Empirical Methods for the Analysis of the Energy Transition: Day 2

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Note on Handbook Chapter

- I added a handbook chapter in the readings for Day 2, which contains an overview of many topics at the intersection of IO and EEE.
- Handbook chapter is joint with Ryan Kellogg (UChicago), covers a wide range of energy and environmental areas.
- There is a section about electricity markets that covers many aspects discussed this week, providing more references and material.

Today's outline

1) The economics of electricity markets

   - Overview of functioning
   - Details on market dispatch

2) Case study: Clearing a simple CAISO market

   - Clustering our data
   - Modeling with JuMP

Dispatching electricity markets

Basic structure is typically designed around a wholesale market for electricity.

Generators submit bids for electricity every day!

- The complexity of these bids varies significantly across markets
  - Bid just one price for energy vs. include start up costs.
  - Have separate products for capacity and energy vs. only energy.
  - Etc.

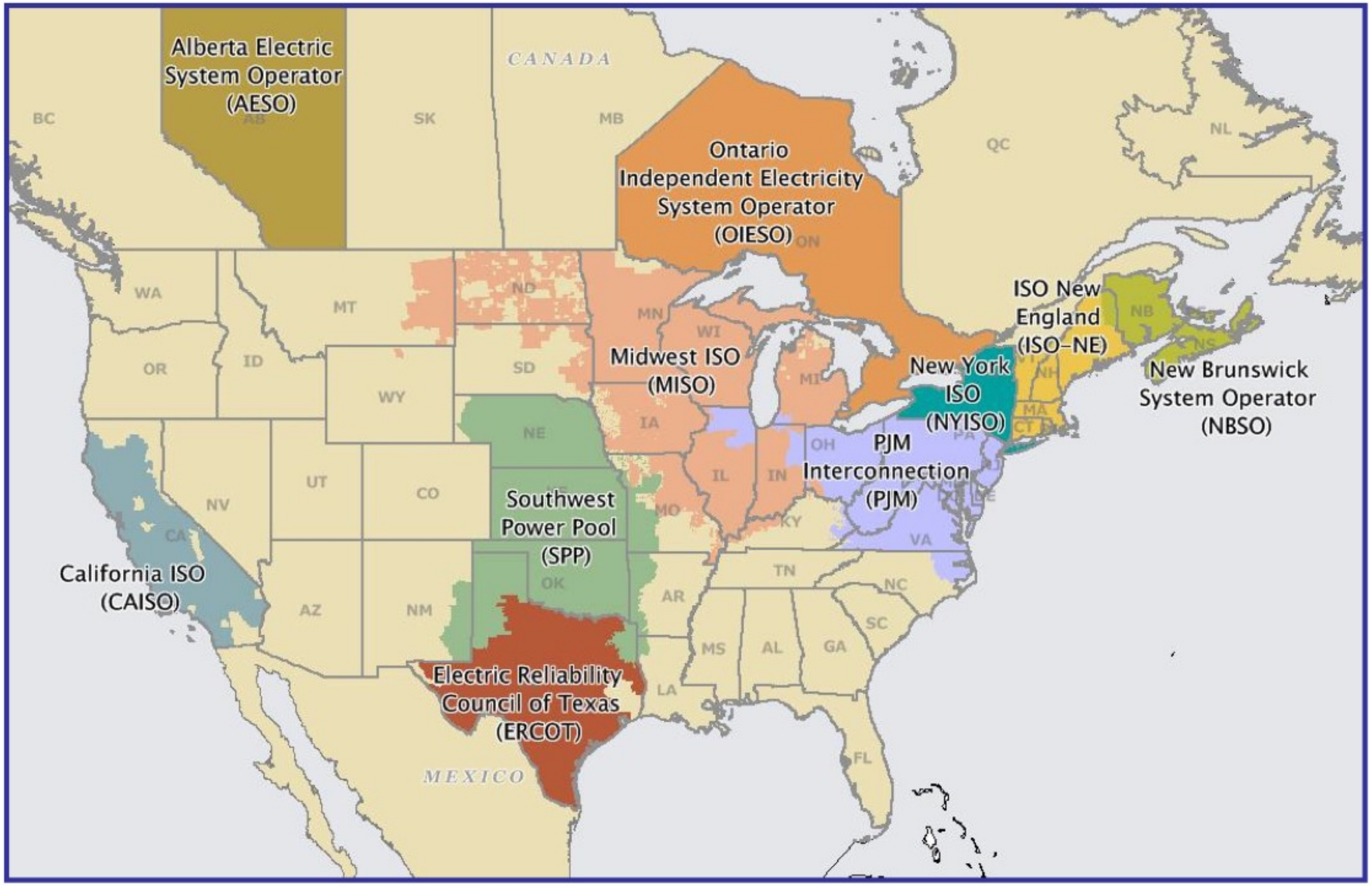
Demand also submits bids for electricity

- Can be sloped or not

Lots of other details that we will discuss

- Price caps, “capacity markets”, etc.

US liberalized markets



An example: Bidding in Chicago

Imagine a power company in Chicago.

It will offer its power on a *daily basis* to the PJM market.

- The typical offer will consist of several price-quantity offers for every hour of the day.
- Example: at 8 am, the firm is willing to produce 200 MWh as long as the price is at least $45/MWh with one of their plants.

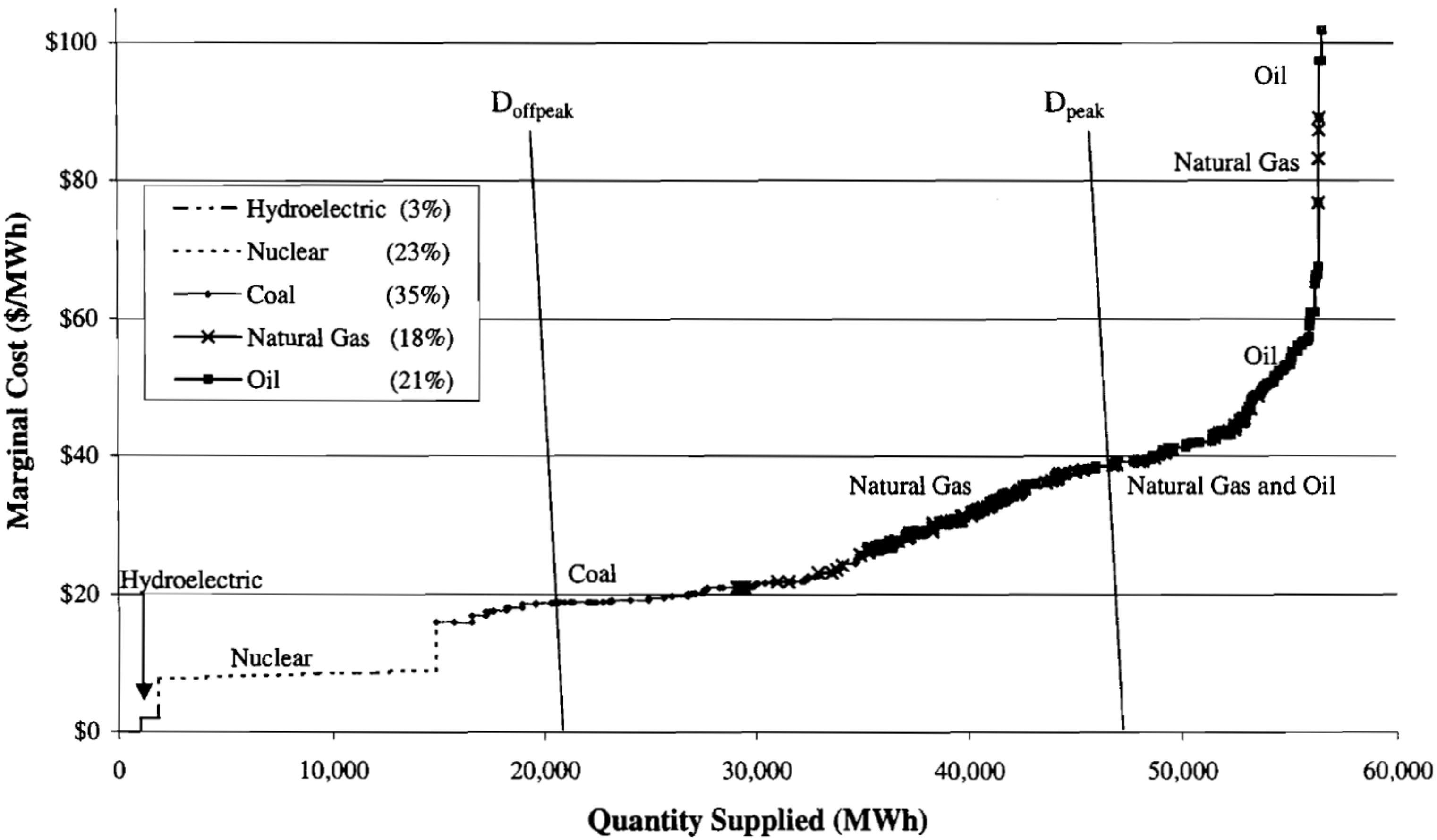
Many other companies will also offer their power at the PJM market.

The system operator will collect all the bids from all the power plants.

It will then cross supply with demand!

A supply example for PJM

Figure 2. Competitive supply and demand in Pennsylvania–New Jersey–Maryland (PJM)



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What do the bids represent?

- If the market is very competitive, the bids will tend to represent the **marginal cost of a given firm**.
- If there is market power, then firms might bid above their marginal cost, to increase prices.
- For the case of hydro power, bids will tend to represent the opportunity cost of water.
    - Note: the opportunity cost of water can be quite high for markets with limited hydro availability or during scarcity conditions (droughts).
- For renewables, bids will tend to be quite low or reflect market power considerations.

What about demand?

Demand also participates in the market, although it is typically quite inelastic.

- Final consumers do not directly demand power: the distribution utilities or retailers do it on their behalf.

Big industrial consumers or commercial customers might participate in the market, and avoid consuming electricity if prices are too high.

- Much more elastic, extensive contracting that may require firms to respond in moments of high prices.
- Some big industrial producers participate directly as generators (co-generators, direct generation).

Is that it?

As we discussed, demand and supply need to balance at all time.

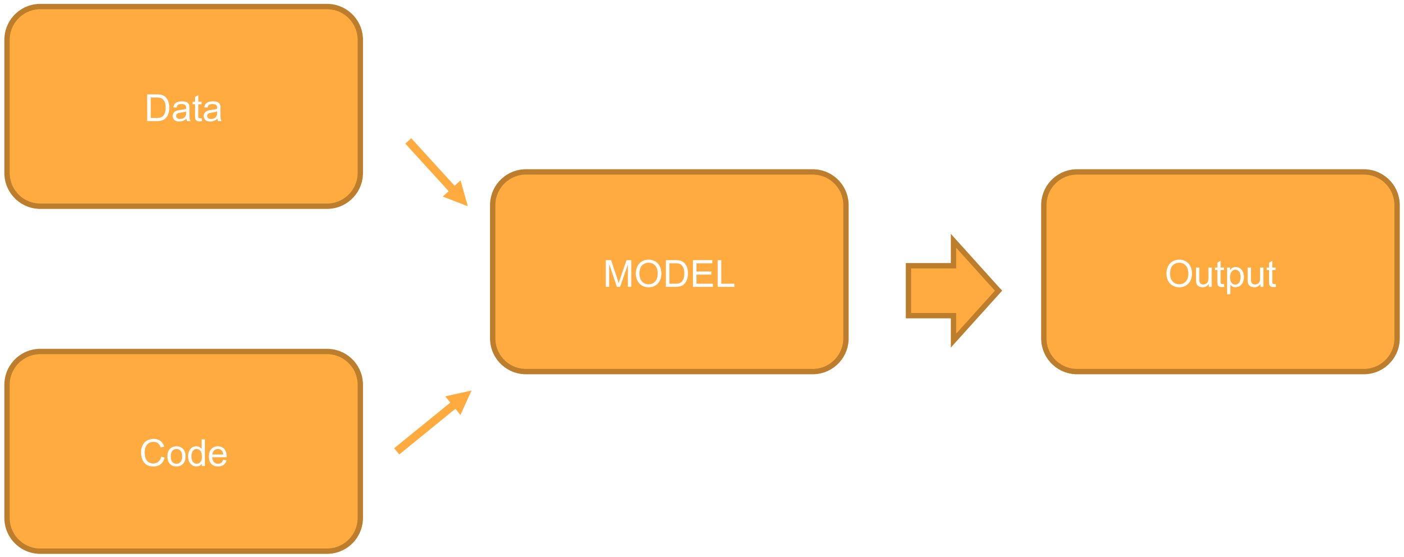
Electricity markets tend to have a day-ahead auction to plan in advance.

- Tends to clear the largest economic volume.

But there are many follow up markets and products to ensure balance in real time.

- Very complicated, and often market-specific!
- Some of these markets are related to congestion.

Building models of electricity markets



Model used to simulate impact of alternative configurations, profitability of investments, impacts of climate policies, etc.

Does output for baseline match data? If not, do we need to expand code?

- Not always, keep an eye on things that are important to our question and that we might not be matching well. <u>A model is a simplification of a complex reality</u>.

Building models of electricity markets

Common elements and options

- Supply side
  - Competitive (cost curves) or strategic (firms max profit)
  - At tech, firm, or plant level
  - With or without geography (transmission, usually with direct current approximation)
  - With or without startup costs (non-convexities)
- Demand side
  - Inelastic or responsive
  - Granular or aggregated

Horizon and temporal linkages

- Level of aggregation
  - Hourly, daily, etc.
- Links between hours
  - Every hour independent from each other vs. temporal linkages (important for storage or startup costs)
- Horizon of choice
  - Day-to-day operations
  - Seasonal water storage
  - Capacity expansion model (investment)

Empirical analysis of electricity markets

Large literature has used electricity models to analyze the **performance of electricity markets**.

Literature explorations:

- How do market outcomes compare to an idealized operation of the market?
- How do market outcomes compare to an economic model of behavior?
- How do bidding outcomes compare to an auction model of behavior?

I will discuss **two seminal papers** that use different approaches to modeling firm behavior (competitive vs. strategic).

Market Power in Electricity Markets

Market performance in deregulated wholesale markets

- Wolfram (1999), Borenstein, Bushnell, and Wolak (2002), Wolak (2007)

Measurements of incentives and ability to exercise market power (markup components)

- Wolfram (1998), McRae and Wolak (2012)

Vertical integration and market performance

- Mansur (2007), Bushnell, Mansur, and Saravia (2008)

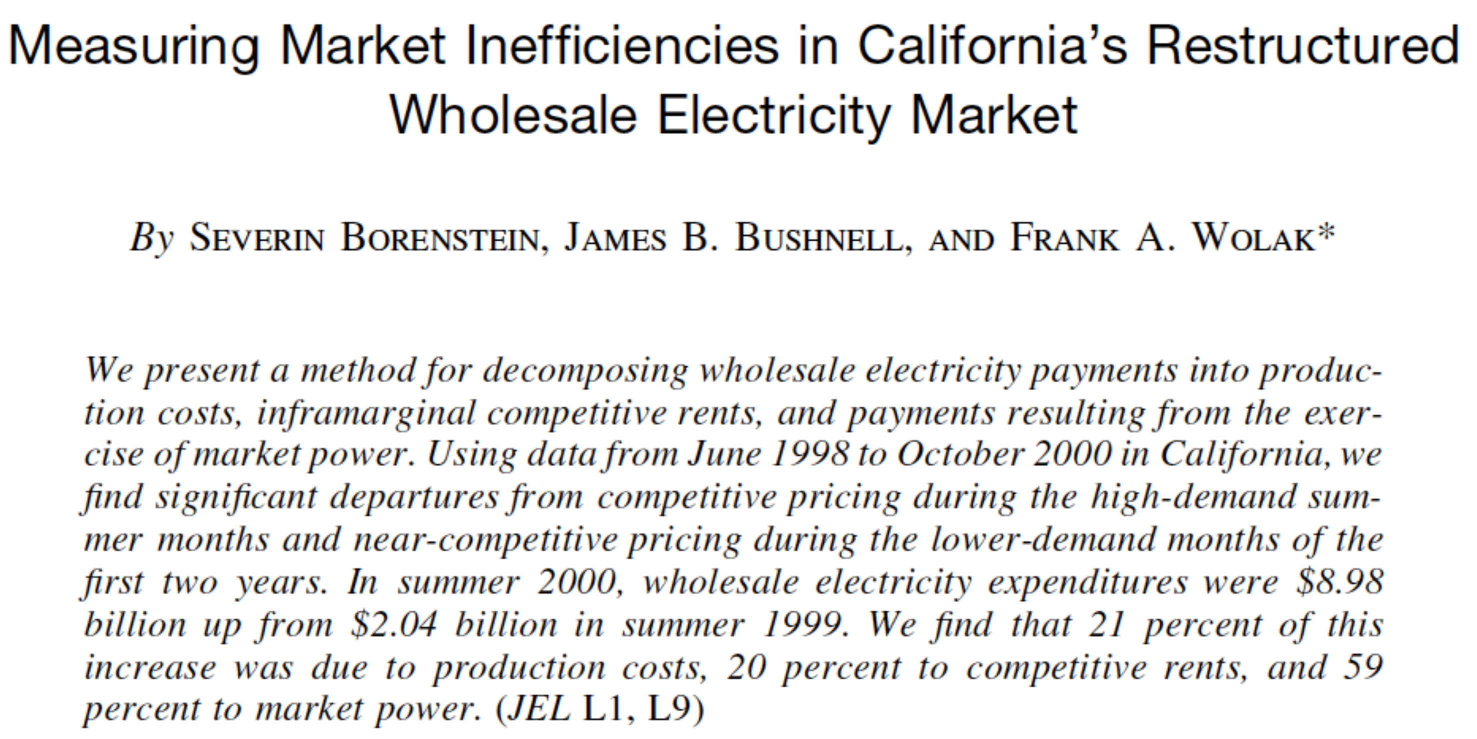
Auction design in wholesale electricity markets

- Wolak (2000, 2003) , Hortacsu and Puller (2008), Reguant (2014)

Market power in sequential electricity markets

- Ito and Reguant (2016)

Borenstein, Bushnell and Wolak (2002)


Measuring Market Inefficiencies in California's Restructured Wholesale Electricity Market

By Severin Borenstein, James B. Bushnell, and Frank A. Wolak*

We present a method for decomposing wholesale electricity payments into production costs, inframarginal competitive rents, and payments resulting from the exercise of market power. Using data from June 1998 to October 2000 in California, we find significant departures from competitive pricing during the high-demand summer months and near-competitive pricing during the lower-demand months of the first two years. In summer 2000, wholesale electricity expenditures were $8.98 billion up from $2.04 billion in summer 1999. We find that 21 percent of this increase was due to production costs, 20 percent to competitive rents, and 59 percent to market power. (*JEL* L1, L9)

Summary of Borenstein, Bushnell & Wolak (2002)

What does the paper do?

1) Empirically estimate the marginal cost of production
2) Construct a (counterfactual) competitive market price
3) Compare it to actual market outcomes to measure market inefficiency

What does the paper find?

- Wholesale electricity expenditures in the summer of 2001 = $8.98 billion (it was $2.04 billion in 1999)
- 21% of this increase was due to production costs
- 20% to competitive rents
- 59% to market power

Data

Hourly price and quantity data at Power Exchange (PX) day-ahead market from 1998-1998, settlement ISO data.

Estimates of heat rates by power plant, O&M, pollution costs (NO_x), from the California Energy Commission.

Spot gas prices times heat rate determines cost.

Outages/unavailabilities from NERC.

Market Structure

TABLE 1—CALIFORNIA ISO GENERATION COMPANIES (MW)

July 1998—online capacity				
Firm	Fossil	Hydro	Nuclear	Renewable
AES	4,071	0	0	0
Duke	2,257	0	0	0
Dynegy	1,999	0	0	0
PG&E	4,004	3,878	2,160	793
Reliant	3,531	0	0	0
SCE	0	1,164	1,720	0
SDG&E	1,550	0	430	0
Other	6,617	5,620	0	4,267
July 1999—online capacity				
Firm	Fossil	Hydro	Nuclear	Renewable
AES	4,071	0	0	0
Duke	2,950	0	0	0
Dynegy	2,856	0	0	0
PG&E	580	3,878	2,160	793
Reliant	3,531	0	0	0
SCE	0	1,164	1,720	0
Mirant	3,424	0	0	0
Other	6,617	5,620	430	4,888

Source: California Energy Commission (www.energy.ca.gov).

Methodology

1) Cost estimation
   - Based on engineering estimates
   - Need to deal with water (complicated dynamic program, simplify with "peak shaving") and "must-take" (fixed)
   - Need to estimate import supply elasticity
   - Montecarlo to control for outages, maintenance
2) Counterfactual
   - Construct marginal cost curves using above assumptions
   - Competitive equilibrium as P = MC.
3) Market power
   - Compare observed prices to competitive prices

Comparison to the IO literature

Similarities

Markup calculation as the residual from marginal cost, P = MC + Markup

Differences

Marginal cost not estimated, taken from engineering estimates

Does not consider a strategic model of competition, more “non-parametric”

Drawback: strong assumptions behind interpretation

Weighted Markups

Lerner index:

$$\text{Markup} = (P - MC)/P$$

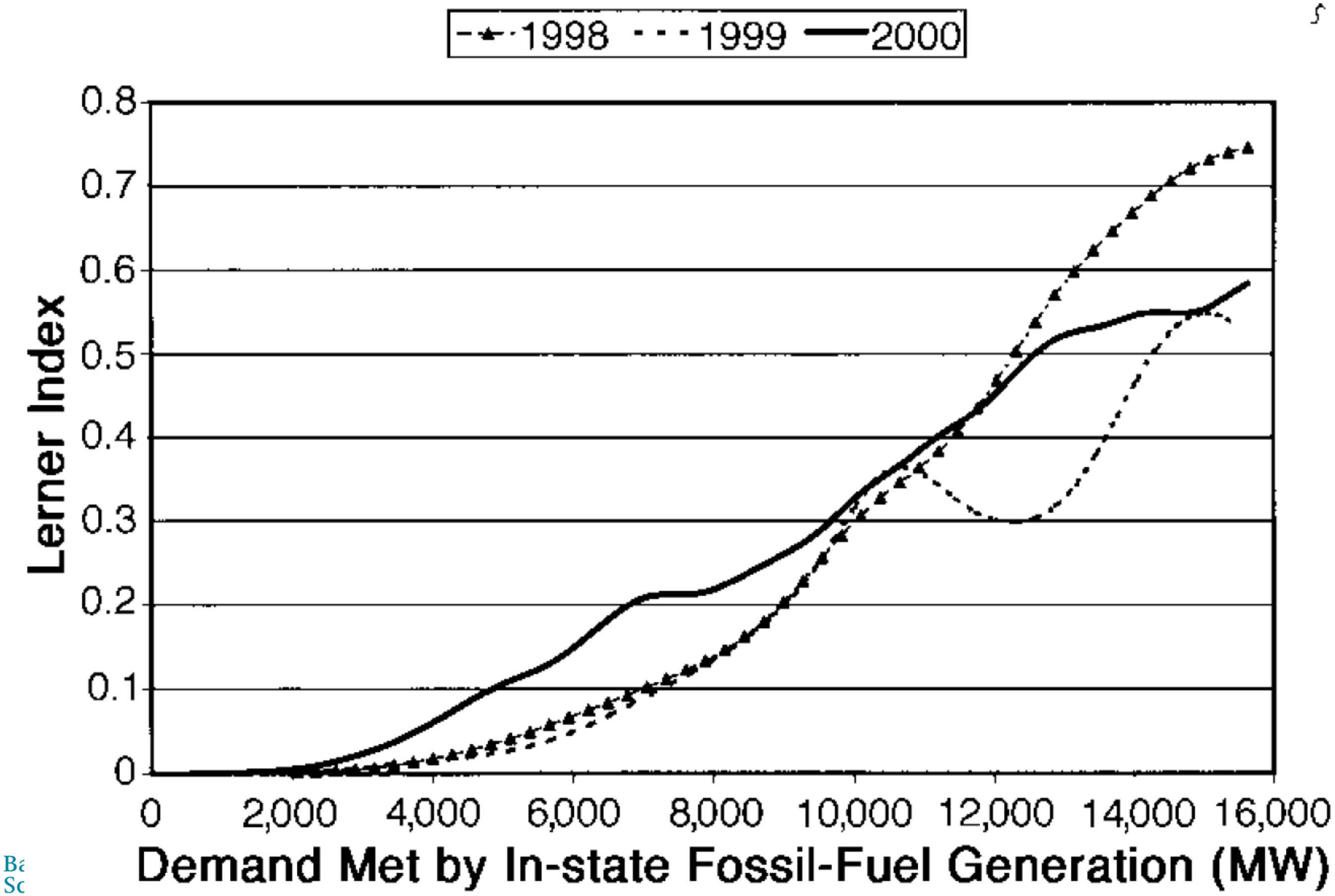
In this setting,

$$\text{Markup} = (P_{\text{observed}} - P_{\text{competitive}})/P_{\text{observed}}$$

Note 1: Paper weights each price with quantities, more weight when total quantity is larger (after taking away "must take", which they hold fixed).

Markups increase as a function of production

Lerner index higher during the events of 2000.



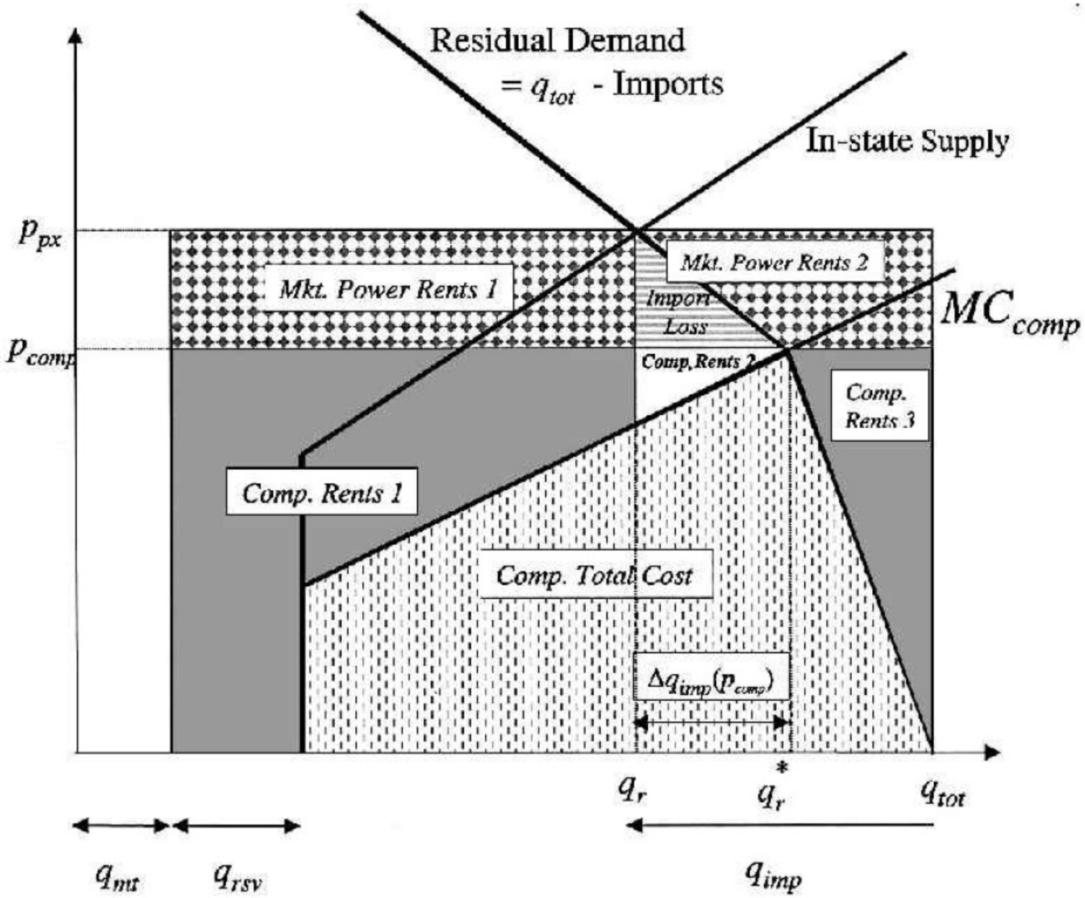
Rent Division

Total wholesale market payment can be divided into the three types:

- Production costs
  - Even holding quantity fixed, potentially larger under oligopoly, specially with asymmetric firms (e.g., see Mansur 2008)
- Infra-marginal competitive rent
- Rents due to market power (higher prices)

Important to understand the difference between the three types of costs

Decomposition of Expenditures



Decomposition of Expenditures

Table 3—Production Costs and Rent Distribution ($ Million) June–October

	1998	1999	2000
Total actual payments	1,672	2,041	8,977
Total competitive payments	1,247	1,659	4,529
Production costs—actual	759	1,006	2,774
Production costs—competitive	715	950	2,428
Competitive rents	532	708	2,101
Oligopoly rents	425	382	4,448
Oligopoly inefficiency—in state	31	31	126
Oligopoly inefficiency—imports	13	24	221

Bushnell, Mansur, and Saravia (2008)

Vertical Arrangements, Market Structure, and Competition: An Analysis of Restructured US Electricity Markets

By James B. Bushnell, Erin T. Mansur, and Celeste Saravia*

This paper examines vertical arrangements in electricity markets. Vertically integrated wholesalers, or those with long-term contracts, have less incentive to raise wholesale prices when retail prices are determined beforehand. For three restructured markets, we simulate prices that define bounds on static oligopoly equilibria. Our findings suggest that vertical arrangements dramatically affect estimated market outcomes. Had regulators impeded vertical arrangements (as in California), our simulations imply vastly higher prices than observed and production inefficiencies costing over 45 percent of those production costs with vertical arrangements. We conclude that horizontal market structure accurately predicts market performance only when accounting for vertical structure. (JEL L11, L13, L94)

Bushnell, Mansur & Saravia (2008)

What does the paper do?

- Compare market performance in three US wholesale electricity markets using strategic models
  - California
  - New England
  - PJM (Pennsylvania, New Jersey, and Maryland)

- Examine which of three models fit actual market outcomes best
  - Perfect competition
  - Cournot oligopoly
  - Cournot oligopoly with vertical integration

- Analyze how the **vertical integration** of retail and wholesale parts affect the competitiveness of wholesale electricity markets

Motivation: Why California?

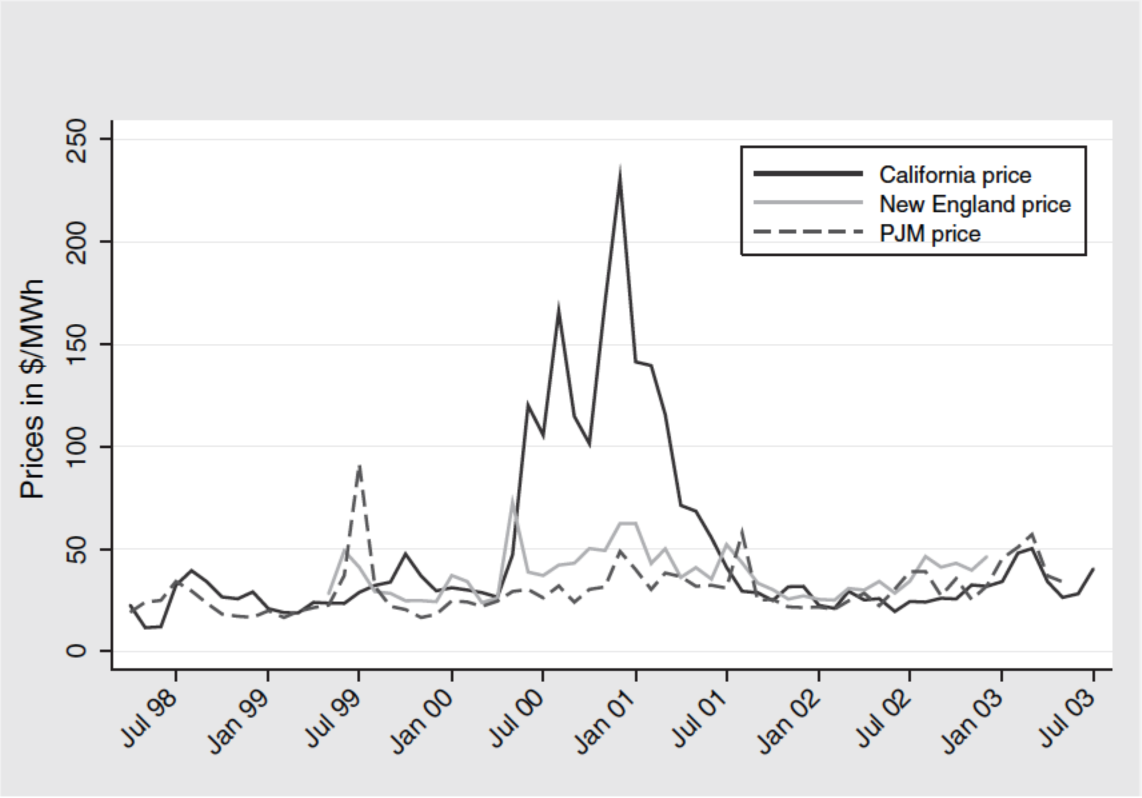


FIGURE 1. PRICE PATH IN ALL MARKETS
(*California, New England, and PJM Monthly Averages*)

Comparison Across the Three Markets

	California	New England	PJM
When did transactions start?	April, 1998	May, 1999	April, 1999
Who controls transmission lines?	California ISO (CAISO)	New England ISO (ISONE)	PJM Interconnection
Output max summer 1999 (GWh)	44.1	25.7	56.7
Load max summer 1999 (GWh)	45.9	22.3	51.7
Horizontal market concentration (HH)	620	850	1400
Import	25%	10%	little

Vertical Integration after deregulation

PJM

- Retailers retained their generation assets
- In other words, retailers and wholesalers were vertically integrated

New England

- Divestitures of generation from vertically integrated utilities
- However, retail utilities signed long-term supply contracts with wholesalers
- Retailers signed contracts with the wholesaler that they previously owned

California

- No meaningful long-term contracts
- Most electricity was sold in the pool spot market
- Large utilities still owned some generating plants in 1999, but they were low marginal cost capacity (nuclear and hydro)

Vertical Integration and Market Power

Vertical integration in the three markets

- PJM and New England: vertically integrated or long-term contracts between retailers and wholesalers
- California: almost no vertical integration for high marginal cost plants

Hypothesis

- Vertically integrated firms have LESS incentives to raise wholesale prices
- This is because integrated firms make retail price commitments before committing production to their wholesale market
- On the other hand, non-integrated wholesalers have larger incentives to raise wholesale prices because they do not need to care about retail prices

Vertical Arrangements in a Cournot Setting

Assume profit maximizing firms,

$$(1) \qquad \pi_{i,t}(q_{i,t}, q^r_{i,t}) = p^w_t(q_{i,t}, q_{-i,t}) \cdot [q_{i,t} - q^r_{i,t}] + p^r_{i,t}(q^r_{i,t}, q^r_{-i,t}) \cdot q^r_{i,t} - C(q_{i,t}),$$

Implied first order condition,

$$(2) \qquad \frac{\partial \pi_{i,t}}{\partial q_{i,t}} = p^w_t(q_{i,t}, q_{-i,t}) + [q_{i,t} - q^r_{i,t}] \cdot \frac{\partial p^w_t}{\partial q_{i,t}} - C'_{i,t}(q_{i,t}) \geq 0.$$

Key is that q^r and p^r are considered sunk at this stage.

Firms only care about the impact of marginal price increases on the net day-ahead market quantity.

For competitive, assume no markup term.

Note: Paper shows equilibrium can be solved as a complementarity problem (this will be part of the exercise today, so that you can learn how to build these models).

Data

PJM, New England and California data.

Similar cost data to BBW (California), Saravia (2003) for New England, and Mansur (2007) for PJM.

Important addition with vertical arrangements and long-term contracts.

- Vertical position inferred for vertically integrated firms
- Publicly available data on long-term contracts for PJM and New England
- No data for California on long-term contracts, but by construction there were limited

Results: All hours

Variable	Mean	Median
Panel A: Peak hours (11 am to 8 pm weekdays)		
California actual	43.15	34.52
Competitive	35.01	30.88
Cournot	45.17	40.19
New England actual	55.05	33.16
Competitive	41.72	35.04
Cournot	54.63	40.44
Cournot n.v.a.	280.47	145.86
PJM actual	97.31	33.17
Competitive	35.08	33.27
Cournot	87.05	36.00
Cournot n.v.a.	1,000.00	1,000.00

Cournot much better

Vertical arrangements crucial

Very nice fit across markets

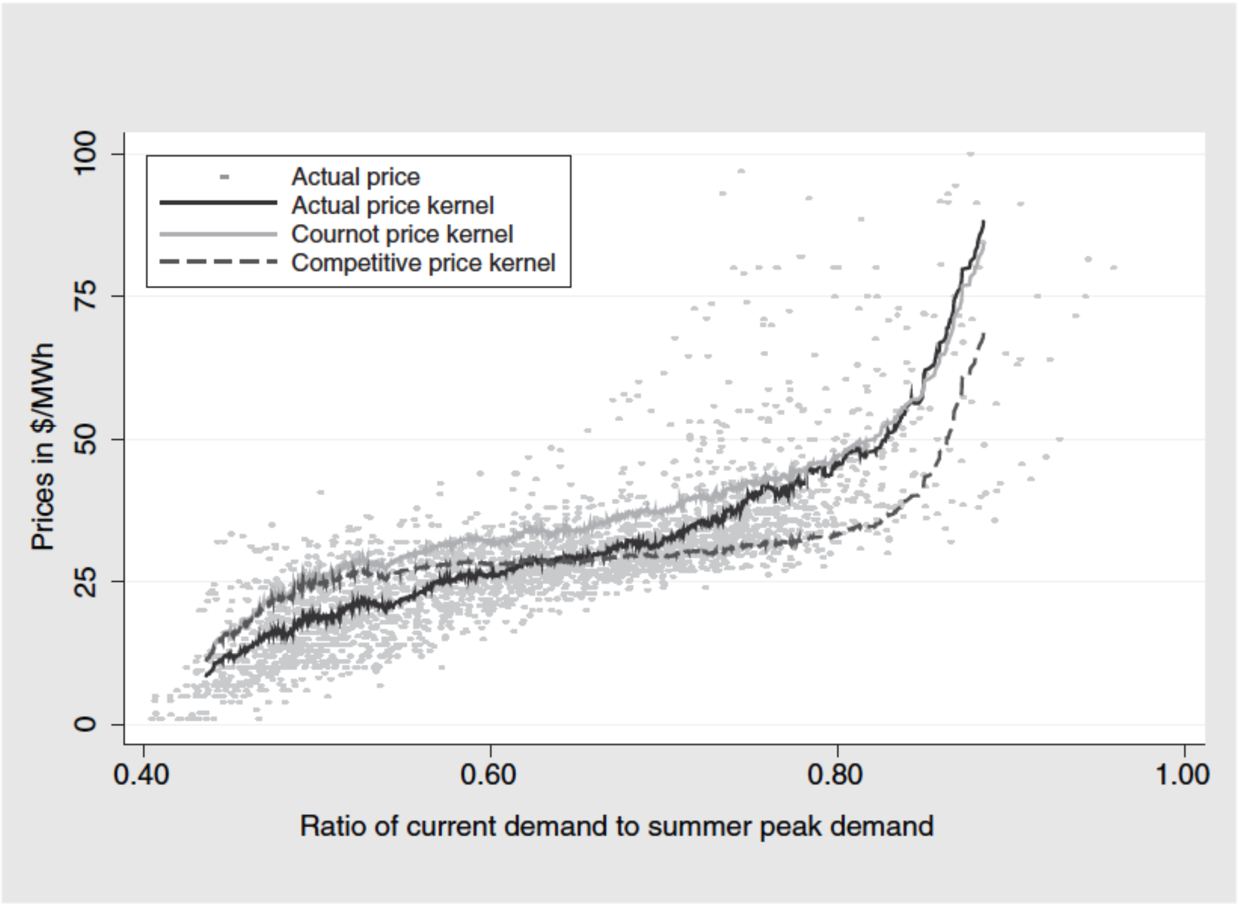


FIGURE 2. PRICES BY QUANTITY DEMANDED IN CALIFORNIA
(Actual, competitive, and Cournot price kernels)

Very nice fit across markets

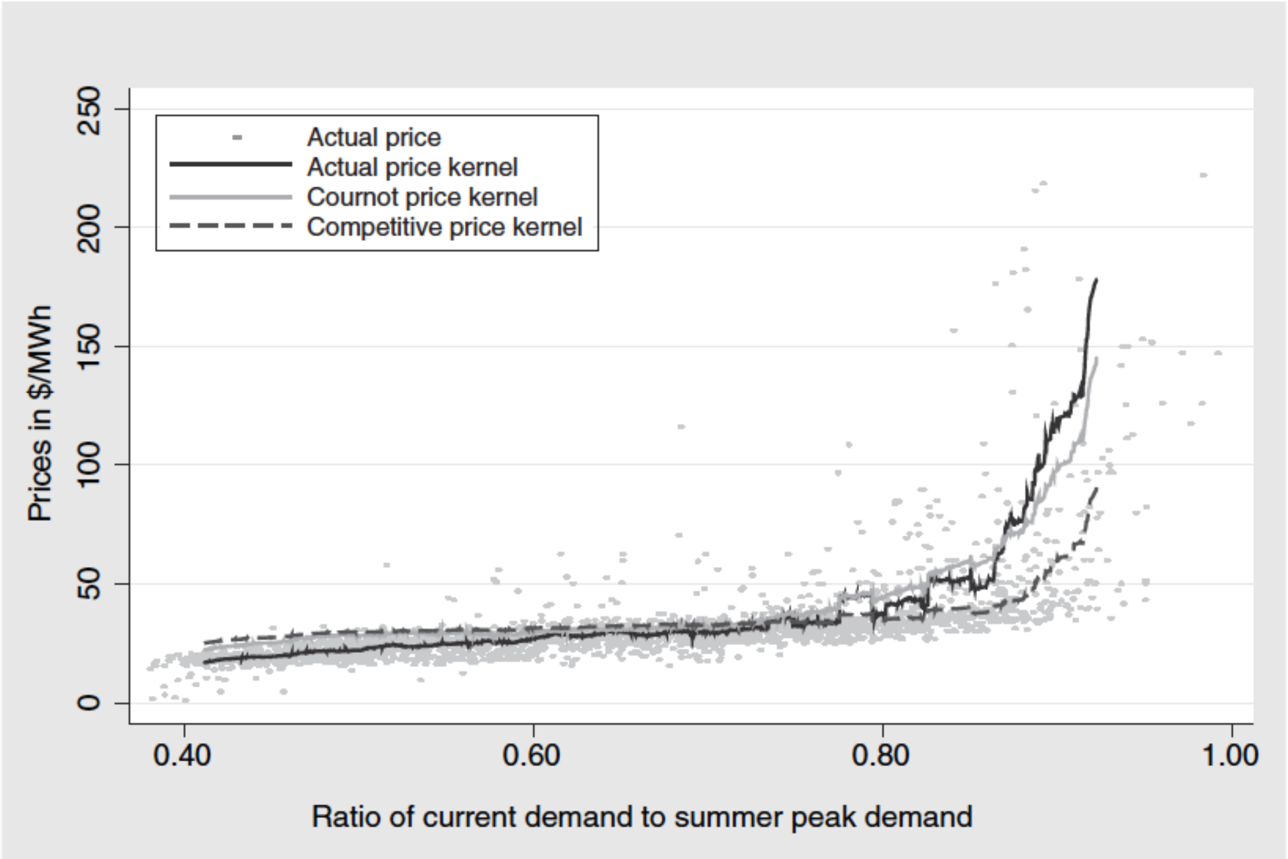


FIGURE 5. VERTICAL ARRANGEMENTS IN NEW ENGLAND
(Actual, competitive, and Cournot price kernels)

Very nice fit across markets

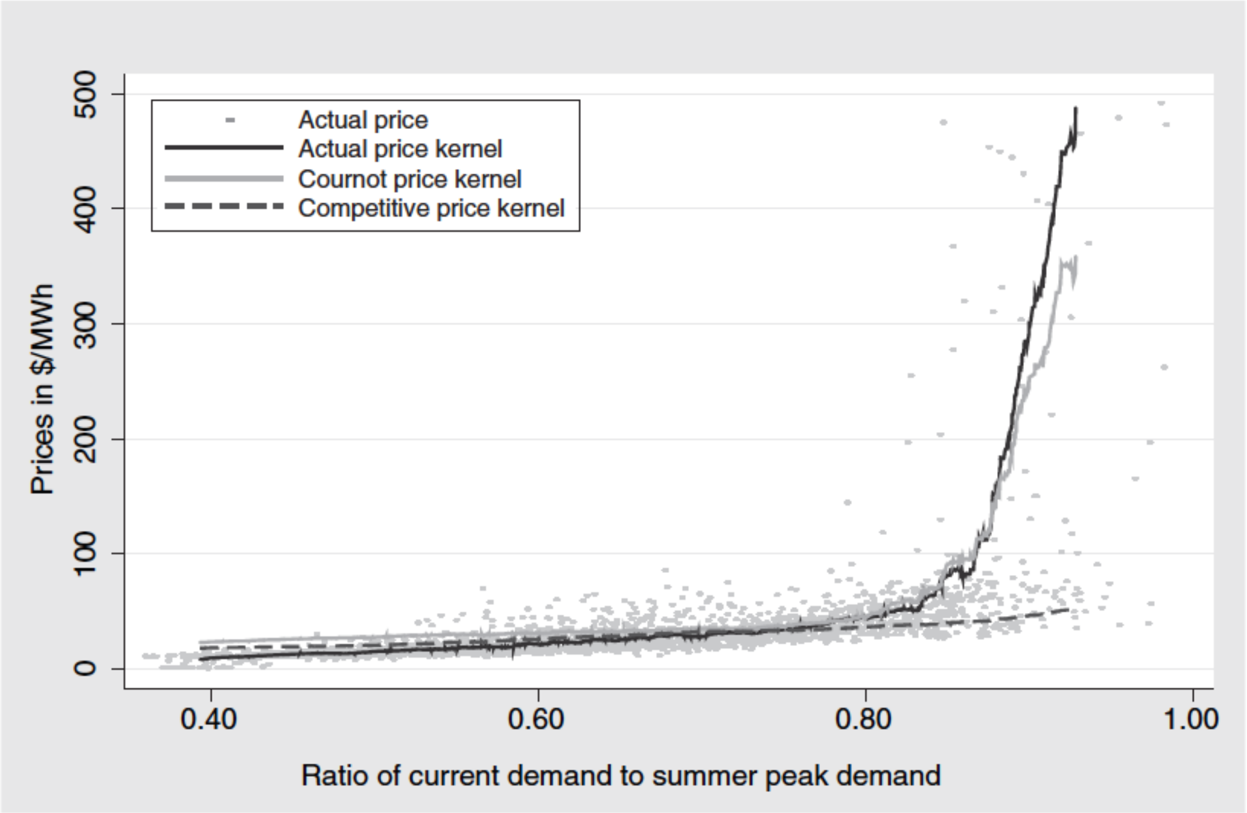


FIGURE 6. VERTICAL ARRANGEMENTS IN PJM
(Actual, competitive, and Cournot price kernels)

Comparison Across Hours

Variable	Mean	Median
Panel A: Peak hours (11 am to 8 pm weekdays)		
California actual	43.15	34.52
Competitive	35.01	30.88
Cournot	45.17	40.19
New England actual	55.05	[illegible]
Competitive	41.72	
Cournot	54.63	
Cournot n.v.a.	280.47	
PJM actual	97.31	
Competitive	35.08	
Cournot	87.05	
Cournot n.v.a.	1,000.00	
Panel B: Off-peak hours		
California actual	23.90	24.99
Competitive	26.10	27.44
Cournot	30.00	31.25
New England actual	29.18	26.61
Competitive	31.73	31.14
Cournot	32.63	30.54
Cournot n.v.a.	86.16	55.82
PJM actual	23.84	18.10
Competitive	25.42	23.78
Cournot	32.73	30.00
Cournot n.v.a.	900.57	1,000.00

Check Reguant (2014) for a correction on markups

Potential biases due to dynamic costs of operation

Summary of BMS (2008)

- Vertical arrangements are of crucial importance to explain firm behavior
- When vertical arrangements are accounted for, Cournot model gives a good fit to the data
    - Ideally, SFE. But not as tractable.
- Other work has been using the BMS framework to look at other questions.
    - E.g., Ito and Reguant (2014).

Today’s outline

1) The economics of electricity markets
   - Overview of functioning
   - Details on market dispatch
2) Case study: Clearing a simple CAISO market
   - Clustering our data
   - Modeling with JuMP

Today's application paper

We will be building the simplest version of an electricity market with data from Reguant (2019).

Paper has investment and retail equilibrium prices, but today we will focus on simple short-run model.

Analogous to models in Bushnell, Mansur, and Saravia (2008) and the second stage of Ito and Reguant (2016), but without market power.

Main goal is to get some familiarity about how these models are formulated as mathematical programming objects and how they are built in Julia.

Summary of Reguant (2019)

Question: Examine current practice of charging renewable costs mostly to residential sector.

Data: California market data to calibrate a stylized model of an electricity market with 3 types of end users (I, C, R).

Methods: Ramsey pricing theory with externalities, computational tools for quant assessment.

Finding: Charging residential HH cannot be justified by Ramsey pricing unless industrial sector leaks.

Equilibrium model for the paper

Model needs to solve for:

- Supply and demand choices, market and retail prices.
- Investment level of each technology. <u>This step makes model more expensive</u>, cannot solve each hour fully separately.
- Retail prices that include subsidies to renewable power, with taxes that can be split in different ways and designed optimally. <u>This step makes the problem more expensive as well,</u> not nice equations, need to solve iteratively many times.

How to simplify the model?

Simplifying the data and the model

Simplifying the data

You will learn how to use k-means clustering to vastly reduce the number of hours that are used.

Results are still very similar, but it takes a much shorter time.

Simplifying the model

The model will be simple: supply aggregated at the technology level, without hydro modeling.

Demand will be aggregated (one category today, three in the paper).

Model will treat firms as competitive, offering their power at their marginal cost (social planner equivalent).

Simplifying the data

You will see more about this in the afternoon session.

Key idea is to identify “representative hours” with some “weights” for how important each hour is.

These representative hours can then be used in the model (together with the weights) to ensure that the model is representative (but runs much faster).

Note: The hourly clustering is easiest, but it treats each hour as independent. Depending on the problem, clustering days or weeks might be better.

- E.g., for a short-term battery problem, need to look at battery behavior for at least three days; for hydro, very difficult to cluster due to seasonal rains and long-term storage.

Solving the model with JuMP

JuMP makes the formulation of electricity dispatch models relatively seamless.

One code to express the model, one can then call several solvers depending on the needs.

I will give you a “hint” of what JuMP can do.

Example of highly configurable electricity expansion model based on Julia + JuMP:

- https://genxproject.github.io/

Solvers

- There is an array of optimization resources that are tailored to be particularly efficient in certain problems.
- Developed/used more in engineering and operations research.
- Examples:
  - Quadratic programs
  - Linear programs with integer variables
  - Nonlinear programs with integer variables
  - Programs with complementary conditions

Model follows Bushnell (2010) – Building blocks

- Model with perfect competition and free entry.
- Continuous investment in different technologies.
- Equivalent to least-cost social planner outcome.
- Entry of each technologies occurs until revenues of the marginal unit equal levelized costs of investment and operating costs.
- Assess long-run generation mix (coal, CCGT, peaking gas).
- Focus on thermal generation.

Model equations and solution

The model equations are as follows:

[Demand] $Q_t(p_t) = a_t - f(p_t)$ (we will assume it is linear)

[Quantity] $q_{it} \geq 0 \perp p_t - c_i - \psi_{it} \leq 0 \ \forall \text{ i, t}$

[Shadow] $\psi_{it} \geq 0 \perp q_{i\,t} - K_i \leq 0 \ \forall \text{ i, t}$

[Zero profit] $K_i \geq 0 \perp F_i - \sum_t \psi_{it} \leq 0 \ \forall \text{ i}$

The model is a complementarity problem. To solve these problems one can use special software or do it “brute force”.

Complementary conditions formulation

- We can think of each complementarity condition as the product of two variables.
- We want to minimize the objective function and make sure it is zero.

$$\min \quad z'w$$

subject to the constraints of *z* and *w* being non-negative:

$$z >= 0, w >= 0.$$

- We need to check objective function is zero.
- Special solvers are tailored to solve these problems, such as PATH.

Mixed-integer formulation

- Mixed integer programs can be used very generally to express constraints or model discrete decisions.

- We can also use “tricks” to mimic Khun-Tucker conditions.

- For our complementarity-equivalent problem, we have:

$$z >= 0, w >= 0$$

$$z <= M\,u, \mathrm{w} <= M\,(1 – u)$$

where M is a big large number.

- Either z is zero or w is zero.

- This is more general but will tend to be less efficient (less tailored).

Next class

Supply II.

- What environmental policies affect electricity markets?
- How can we model these regulations?

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