Empirical Methods for the Analysis of the Energy Transition

Slide Set 3

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Roadmap

I. Empirical analysis of electricity market performance

Borenstein, Bushnell, and Wolak (2002)

Bushnell, Mansur, and Saravia (2008)

II. Building a model

III. Case Study: Clearing a simple CAISO market

Concerns over the performance of electricity markets

- Recent high energy prices have resurfaced concerns about the performance of electricity markets:
  - Are they competitive?
  - Are they *fair*?
  - Do they have an appropriate design?
  - Is marginal pricing justified?

- A key question is to which extent firms behave as economic agents through the lens of stylized models, which can be used to benchmark competition levels.

Economics tools to analyze market performance

- Theoretical models of market design
- Empirical analysis of previous market performance
- Simulation models to examine counterfactuals (alternative market rules, configurations, input costs, etc.)

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, and 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)

Firm	Fossil	Hydro	Nuclear	Renewable
July 1998—online capacity				
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).

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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

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Comparison to the IO literature

Similarities

- Markup calculation as the residual from marginal cost, $\mathrm{P} = \mathrm{MC} + \mathrm{Markup}$

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

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Weighted Markups

- **Lerner Index**

$$\text{Markup} = \frac{P - MC}{P}$$

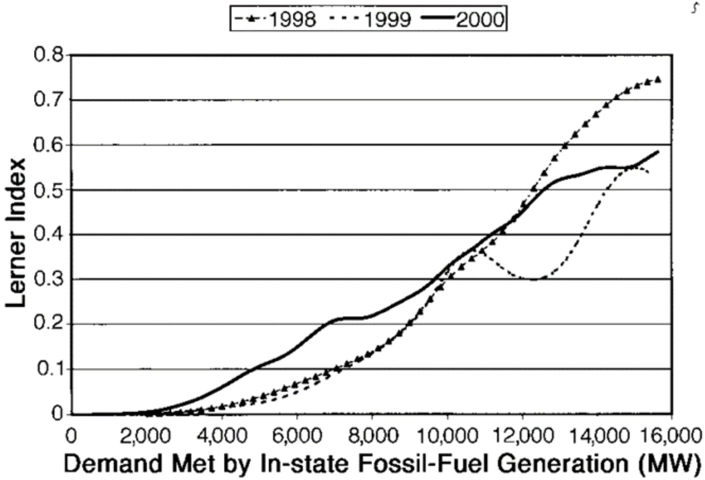
- In this setting:

$$\text{Markup} = \frac{P_{observed} - P_{competitive}}{P_{observed}}$$

- Note: 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

Markups higher during the events of 2000



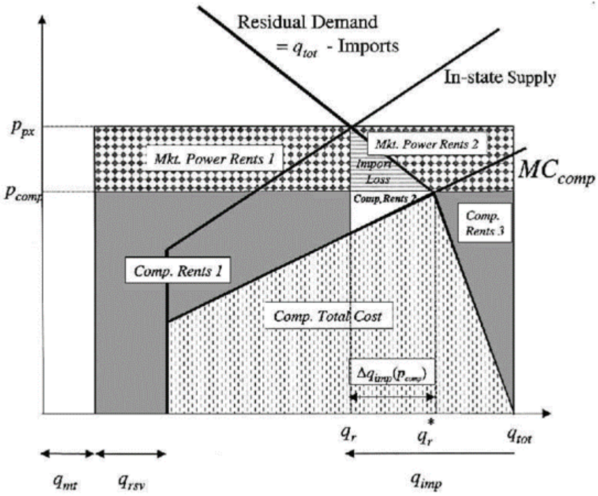
Rent division

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 expenditure



Decomposition of expenditure

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

Summary Borenstein, Bushnell, and Wolak (2002)

- This is one of the first papers to quantify the inefficiencies in electriciting market, decomposing it into several channels: cost shifts, inframarginal rents, effects on imports, market power.
- The paper compares the data to a stylized model, finding substantial market imperfections.
- Engineers pointed out that many of those efficiencies are real physical limits or operational constraints.
- A new literature perform similar analysis to assess potential gains from trade in the US, calculating the gains from "perfect trade", which might not be realistic (Hausman, 2025).

How can better models get better answers? How to best frame our exercise?

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, and 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

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Motivation: Why California?

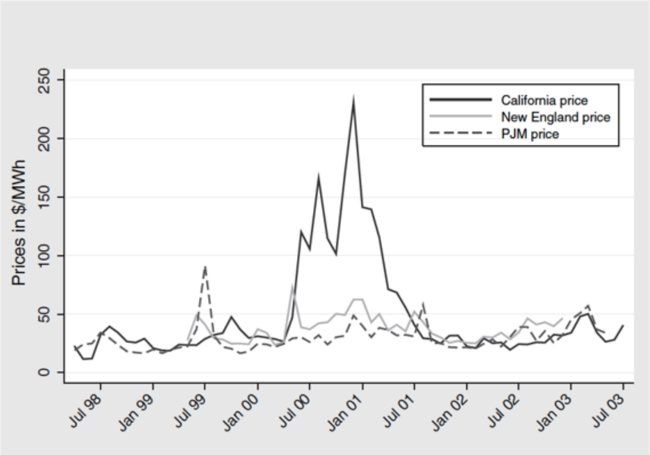

Figure 1. Price Path in All Markets
(California, New England, and PJM Monthly Averages)

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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

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

Implied first order condition

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

- 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

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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 setting much better at replicating observed prices than Competitive setting
- Vertical arrangement crucial (see substantially higher prices for n.v.a rows)

Very nice fit across all markets

Calefornia

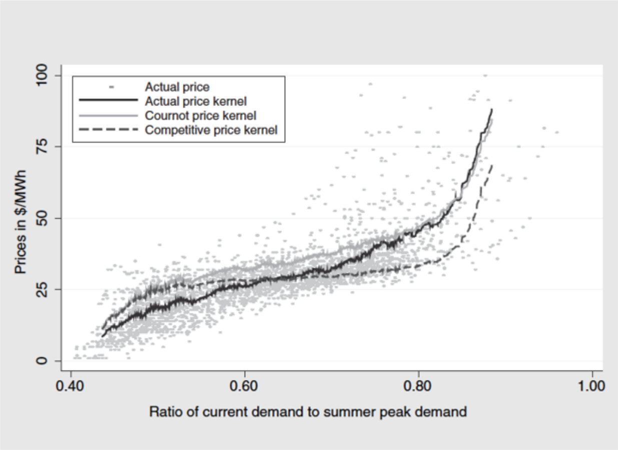

FIGURE 2. PRICES BY QUANTITY DEMANDED IN CALIFORNIA
(Actual, competitive, and Cournot price kernels)

Very nice fit across all markets

New England

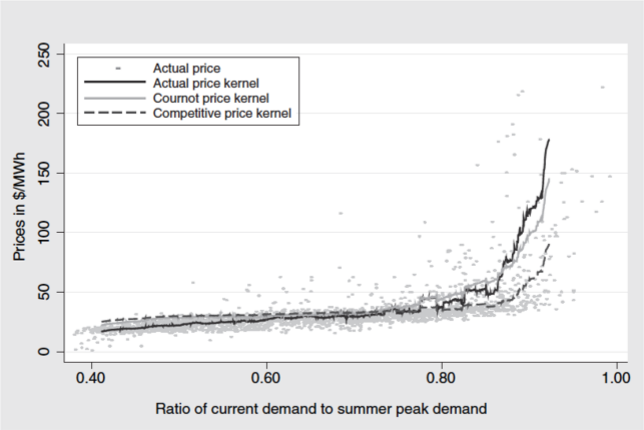

FIGURE 5. VERTICAL ARRANGEMENTS IN NEW ENGLAND
(Actual, competitive, and Cournot price kernels)

Very nice fit across all markets

PJM

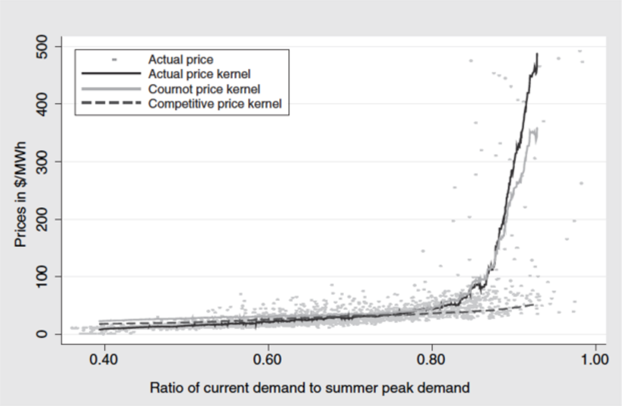

FIGURE 6. VERTICAL ARRANGEMENTS IN PJM
(Actual, competitive, and Cournot price kernels)

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Comparison Across Hours

Variable	Mean	Median
Panel A: Peak hours (11 am to 8 pm weekdays)		
California actual	43.15	34.52
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PJM actual	97.31	
Competitive	35.08	
Cournot	87.05	
Cournot n.v.a.	1,000.00	

Check Reguant (2014)
for a correction on markups

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

Potential biases due to
dynamic costs of operation

Summary of Bushnell, Mansur, and Saravia (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.
  - Sequential markets: Ito and Reguant (2014)
  - Batteries: Butters et al. (2024)
  - Reliability: Gowrisankaran et al. (2016)
  - Startup costs: Reguant (2014), Jha and Leslie (2024)

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Modeling economics in electricity markets

- At its heart, all electricity market models have firms/technologies and information about demand (as a curve or fixed) to find the best allocation that ensures demand = supply (called economic dispatch).
  - In the simplest setting, we cross demand and supply, and the crossing point determines the price.
- If the model takes into account discrete decisions about which power plants to turn on/off, it is called a unit committment problem (more difficult to solve).
- Depending on the question at hand, the electricity markets in economic analysis are modeled abstracting away from many features.
  - E.g., big long-run policy questions like climate policy might be answered with a simplified version of the market.
- Depending on the question, some more detailed features need to be brought back (e.g., transmission congestion regarding renewable expansion).

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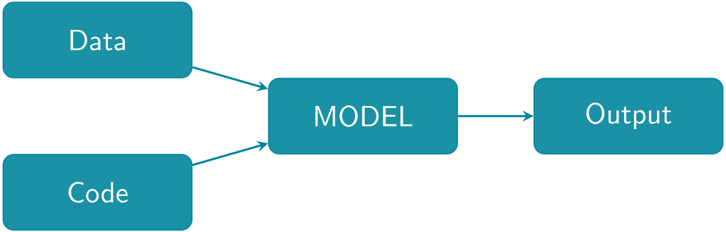
Building models of electricity markets



- 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. A model is a simplification of a complex reality.

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)

Why these modeling frameworks?

- There are many models (proprietary or open source) that are used to optimize many economic decisions:
  - To maximize trading profits at high frequency.
  - To make investment decisions.
  - To model the impact of energy/climate policies (companies or policymakers).
  - As an input to bigger macroeconomic/climate models due to the importance of energy as an input.
  - Etc.

- In all these cases, modeling tools are combined with market data and forecasts to determine the optimal decisions.
- The modeling language can change, but all use similar constrained optimization languages (GAMS, AMPL, pyomo, JuMP, etc.) or code that works with specific proprietary solvers (Cplex, Gurobi).

Some examples of modeling frameworks

- GenX and the Net-Zero America project: https://energy.mit.edu/genx/, https://netzeroamerica.princeton.edu
- OseMOSYS: http://www.osemosys.org/
- Plexos: https://www.energyexemplar.com/plexos
- EU METIS model: https://energy.ec.europa.eu/data-and-analysis/energy-modelling_en
- UN IAMs compilation: See link for various models.
- pyPSA and pyPSA Europe impelemtation: https://pypsa.org/, https://pypsa-eur.readthedocs.io/en/latest/

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Auctions in electricity markets

- To decide supply and demand, the centralized planner clears an auction.
  - Suppliers submit willingness to produce.
  - Consumers submit willingness to pay.

- Planner maximizes the net surplus based on these offers, sometimes considering **constraints** due to the complexities of electricity generation and delivery.
- This is not an abstraction, every single day, several times, electricity market operators are solving these optimization problems.

Inputs to the auction

- At the very least:
  - Demand curve.
  - Supply curve.
- Often:
  - Some additional rules and constraints.

Our goal today

- Our goal today is to create these inputs based on the data from last week (CAISO).
- We then need to solve for the objective function.

$$\begin{aligned} \max_{q} \quad & GS(q) - C(q) \\ s.t. \quad & \text{demand=supply,} \\ & \text{other constraints.} \end{aligned}$$

- We solve for the quantities that maximize the gross surplus GS minus the costs of generation C.
- Implicitly or explicitly, there is a price to electricity consumption.

Solving the model with pyomo

- pyomo 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 mathematical programming can do.
- All professional and research models are based on these tools, using mixed integer programming.

Ingredients to a mathematical model

- Parameters/Inputs
- Variables
- Constraints
- Objective function
- Sense of the objective function
- The solver we want to use

Note: In mathematical programming, the terms ‘variables‘ and ‘parameters‘ are used the opposite way as in econometrics! Variables: what we are trying to solve. Parameters: what we already have, the inputs.

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

Building blocks: an alternative formulationl

following Bushnell (2011) in the Readings tab

- 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 solution

The model equations are as follows

- **Demand** (we will assume this to be linear)

$$Q_t(p_t) = a_t - f(p_t)$$

- **Quantity**

$$q_{it} \geq 0 \perp p_t - c_i - \psi_{it} \leq 0 \quad \forall i, t$$

- **Shadow**

$$\psi_{it} \geq 0 \perp q_{it} - K_i \leq 0 \quad \forall i, t$$

- **Zero Profit**

$$K_i \geq 0 \perp F_i - \sum_t \psi_{it} \leq 0 \quad \forall i$$

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

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

$$\min z'w$$
$$\text{s.t. } z \geq 0, w \geq 0$$

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

Mixed-integer programming

- We refer to mixed-integer programming for problems that have both discrete and continuous variables that we are trying to solve for.
- In the last 10-15 years, this type of problems has become easier to solve.
- Electricity markets are an important application, as there are many discrete decisions:
  - Should we use a power plant or not?
  - Is a technology "marginal" or not?
  - Is a transmission line at capacity or not?
  - For piece-wise linear functions, at which side of the function should we be?
  - Etc.

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:

$$z \geq 0, w \geq 0$$
$$z \leq M \cdot u, w \leq M \cdot (1 - u)$$

- u is a binary variable that sets condition on or off.
- Either z is zero or w is zero.
- M is a large number (convention to call it 'M', literally a big number).

Next class

- **Supply I continued**
  - What are dynamic aspects of electricity markets?
  - How can we solve for investment?