# Dynamic Oligopoly in Environmental Economics Research Questions and Methods

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# Why Study Environmental and Energy Economics (EEE)?

- Scientists describe climate change as potentially an "ice age in reverse" over the next 100 years.
  - Costs of these changes are not fully known, but in expectation they are large.
- There is substantial global momentum toward increased climate policy.
  - Even the U.S. has gotten its act together somewhat!
- Huge need for better economic understanding of policies' cost and effectiveness.
  - Large heterogeneity in policies, constraints, and implied social cost of carbon.
  - Empirical work largely focused on ex-post analysis rather than policy design.

# Why Do We Need to Understand Dynamics?

- At its core, much of EEE is about *dynamics*:
  - Policies enacted today may not have benefits until far in the future.
  - Many approaches require fixed investments by firms and individuals
    - R&D, efficiency upgrades, abatement technology adoption, legacy technology exit.
  - Future costs and benefits are uncertain, which can create option value.
  - Political uncertainty makes legislative strategy dynamic.
- While there has been some empirical work on dynamics in EEE, there is a *ton* more room for excellent papers.
- Today I will do three things:
  1. Survey selected dynamic EEE literature.
  2. Explain approximate equilibrium methods that allow us to answer new questions.
  3. Provide thoughts on important directions for future research.

# Overview of Lecture

1. Single Agent Models:
   - Oil drilling under uncertainty: Kellogg (2014)
   - Residential solar adoption:
     De Groote and Verboven (2019), Langer and Lemoine (2022)
   - Dynamic Enforcement: Blundell, Gowrisankaran, and Langer (2020)
2. Oligopoly Models:
   - Regulation, market power, and leakage: Fowlie, Reguant, and Ryan (2014).
   - Impact of policy uncertainty: Gowrisankaran, Langer, and Zhang (2022).
3. Approximate Equilibrium Models:
   - Oblivious equilibrium
   - Moment-based Markov equilibrium (MME)
   - Our (unnamed) extension to MME
4. Directions for future research

# Dynamics Without Oligopoly

- You have learned a lot about different approaches to estimating dynamic models when decision-makers can act independently.
  - There are *a lot* of questions that we can answer with single agent models!
- Kellogg (2014) "The Effect of Uncertainty on Investment: Evidence from Texas Oil Drilling"
  - How does uncertainty over oil prices affect the choice to drill a new oil well?
  - When you choose to drill today, you:
    1. Give up the option to drill in the future.
    2. (Potentially) start to receive a flow of oil to sell at contemporaneous oil prices.
    3. Are therefore exposed to oil price uncertainty for that stream of oil over that period.

# Uncertainty in Oil Drilling

- Basics of empirical modeling:
  - Wells are small within the global oil market: do not individually influence prices.
  - Firms have rational expectations over future oil price levels and volatility.
- Results:
  - Higher expected oil price variation decreases drilling: effect is consistent with the optimal theoretical response.
  - The economic cost of *not* responding to these shocks is substantial.
  - Forward-looking volatility measures preform better than backward looking.
  - Individual firm counterfactuals are possible, but not economy-wide counterfactuals.
- Why does this matter?
  - Economic and political uncertainty may be affected by policy design.
  - These outcomes will matter for oil extraction (and likely other industries).
  - The costs of increasing this uncertainty could be large.

# Optimal Stopping Problems: Solar Adoption

- Solar panel prices have dropped significantly over the last 20 years.
- Households make optimal stopping problems about whether/when to install solar.
- Modeling these choices helps us to understand effective policy design:
  - Up-front investment subsidies vs electricity production subsidies (de Groote and Verboven, 2019).
  - Efficient shape of a time-varying subsidy schedule (Langer and Lemoine, 2022).
- Both papers seek to inform policy design by understanding household decision-making.

# Solar Policy Design

- Governments may subsidize solar in order to offset negative externalities from fossil fuel electricity generation.
- Can choose between subsidizing the initial adoption of solar panels or subsidizing the electricity generated with solar panels.
- There are levels of each subsidy that make consumers indifferent between them.
  - These levels depend on households' discount factors.
  - If government has a different discount factor than households, then one policy will be preferred to the other.
    - E.g., if consumers are less patient than the government, an up-front subsidy will be cheaper for the government per unit of adoption.
- Even conditional on up-front subsidies, the effectiveness may depend upon whether/how the subsidy changes over time.

# Empirical Design

- Both papers model households' optimal stopping problem for solar.
- This requires specifying expectations over electricity prices, solar prices, and government policies.
  - Papers can assume full information or model expectations.
- De Groote and Verboven make use of changing policies:
  - Guaranteed production subsidy shifts from 20 years to 10 years into the future.
  - This allows them to estimate the discount rate.
- Langer and Lemoine match theory to empirics to understand tradeoffs between:
  - High initial subsidies that encourage early adoption, convince households to stop waiting for lower future solar prices, and may lead to induced technological change and peer effects.
  - High later subsidies avoid "over subsidizing" inframarginal adopters, take advantage of price declines in solar, and potentially exploit peer effects.

# Results

- De Groote and Verboven find that households have a high discount rate.
  - This suggests that government could increase adoption without increasing discounted costs (given government discount rate) by front-loading subsidies.
- Langer and Lemoine find that the efficient solar subsidy in California was *increasing*.
  - Advantage of increasing adoption when solar prices are lower and not “over subsidizing” households with high solar values outweigh value of installed base, induced technological change, and peer effects.
  - This is true for a wide range of assumptions about induced technological change, peer effects, and the value to government of early solar adoption.
  - Nearly all solar subsidies worldwide are flat or decreasing.
  - This suggests that governments may be spending too much money subsidizing early, inframarginal adopters, which also has substantial environmental justice implications.

# Dynamic Enforcement

- For many environmental policies, we see low fines for non-compliance, but high compliance rates.
  - This is very true for the Clean Air Act Amendments in the U.S.
- A static model of optimal compliance (e.g. Becker 1968) would suggest that compliance costs are very low.
  - Yet compliance investments are often large and expensive!
- Threat of high future fines could encourage firms to comply today even if current period fines are low.
- These types of escalation mechanisms are very common!
  - Yellow cards vs red cards in soccer/fouling out of basketball.
  - Three strikes sentencing laws.

# Blundell, Gowrisankaran, and Langer (2020)

- What is the value of having enforcement mechanisms that are state-dependent?
- In a (simple) theory model, we show that dynamic enforcement mechanisms have value when:
  - Regulators dislike imposing penalties.
  - Plants have heterogeneous compliance costs.
- But we would like to understand the empirical tradeoffs involved:
  - How much higher would pollution be if fines were not state dependent (but at the same overall level)?
  - How much higher would non-state-dependent fines need to be to achieve the same level of pollution?
  - How different would outcomes be under Pigouvian fines? Fines with more/less escalation in regulatory state?

# Overview of Empirical Model

- Individual plants play against a government regulator by making investment decisions to minimize their investment and regulatory costs.
  - Plants have heterogeneous costs of investment and regulatory outcomes.
  - Violations arise exogenously and probabilistically move plants into higher regulatory states.
  - Investment only probabilistically resolves non-compliance.
- Regulator announces an enforcement policy that dictates how it will respond in each particular state:
  - Regulator dislikes a weighted average of pollution, fines, and inspections, but we don't know the weights.
  - The regulator effectively ties its own hands by pre-committing to a policy.
  - We estimate regulator CCPs as a function of the state to model plants' expectations of regulator actions.

# Estimation

- Given expectations of regulator actions, plants make optimal investment decisions given their Bellman equations.
  - Quasi-maximum likelihood estimator solved with a nested fixed point algorithm.
  - Assume plants are in a long-run steady state.
- Follow Nevo, Turner, and Williams (2016) to estimate heterogeneous costs to investment, fines, inspections, violations, and high priority violator status.
  - Involves calculating moments for a large number of potential parameter vectors (10,001) and then solving a constrained OLS model for the weights that best match the data moments to the model moments at the different parameters.
  - This creates serial correlation in plants' choices in a different way from papers we saw yesterday.

# Results

- Eliminating dynamic enforcement:
  - Raises pollution damages 164% holding fines constant.
  - Raises fines 519% holding pollution damages constant.
- Doubling fines for high priority violators decreases pollution damages 3% but increases fines 13%.
- Pigouvian fines are *much* higher than observed fines.
- Pigouvian fines scaled to yield constant pollution damages:
  - Increase fines by 392%.
  - Increase the share of plants in priority violator state by 934%.
- Overall, dynamic enforcement substantially improves outcomes if the regulator cares about minimizing a combination of pollution and enforcement actions!

# Carbon Policy, Market Power, and Leakage

- In Fowlie, Reguant, and Ryan (2016), the authors want to understand how carbon policy affects cement plant competition and “leakage” of emissions to other markets.
  - Leakage is when regulating emissions in one location leads to increased emissions elsewhere.
  - Understanding the effectiveness of policy requires understanding whether local firms exit and production moves to unregulated imports.
- Overview of model:
  - Firms choose entry and capacity in a local homogeneous good market
    - State includes current capacity and emissions rate.
  - Demand, import supply curve, and marginal costs estimated in an initial step.
- Counterfactuals:
  - Carbon cap-and-trade/tax, cap-and-trade with free incumbent allocation, border adjustment

# Estimation and Results

- The authors use a CCP estimator that follows Bajari, Benkard, and Levin (2007) and Ryan (2012).
  - Chosen policies must result in higher profits than alternative policies.
  - Value functions are approximated with cubic splines.
- Counterfactuals vary environmental policies:
  - Always assume that the implied tax is the social cost of carbon.
  - Limit counterfactuals to markets with less than 5 firms.
- Results
  - Policy can increase the exercise of market power.
  - It can also lead to substantial leakage.
  - Combined, this can mean that “efficient” policies can actually *decrease* welfare.
  - Policy can be designed to reduce these effects and yield welfare gains if carbon damages are high.

# Approximate Equilibrium

- Dynamic oligopoly is critically important in EEE:
  - Environmental policies often affect investment, technology adoption, or firm exit.
  - Yet these firms are generally earning profits in a product market, and many of these markets are imperfectly competitive.
  - Understanding the interaction between policy and imperfect competition is critical for understanding the potential impact of policy.
- Answering these policy questions requires simulating equilibrium counterfactuals.
  - In a dynamic oligopoly context, this can get very difficult.
  - Victor explicitly pointed out that the state space can explode quickly: 10 states per firm with 6 firms yields 1 million states!
  - Often we have many more than 10 states per firm!
- Approximate equilibrium methods are helpful for counterfactuals.
  - They can also make NxFP estimation computationally feasible.

# Approximate Equilibrium Approaches

I will go through three potentially useful approaches to approximate equilibrium.

1. Oblivious equilibrium:
   - Many small firms that play against a steady state market distribution of firms.
   - Players know that they'll always remain in the steady state.
2. Moment-based Markov equilibrium:
   - Players keep track of the state for a set of dominant firms and an aggregate market distribution of fringe firms.
   - Only the dominant firms can affect the market state.
3. GLZ extension to MME:
   - Players keep track of aggregate market states that affect payoffs.
   - All players understand that they can affect the market states.

You should think of these as giving you a taste of what is potentially possible.

# Oblivious Equilibrium (OE)

- Developed by Weintraub, Benkard, and Van Roy (2008)
  - Used in e.g. Brancaccio, Kalouptsidi, and Papageorgiou (2020), Bucholtz (2021).
- Basic idea:
  - Many small players make decisions given a distribution of competitors.
  - Each player therefore only needs to keep track of her state and the distribution of competitors.
    - This could be the distribution of equilibrium share of firms by cost/quality/capacity type.

# Oblivious Equilibrium Computation

- Solving equilibrium requires solving for strategies and the steady state distribution.
- For each potential coefficient vector, $\theta$:
  1. Specify a potential steady state distribution of industry outcomes.
  2. Simulate firms' optimal decisions given this steady state distribution and $\theta$.
     - This will generally involve solving Bellmans and recovering choice probabilities.
  3. Use simulated decisions to specify a new industry steady state distribution.
  4. Repeat steps 1-3 until the change in the distribution is small.
- For estimation, you may need to repeat these steps for each potential $\theta$ in your likelihood maximization.
  - However, you may be able to recover the steady state distribution from the data.
  - In this case, you can calculate the likelihood with just step 2.

# Pros and Cons of Oblivious Equilibrium

- Oblivious equilibrium has some appealing characteristics:
  - Aligns individual strategies with market equilibrium outcomes.
  - Allows the researcher to summarize actions of many small actors.
- But it also has drawbacks:
  - In its base formulation, cannot be used for estimation if industry is not in the steady state.
    - For instance, the electricity industry is transitioning between fuels, so this wouldn't work there.
    - For counterfactuals also, it cannot get at transitions to new steady states.
  - Actors cannot influence the market state, so there are many interesting questions for which this won't work.

# Moment-based Markov Equilibrium

- Developed by Ifrach and Weintraub (2017)
  - Used in e.g. Vreugdenhil (2020), Gerarden (2022), Jeon (2022).
- Basic idea:
  - Divide players into “dominant” and “fringe” participants.
  - All players keep track of dominant players’ states and the distribution of fringe players’ states.
  - Dominant players can affect the state, but fringe players cannot.
    - Both groups are aware of this.
  - Equilibrium: expected state evolutions match optimal strategies given these expectations.

# MME Computation

- For each potential $\theta$:
  1. Specify distributions of potential dominant firm and market state evolutions.
  2. Simulate firms' optimal decisions given these distributions and $\theta$.
  3. Use simulated decisions to specify new distributions.
  4. Repeat steps 1-3 until the change in distributions is small.
- Similarly to OE:
  - Solving for equilibrium at each $\theta$ may not be required for estimation.
  - Counterfactuals generally require resolving the equilibrium.

# Pros and Cons of MME

- MME has some appealing characteristics:
  - Keeps the state space (relatively) tractable.
  - Allows for more interesting forms of competition as dominant players can take strategic actions.
  - Nested fixed point estimation (though not counterfactuals) can be done with single agent dynamic solutions.
- But it also has drawbacks:
  - Market power is assumed to be limited to dominant players.
    - Fringe players cannot affect the aggregate state.
  - Choosing which players are “dominant” vs “fringe” can be arbitrary.

# Gowrisankaran, Langer, and Zhang, 2022

- In the paper I presented yesterday, we want to understand the implications of policy uncertainty for coal-fired electricity generators.
- Recall that generators compete in local (U.S. state) markets to earn profits and make technology adoption or exit decisions to comply with regulations.
  - The key issue is that the time to potential MATS enforcement, $\tau$, combined with the probability of enforcement, $P_\tau$, changes incentives to invest or exit.
- We model the dynamic oligopoly equilibrium where every generator understands that it can potentially affect the market states.
  - Market states: share of coal that has adopted abatement technology, coal capacity relative to load, and fuel price ratio.

# Equilibrium Implementation

- We model market states as evolving according to AR(1) regressions.
- For every potential value of $\theta$, we assume starting AR(1) coefficients for state variable transitions, and then simulate choices for each U.S. state, year to potential enforcement, $\tau$, and market state.
- We run 4 AR(1) regressions on the simulated data for each $\tau > 0$:
  - Coal capacity relative to load.
  - Share of coal that has adopted technology (fuel price ratio is an additional covariate):
    - If the generator has already adopted.
    - If the generator adopts.
    - If the generator continues without adopting.
  - All regressions include the lagged fuel price ratio and its interaction with the lagged outcome.
- We then re-simulate generators' choices using these regression coefficients and repeat until the change in regression coefficients is small.

# Pros and Cons of this Approach

- This approach has a few key advantages:
  - All players can to affect the market state: allows for e.g. preemption.
  - Allows for market transitions (via the fuel price ratio, in our case).
  - Flexibility in modeling market states and transitions between states.
    - For example, serially correlated unobservables could be captured with generator fixed effects in profit regressions, the average value of which is a market state.
- But also some limitations:
  - Players cannot value actions differently from different individual competitors.
  - Modeler needs to make a judgment of which factors are important.
- Overall, I think that these types of approaches will allow us to understand strategic implications of many different environmental policies (and more).

# Future Directions

What do I see as a few of the big questions in EEE that require dynamics?

- Political economy:
  - Economists have suggested many policies to improve policy efficiency, but these policies often aren't adopted? Why?
  - How do policymakers decide when to pass legislation vs. continue to argue for better legislative terms?
- Green innovation:
  - What increases/decreases innovation in "clean" technologies?
  - What affects firms' decisions to offer cleaner products? What affects consumers' willingness to adopt these products? What role does policy play?
  - What affects external financing of long-run environmental or R&D investments?

# Future Directions

- Market design
  - Can policy change risk or uncertainty in ways that are low cost to government but high value to firms investing in environmental technologies?
  - Are there ways for policy to move us to “better” equilibria? If so, what are they and how sure are we that they could work?
- Interdependencies
  - There has been a lot of work on induced technological change and peer effects, but empirical identification has generally been quite bad.
  - Theory shows that these effects can matter, but disentangling them from correlated unobservable shocks (both over time and across firms) is hard. Return to good work here is high.

Thanks!

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# Jha and Leslie, R&R at *AER*

- This paper wants to understand how natural gas power plants' ramping costs affect competition, particularly with increases in renewable generation.
- To turn a power plant on, you need to burn extra fuel and bear other startup costs.
    - Earlier work (e.g. Borenstein, Bushnell, and Wolak, 2002) ignored these costs: recovered marginal costs from fuel efficiency times fuel price.
- Startup (and ramping) costs make operation decisions dynamic.
    - When electricity demand increases, plants that were not already producing must bear startup costs while those that were producing do not.
- Solar generation reduces the number of fossil fuel generators producing at sun set.
    - The generators who are running potentially have greater market power than they would have if solar had not been generating.

# Empirical Approach

- Jha and Leslie recover fuel startup costs with a simple OLS regression of daily fuel consumption on electric generation and number of generator start-ups.
  - Estimate startup costs as excess fuel consumed times fuel price.
- Then solve the social planner's integer programming problem of which generators to operate in each 30 minute period of each day given marginal fuel costs, O&M costs and startup costs.
  - Find the prices that lead to this generation pattern.
  - Constrain all generators that produce in a day to earn revenues to cover costs (including startup)
- Compare 3 sets of outcomes:
  - Static competition (static cost minimization)
  - Dynamic competition (dynamic cost minimization)
  - Observed behavior (difference from dynamics assumed to be market power)

# Results

- The authors estimate their model on data from Western Australia.
  - Isolated market (no imports/exports) with world-leading solar penetration.
- They find that increasing solar penetration actually *increases* fossil fuel generators' profits.
  - Generators operating during the day have market power when the sun sets.
  - These profits stem from dynamic startup costs

# Pros and Cons of this Approach

Advantages of this approach:

- Doesn't assume a model of generator optimization.
- Assuming you can solve the integer programming problem, this approach is straightforward to implement.
  - Complexity of integer programming likely limiting the authors to 48 30-minute periods.

Drawbacks:

- Likely under-estimates dynamics by focusing only on startup fuel costs (no ramping, no non-fuel costs).
- By focusing on the difference between observed behavior/prices and dynamic optimal, any misspecification is attributed to market power.
- Relatedly, without estimating a model of generator behavior, the authors can't effectively conduct counterfactuals.
  -