Start Me Up: Competitive Dynamics in Wholesale Electricity Markets

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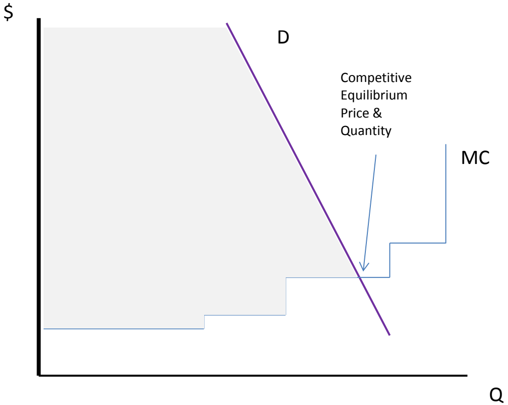
Electricity Restructuring Led to Concerns About Market Power

- During last 25 years many parts of the world have restructured their electricity sector to facilitate active wholesale market trading systems. This created the potential for suppliers to exercise ***market power***.
- California energy crisis in 2000-2001 was a dramatic episode of high and volatile wholesale prices; market power of suppliers appeared to play a large role.
- Market power remains a concern in many other restructured markets.
  - Almost all restructured markets have a market monitoring or market surveillance committee.

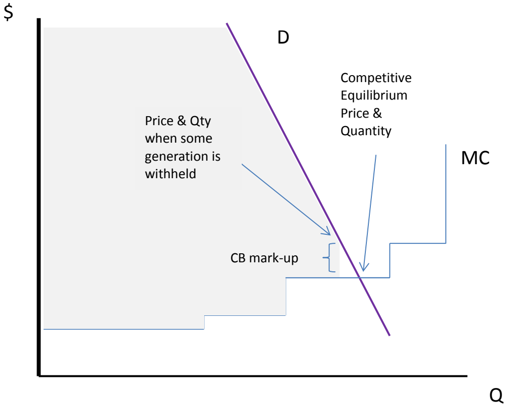
How Do Economists Measure Market Power?

- Most economic analyses of wholesale electricity markets use a static model of perfect competition - *Competitive Benchmark Model*.
  - Supply curve for CB model is based on capacity, availability, and marginal cost of generation units.
- Anaysis with CB model proceeds by comparing actual prices to what *prices would have been if perfect competition prevailed* [see next 2 slides].

Supply (MC) & Demand Graph to illustrate Competitive Benchmark Model



Supply (MC) & Demand with lower output, higher price



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    - Supply curve for CB model is based on capacity, availability, and marginal cost of generation units.
- Anaysis with CB model proceeds by comparing actual prices to what *prices would have been if perfect competition prevailed*.
- However, a static model neglects potentially important features of electricity generation technology - ramping constraints, minimum generation rate constraints, and start-up costs - that create ***dynamic linkages*** across supplier decisions.

Why Might Dynamics Matter? #1

- Prior studies, such as Borenstein, Bushnell & Wolak (2002), that find large deviations from marginal cost pricing attribute this to market power.
- Harvey and Hogan (2001) critique of studies of California crisis that are based on static models.
- Mansur (2008) studies PJM before and after introduction of market-based bidding. He uses a reduced form approach to estimate generation cost that implicitly incorporates technological constraints.
    - "I find that intertemporal constraints result in significant non-convexities in the costs of producing electricity. This suggests that one should be cautious using measures of welfare effects that ignore the firms' dynamic optimiztion problem."
    - Estimated price mark-ups are less than 1/2 of estimates based on the competitive benchmark model.

Why Might Dynamics Matter? # 2

- The proportion of ***generation from intermittent renewable sources is rising*** in many areas.
- Intermittency of renewables such as wind and solar introduces more variability into the system. High penetration of renewables requires more frequent start-ups and shut downs of conventional generation units - a feature missing from static models.
- Suggests that the extent of bias in market power measurement from the CB model would be rising as renewable penetration increases.

What Is Done In This Paper?

- Theory
  - Formulate a dynamic competitive model that incorporates: demand uncertainty, multiple generation technologies, min generation rates, and start-up costs.
  - Analyze competitive equilibrium short run operating dynamics.
  - Develop an approach for computing competitive equilibrium prices.
- Application
  - Use Texas ERCOT in summer 2008 as a test-bed for the model. The model is calibrated / estimated based on ERCOT data.
  - Compute dynamic competitive equilibrium prices.
  - Estimate price mark-ups based on the dynamic model, and compare to price mark-ups from CB model.

Outline for this Presentation

- Introduction & Motivation
- Related Literature
- Model formulation
- Computation approach
- ERCOT background and data
- Explanation of results on prices and mark-ups

Haven't start-up costs and dynamics already been tackled in the Engineering Literature?

- There is a vast literature in power systems engineering on computation of detailed models of electricity generation and distribution. ***Unit Commitment Models*** are used for optimization subject to numerous generator constraints (ramping, start-up cost, min/max rates, etc) and transmission flow constraints.
- The main limitation of Engineering Models for market power assessment - ***Optimization solution is not linked to competitive equilibrium pricing.***

There are 2 recent closely related papers that incorporate start-up costs in a dynamic framework.

- Reguant (2013)
  - ...estimates dynamic structural model of generator costs using Spanish wholesale auction data.
  - Start-up cost estimates are fairly large: $28,000 for 400 MW natural gas CC unit, $35,000 for a 350 MW coal steam turbine.
  - Mark-ups estimated from a competitive benchmark model with the Spanish data are high during peak periods and low off-peak. Estimates of mark-ups from Reguant's dynamic model are smoother over time. Provides evidence that CB model overestimates price mark-ups during peak periods.

There are 2 recent closely related papers that incorporate start-up costs in a dynamic framework.

- Cullen (2013)
  - ... estimates a dynamic structural model of generator costs using ERCOT data. His estimates of start-up costs are higher than those of Reguant.
  - Develops a dynamic competitive equilibrium model - used to compute counterfactual simulations of impact of changes in environmental policies.
  - Does not examine price mark-ups.

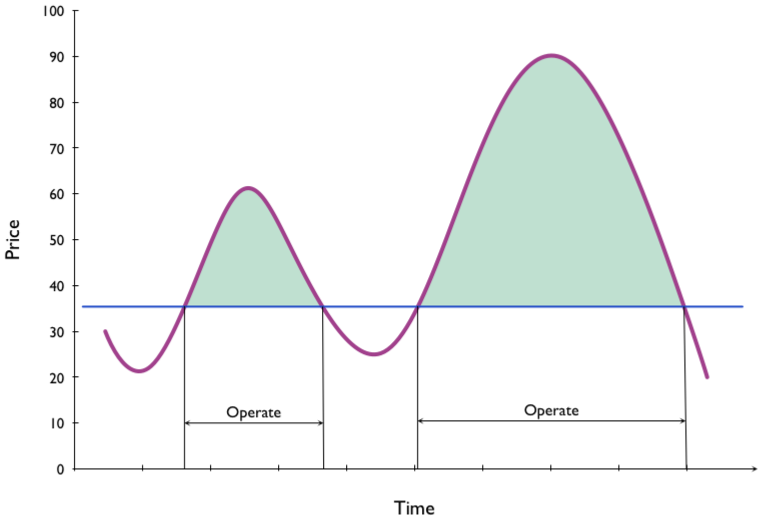
How has Dynamic Competition been modeled in the Economics Literature?

- A series of papers analyze dynamic competitive equilibrium for models with uncertainty about future prices and demand levels, firm-specific differences in production cost, and rational expectations about future prices. These models allow for production non-convexities at the firm-level, but yield a convex aggregate production technology via a ‘small firms’ assumption.
  - Jovanovic (1982)
  - Hopenhayn (1990, 1992)
  - Jovanovic and MacDonald (1994)
- A similar modeling approach is followed in this paper.

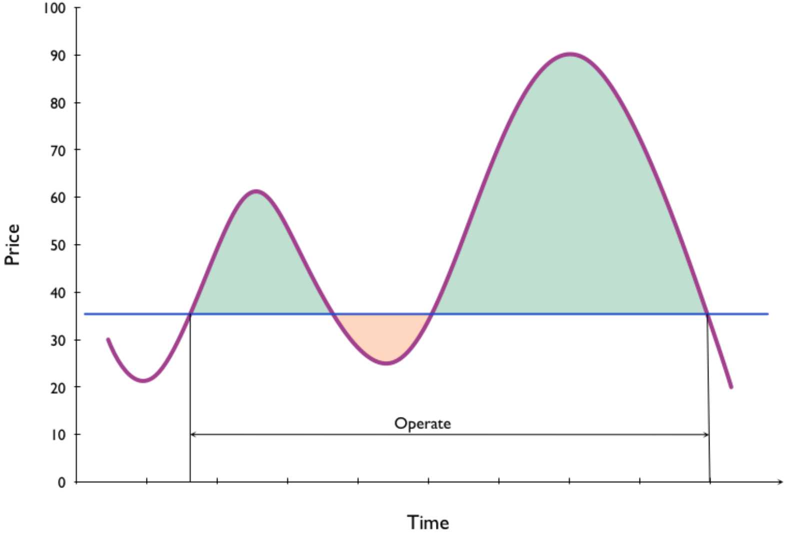
What are the building blocks of my model?

- A finite # of time periods $= T$ [e.g., 24 hours of a day]
- Demand - varies over time with both predictable and random components
- Generation
  - Multiple technologies
  - Fixed amount of total capacity for each technology
  - All units for a given technology have same marginal cost, start-up cost, min generation rate, capacity
- Firms make decisions about unit start-ups, shut-downs and operating rates in each period [see next 4 slides].

Static Model - Operating Decisions



Dynamic Model - Operating Decisions



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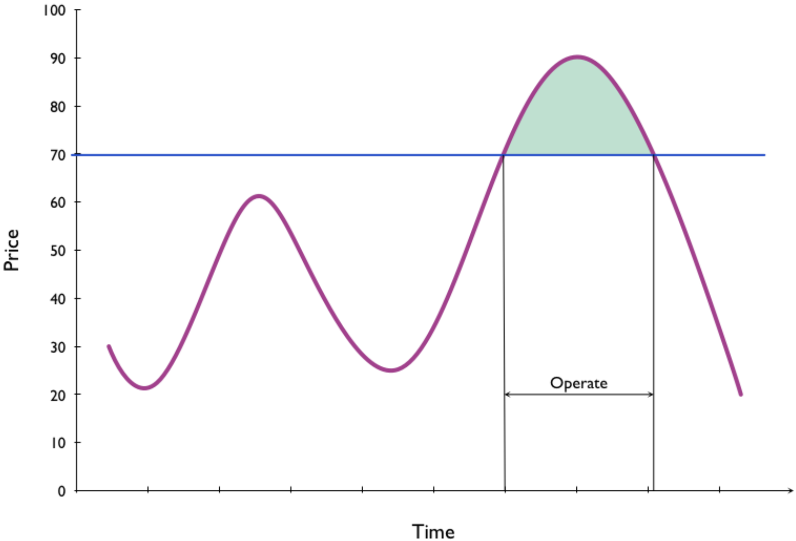
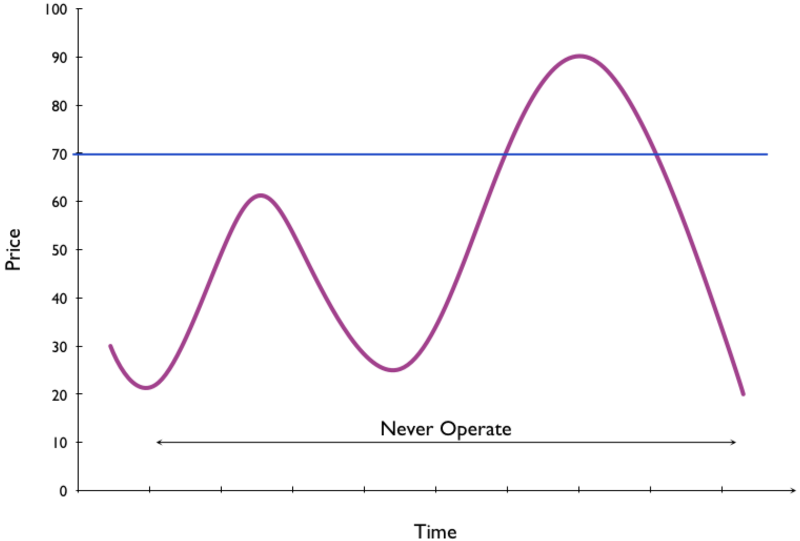


Dynamic Model - Operating Decisions



What are the characteristics of a dynamic competitive equilibrium?

- A dynamic competitive equilibrium satisfies the following:
  - Quantity demanded = quantity supplied each period
  - Firms choose start-ups, shut downs, and generation rates in each period to maximize sum of current profits and future expected profits over the operating horizon.
  - Firms' expectations of future prices are consistent with distribution of prices in equilibrium.

A technical challenge ...

- The production technology for a firm is not convex because of unit start-up costs. Non-convexity of production technology can lead to non-existence of competitive equilibrium.
- This is addressed via a ***small-firms assumption***.
  - Each firm is assumed to operate a single unit of one type of generation.
  - Each firm is very small compared to size of market [measure zero is technical term]. This is a standard assumption in the literature on dynamic perfect competition - e.g., see Hopenhayn [1990, 1992]
  - Note that even a 800 MW coal unit is less than 1% of ERCOT total capacity and less than 0.5% of PJM capacity.

The Main Theoretical Result

Proposition 1 - If the small firms assumption holds then an allocation for a dynamic competitive equilibrium corresponds to the solution to a planner's problem of maximizing expected total (consumer plus producer) surplus over T periods subject to constraints.

The implication of this Proposition is that ***a single maximization problem can be solved to find a dynamic competitive equilibrium***.

The Planner's Problem

- This is a finite horizon stochastic dynamic programming problem.
- State vector at the start of a period
  - Current demand level, and
  - Vector of amounts of ‘on’ capacity for each type of generation technology.
- The decision (control) for the planner is:
  - How much of each type of generation to leave ‘on’.
  - How much to produce from ‘on’ capacity of each type of generation.
  - How much of each type of generation to start-up for the next period.

ERCOT System in Summer 2008

- ERCOT operates over most of the state of Texas, serving a population of 23 million.
- There are very limited inter-ties with the rest of the U.S. grid, so ERCOT operates as essentially a self-contained system.
- Electricity generation and retailing are deregulated.
- Market divided into 4 zones; prices may differ across zones.
- Total generation capacity is around 82,000 MW. Nuclear, coal, natural gas and wind are major sources.
- Ownership of generation is not highly concentrated; the largest 3 firms each account for less than 10% of total generation capacity, with remaining capacity divided among many smaller firms.

Summary of Data

- 4 weeks of hourly data from August 2008; a period of fairly high and volatile prices. Prices range from $16 - $1900/MWh. Prices are the same in all 4 zones in 96% of hours.
- Hourly loads range from 22,000 to 62,000
- 6100 MW of wind capacity. Wind generation is intermittent.
- EPA eGrid data on generator heat rates, emissions rates, and capacities.
- EIA data on coal and natural gas prices.
- EPA data on SO_2 and NOx permit prices.
- MC = heat rate $\times$ fuel price + SO_2 rate $\times$ SO_2 permit price + NOx rate $\times$ NOx permit price.

▸ Wind Output ▸ Marginal Cost of Generation

Calibration and Estimation

- The planner's problem is solved for $T = 24$ one-hour periods for each day of 4 weeks of August 2008.
- Assume a single market (4 zones aggregated to 1 market)
- Focus on $netload = load - wind\ generation$. Net load demand is parameterized as a linear function of price with average price elasticity = 0.01 (very inelastic).
- Net load demand shift variable (NL) assumed to follow 1st order Markov process - coefficients estimated using OLS regression.
  - $NL_{h+1} = constant_{h+1} + \beta NL_h + \epsilon_{h+1}$
- Assume 4 generation technologies: coal, combined cycle natural gas, natural gas turbine, natural gas steam turbine
- Estimates for minimum generation rates taken from Cullen [2013]. Estimates for start-up cost/MW taken mainly from Reguant [2013]

Marginal Cost of Generation

Computation

- The planner's value function is a continuous function of the state. I use Chebyshev collocation to approximate the value function; programmed in Matlab.
- I report results for 2 types of simulations.
  - Dynamic Model - The control function for the planner's solution yields competitive equilibrium price predictions. The realizations of hourly net load (NL_h) are used for computing the planner's optimal choices.
  - Competitive Benchmark (static) Model - This uses computed marginal cost for each fossil fuel plant.

Actual and Simulated Wholesale Prices ($/MWh)

	Actual	Dynamic Model	Competitive Benchmark Model
Average	91.38	75.19	63.37
5th Percentile	33.06	23.94	55.39
95th Percentile	133.33	138.08	81.25
Average Peak*	152.96	83.28	68.95
Average Off-Peak	60.58	72.15	60.58

* Peak hours are defined as noon - 8 pm.

Implied Mark-Ups ($/MWh)

	Dynamic Model	Competitive Benchmark Model
Average	16.18	28.18
Average Peak	71.69	84.02
Average Off-Peak	-11.56	0.01

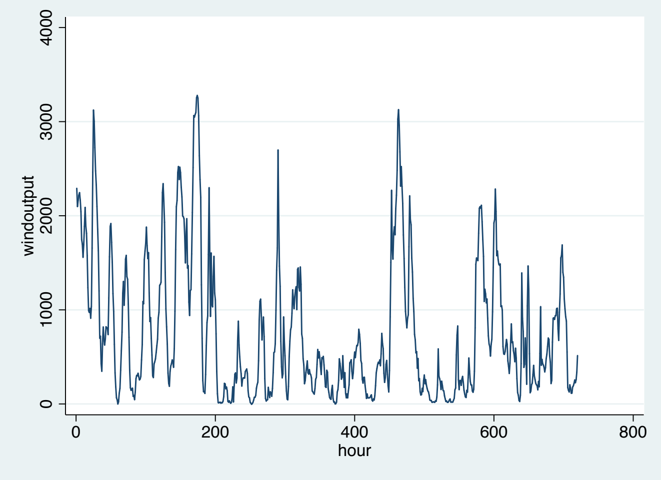
What are the main limitations of this analysis?

- The analysis presented today has several limitations.
  - The ‘small firms’ assumption.
  - Generation unit outages not considered.
  - Dynamic model assumed just 4 fossil fuel technologies - not enough to capture observed variability in heat rates and emission rates.
  - Assumed 1 hour start-up time for all units.
  - Assumed no transmission constraints.

Conclusions

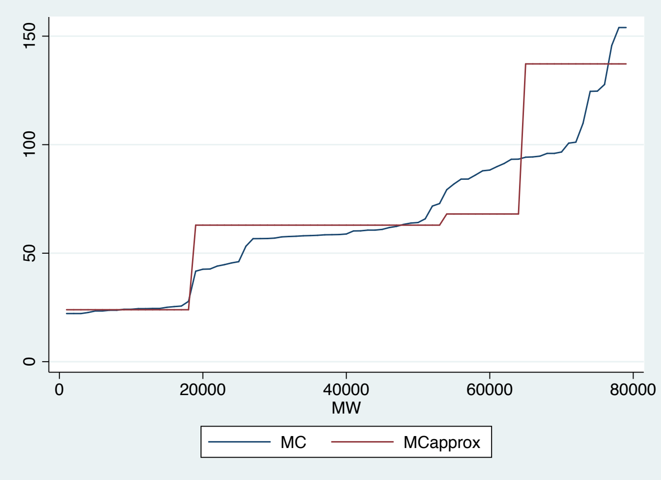
- I have developed a dynamic competitive approach as alternative to the static competitive benchmark model for assessment of market power.
- I've developed and implemented an approach for computing the dynamic equilibrium benchmark.
- Preliminary computation results for ERCOT suggest that the dynamic model is able to capture more of the observed variability in wholesale prices than the static competitive benchmark model. The dynamic model predicts smaller mark-ups than the static model; consistent with evidence from Mansur (2008).

Hourly Wind Ouput (MWh) During Sample Period



Return

Marginal Cost ($/MWh) of Fossil Fuel Generation



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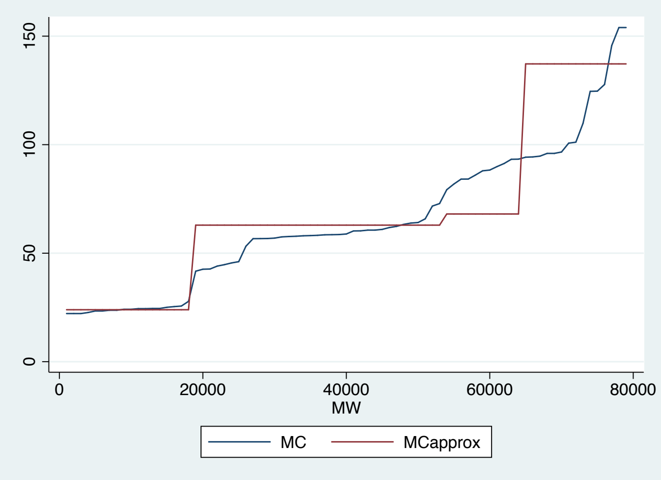

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