Empirical Methods for the Analysis of the Energy Transition

Slide Set 4

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2025/2026

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Roadmap

I. Dynamics in the electricity sector

II. Adding investment to the model

Modeling of dynamics

In any sector, important to decide how dynamics are modeled:

- One-shot vs. multiple periods?
- Stationary infinite horizon vs. finite horizon?
- Relevant dynamic variables vs. those that can be simplified?
- Strategic vs. competitive vs. social planner? When are the last two equivalent?
- Level of aggregation: hourly, monthly, annual?

Dynamics in electricity

Several dimensions involve dynamics:

- Startup of power plants (Reguant 2014; Cullen, 2015).
- Allocation of hydro resources (Crampes and Moreaux, 2001; Bushnell, 2003).
- Batteries (Karaduman, 2021; Butters, Dorsey and Gowrisankaran, 2022).
- Divestitures (Linn and MacCormack, 2019).
- Renewable entry (Gonzales, Ito, and Reguant, 2023).

Implementation across papers can differ widely from a technical perspective.

Competitive equilibrium definition

- In energy markets, firms need to recover their capital investment, which is often very sizeable:
  - Nuclear plant, gas power plant, wind mill...
- Firms make profits in day-to-day operations.
- In the long-run definition of equilibrium, profits cover the long run fixed costs of the marginal unit.

Competitive investment

- From “day 3”, we had that firms earned some “competitive’ rents”.
- For the marginal ”last unit”, zero profit condition means:

$$\sum_t \psi_{it} = F_i \quad \forall i$$

- Remember ψ_{it} is the infra-marginal rent of the technology (for the last unit).
- Other firms / technologies that are not marginal could be making profits.
- Positive entry requires the technology to not always be marginal (i.e., $P > MC$ for some hours).

Note: In the presence of short-run market power, ψ could still distort entry even if entry is competitive.

Empirical interpretation

- Firms look forward to forecast industry supply, possible demand, and possible profits, then decide how much to invest.
- A firm invests if the expected net present value of short-run profits exceeds the investment cost.
- Different beliefs about future demand and costs are one cause of differentiated firm investments.
- Additionally, this is a completely changing environment (costs, demand due to electrification, regulation,....!).
- Some investments will end up being profitable, while others will not. In practice, almost no firms exactly break even.

The peak-load pricing model

If the price is equal to the marginal cost of each unit, they will also recover the fixed cost. (Boiteux, 1960).

- Building a market with short-run efficiency guarantees the optimal amount of entry of each technology.

Short-run efficiency

- The market clears where demand crosses supply.
- During peak periods this may be where supply is vertical.
- The extent to which price exceeds marginal cost at peak output represents the "shadow value" of more capacity.
- Marginal cost pricing essential for short-run efficiency.

Long-run efficiency

- The shadow value of capacity represents the net revenue that a new entrant could earn if it has costs equal to the marginal producer.

- If shadow value is greater than fixed cost of capacity, new entry will occur and drive down prices.
- If shadow value is less than fixed cost of capacity, exit will occur and prices will rise.

Limitations to the peak-load pricing model

- The Boiteux result:
  - If P=MC, we will get the right kind and amount of power plants
- Regulators worry that there will not be enough investment.
  - Boiteux model is too stylized in practice.
  - Constant market and non-market interventions to guarantee security of supply.

Some of the limitations of the Boiteux model

- Volatility
  - The market is too volatile, power plants rely on very few hours of the day when electricity is very expensive.
- "Missing money" problem (e.g., see work by Joskow)
  - The "energy only" market is not enough to compensate the power plants, regulators limit prices.
  - Electricity markets often complemented with capacity payments/markets that pay existing investments to "stick around".
- Hold up
  - Rules in the market change too often, especially when prices rise.

Hold-up

- Concerns about opportunistic behavior by the regulator.
  - For peaking plants, most revenues come from days of extremely high prices.
  - Investors could be concerned about discretionary behavior in those instances.

- More broadly, changes in policy goals can have important impacts on firm revenue.
- Regulatory intervention can also impact rents (e.g., clawback of carbon price rents).
- Unfortunately, credibility in ability to pay can also lead to hold up even in fixed-price auctions!!! (Spanish experience, Ryan, 2023).

The European energy crisis and the peak-load pricing model

- The natural gas crisis in Europe led to extreme prices that raised electricity gross revenues across all technologies (via the short-run marginal price in the peak-load pricing mechanisms, set typically by gas plants).
- Many governments gradually put regulations in place to limit infra-marginal rents.
- Policy and academic debates have emerged on whether these policies have efficiency implications via short and long-run distortions.

- *Do they affect efficiency? In which instances?*

Renewables and the peak-load pricing model

- This is an active area of research *and* policy-making: theory and empirics quite open.

- How should markets be designed in the presence of renewable energy (high fixed cost, almost zero marginal cost)?
- What is the role of centralized auctions for new and existing investments?
- Are renewables cannibalizing themselves and deterring future investments?

- See two references as potential "higher-level" readings (Botterud and Auer, 2018, Fabra, Motta, and Petiz, 2022).

Roadmap

I. Dynamics in the electricity sector

II. Adding investment to the model

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Adding investment to the model

- We will add optimal investment to our previous model.
- We will find the optimal power plant additions for a given set of assumptions.
- We will review several *equivalent* ways to get the same outcome.
- Why?
  - Computing electricity models is hard.
  - Depending on the question/policy simulation, one method could be better than another.

Building blocks of the model

following Bushnell (2010)

- Model with perfect competition and free entry.
- Continuous investment in different technologies.
- Equivalent to least-cost social planner outcome.
- Entry of each technology 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 in the original paper, we will have renewables, too.

Alternative ways of solving the problem

- We can solve the investment model in several ways:
  1. Solving the zero-profit condition in a loop.
  2. Solving the social planner problem with investment.
  3. Using mixed integer modelling with zero profit condition for investment.

1) Solving the zero-profit condition in a loop

- We already have a function with technology GW as an input (solar, wind, adding gas).
- We can check different values of investment, to see how much profit technologies are making.
- We can check for the zero profit condition “manually”.
- We can solve the basic model with social planner model or the mixed integer program.

- **Challenge**: might get tricky to find zero profit for all techs as we add more regions/technologies.
  - Need to try one at a time, update the profit for others, and loop.

2) Solving the social planner problem with investment

- We already had a function solving for the least-cost dispatch taking capacity as given.
- We can make capacity a choice.

- **Challenge**: the social planner oftentimes does not make the "free market" choice unless the model is very stylized.
  - Social planner takes into account other "quirks", even more true as we add externalities that are mispriced or households that are behaving suboptimally.

3) Model equations with mixed-integer variables

- 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**

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

  where $\perp$ denotes complementarity: one of the two conditions needs to be zero.
- **Challenge**: computationally burdensome, less intuitive to code.

Next class

- **Supply II.**
  - Climate policies in electricity
  - Adding them to the model