-9.23%	1,456.4/22.20%	1,619.3/35.87%
$C2$	1,185.3	1,077.3/-9.11%	1,459.9/23.16%	1,617.9/36.49%
$R1$	8.0	4.6/-43.22%	17.5/117.18%	38.0/371.84%
$R2$	8.6	5.0/-41.67%	17.4/101.88%	38.0/342.10%
$P1$	6.9	6.0/-12.93%	10.2/46.48%	14.8/114.10%
$P2$	6.9	6.0/-13.17%	9.8/42.93%	14.3/107.82%
$M1$	399.4	324.0/-18.88%	469.7/17.60%	0/-100%
$M2$	399.4	324.0/-18.88%	469.7/17.60%	0/-100%
$M3$	458.1	376.0/-17.91%	536.3/17.07%	0/-100%
$M4$	458.1	376.0/-17.91%	536.3/17.07%	0/-100%
Producer Surplus	4,122.5	3.580.8/-13.14%	4,983.1/20.87%	3,342.4/-18.92%
$RD1$	525.9	423.1/-19.55%	628.4/19.48%	1,031.7/96.16%
$RD2$	602.5	496.6/-17.57%	706.6/17.29%	1,204.3/99.89%
$CD1$	272.8	224.9/-17.57%	311.0/13.99%	504.5/84.92%
$CD2$	313.7	255.4/-18.56%	365.9/16.67%	596.4/90.14%
Consumer Surplus	1,714.9	1,400.0/-18.36%	2,011.9/17.32%	3,336.8/94.58%

Wait-and-See Solution

- WS: wait-and-see solution
  - Stochastic Program
    - $WS = E_{\boldsymbol{\xi}}\left[z(\overline{x}(\boldsymbol{\xi}), \boldsymbol{\xi})\right]$
      - where $\overline{x}(\boldsymbol{\xi})$ is the solution to $\max\limits_{x \in S} \; z(x, \boldsymbol{\xi})$
  - Stochastic Equilibrium Program
    - $WS^i = E_{\boldsymbol{\xi}}\left[z^i(\overline{x}(\boldsymbol{\xi}), \boldsymbol{\xi})\right]$ for player *i*
      - where $\overline{x}(\boldsymbol{\xi})$ is the solution to a Nash equilibrium problem which simultaneously maximizes all the players' profits given other players' decisions, that is, $\max\limits_{x^i \in S^i} \; z^i(x^i, \overline{x}^{(-i)}, \boldsymbol{\xi})$ for each player *i*

Here-and-Now Solution

- RP: here-and-now solution
  - Stochastic Program
    - $RP = \max_{x \in S} E_{\boldsymbol{\xi}} z(x, \boldsymbol{\xi})$
      - whose solution is x^*
  - Stochastic Equilibrium Program
    - $RP^i = z^i(x^*)$ for player *i*
      - where x^* is the solution to a <u>stochastic</u> Nash equilibrium problem which simultaneously maximizes all the players' <u>expected</u> profits given other players' decisions, that is, $\max_{x^i \in S^i} E_{\boldsymbol{\xi}} z^i(x^i, \overline{x}^{(-i)}, \boldsymbol{\xi})$ for each player *i*

EEV

- EV: mean value ($\bar{\xi}$) problem, whose solution is $\bar{x}(\bar{\xi})$
- EEV: Expected result of using $\bar{x}(\bar{\xi})$
  - Stochastic Program
    - $EEV = E_{\boldsymbol{\xi}}\left(z(\bar{x}(\bar{\xi}), \boldsymbol{\xi})\right)$
      - where $\bar{x}(\bar{\xi})$ is the solution to $\max_{x \in S} \; z(x, \bar{\xi})$
  - Stochastic Equilibrium Program
    - $EEV^i = E_{\boldsymbol{\xi}}\left(z^i(\bar{x}(\bar{\xi}), \boldsymbol{\xi})\right)$ for player i
      - where $\bar{x}(\bar{\xi})$ is the solution to a Nash equilibrium problem which simultaneously maximizes all the players' profits given other players' decisions, that is, $\max_{x^i \in S^i} \; z^i(x^i, \bar{x}^{(-i)}, \bar{\xi})$ for each player i

Value of Stochastic Solution

- Stochastic Program
  - *RP*: here-and-now solution
    - $RP = \max_{x \in S} E_{\boldsymbol{\xi}} z(x, \boldsymbol{\xi})$
  - Solve an expected value problem,

    $EV = \max_{x \in S} z(x, \bar{\xi})$, whose solution is $\bar{x}(\bar{\xi})$
  - *EEV*: the expected result of using the *EV* solution $\bar{x}(\bar{\xi})$
    - $EEV = E_{\boldsymbol{\xi}}\left(z(\bar{x}(\bar{\xi}), \boldsymbol{\xi})\right)$
  - *VSS*: Value of Stochastic Solution
    - $VSS = RP - EEV \geq 0$
    - Measures the cost of using the expectation of the uncertainty thus ignoring the stochastic elements in the decision making process.

Value of Stochastic Solution

- Stochastic Equilibrium Program
  - Define $z^i(x, \xi)$ as the profit or surplus function for player i,
    - x is the decision variable,
    - ξ is the random variable.
  - Solve the stochastic equilibrium model, the solution is x^*
  - $RP^i = z^i(x^*)$ for player i
  - Solve an expected value (EV) problem of above stochastic equilibrium problem, the solution is $\bar{x}(\bar{\xi})$
  - $EEV^i = E_{\boldsymbol{\xi}}\left(z^i(\overline{x}(\overline{\xi}), \boldsymbol{\xi})\right)$ for player i
  - $VSS^i = RP^i - EEV^i$ for each player i

EVPI and VSS

- Stochastic Program
  - $EEV \leq RP \leq WS$
  - $EVPI = WS - RP \geq 0$
    - Measures the maximum amount a decision maker would pay in return of the complete information about the future.
  - $VSS = RP - EEV \geq 0$
    - Measures the cost of using the expectation of the uncertainty thus ignoring the stochastic elements in the decision making process.
- Stochastic Equilibrium Program
  - For each player i
    - $EVPI^i = WS^i - RP^i$
    - $VSS^i = RP^i - EEV^i$

EVPI

Player	Base Case	Case 1	Case 2	Case 3
Producer C1	-0.1	-0.4	-2.0	0.9
Producer C2	-0.5	-0.5	-4.3	-0.4
Storage Operator R1	0.4	0.1	4.1	1.2
Storage Operator R2	0.4	0.1	4.4	1.4
Peak Gas Operator P1	0.0	0.0	0.5	0.3
Peak Gas Operator P2	0.0	0.0	0.5	0.3
Marketer M1	0.1	0.2	-0.3	0.0
Marketer M2	0.1	0.2	-0.3	0.0
Marketer M3	0.1	0.3	-0.7	0.0
Marketer M4	0.1	0.3	-0.7	0.0
Producer Surplus	**-0.3**	**0.3**	**1.2**	**3.7**
Residential Surplus RD1	0.2	0.3	-0.4	-0.6
Residential Surplus RD2	0.1	0.4	-0.8	-0.9
Commercial Surplus CD1	0.2	0.2	-0.2	-0.3
Commercial Surplus CD2	0.1	0.3	-0.5	-0.5
Consumer Surplus	**0.6**	**1.2**	**-1.9**	**-2.3**

Numerical Values of *VSS*

Player	Base Case	Case 1	Case 2	Case 3
Producer C1	-0.3	-0.5	27.6	-5.7
Producer C2	4.8	3.2	45.7	17.0
Storage Operator R1	0.0	0.3	5.9	2.0
Storage Operator R2	-0.4	0.0	4.4	-0.3
Peak Gas Operator P1	-0.1	-0.1	1.7	0.8
Peak Gas Operator P2	0.1	0.0	1.5	0.6
Marketer M1	4.4	3.5	2.7	0.0
Marketer M2	4.4	3.5	2.7	0.0
Marketer M3	3.6	2.6	3.3	0.0
Marketer M4	3.6	2.6	3.3	0.0
Producer Surplus	**20.10**	**15.5**	**98.5**	**14.6**
Residential Surplus RD1	5.7	4.5	4.7	2.9
Residential Surplus RD2	4.3	3.3	4.7	5.6
Commercial Surplus CD1	2.9	2.5	0.7	-0.1
Commercial Surplus CD2	2.8	2.0	1.8	3.2
Consumer Surplus	**15.7**	**12.3**	**11.9**	**11.6**

Value of Stochastic Solution

- Observations
  - $VSS^i \geq 0$ does not hold for every player in the stochastic equilibrium program.
  - $VSS^i \geq 0$ holds for all marketers in all cases.
  - $VSS^i \geq 0$ holds for the producer and consumer surplus in all cases.

EVPI and VSS

- Conclusions
  - The relationship $EEV^i \leq RP^i \leq WS^i$ does not hold for a stochastic equilibrium program.

Conclusions & Future Work

- Summary of Work:
  - Stochastic NCP model of natural gas market developed
  - Theoretical results concerning relationship between long-term and expected spot market prices developed
  - Model run on several cases, initial exploration of VSS, verification of results on a small-scale duopoly

Conclusions & Future Work

- Future Work:
  - To further explore the concept of the value of a stochastic solution (*VSS*) for a stochastic equilibrium program
  - Development of specialized algorithms to solve stochastic NCP equilibrium problem and testing on large-scale problems