Successes in the renewable expansion: learning from Spain and Chile

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Energy transition underway

- Need to reduce Green House Gas emissions (GHGs).
- Electricity sector ($\approx$35-40% of CO_2 emissions) has been **most active** and has the greatest potential in making the transition.
- Ambition to move towards **net-zero economies** by 2050.
- **Decarbonization strategy**:
  - Supply side: push towards renewable generation and batteries.
  - Demand side: flexible demand management, distributed generation, and dynamic pricing.

An immense challenge

- The energy transition needs to happen **very fast** at the same time that *climate impacts increase*.
- Low-income countries and households are already suffering the worst impacts of climate change.
- International cooperation has proven to be quite limited.
- Even for countries that stately strive for net zero, we are now seeing some growing tensions with the rise in energy and CO_2 prices.
- Few good news in this space except for massive cost reductions in wind and solar.

In my research

- ERC Consolidator grant to study the energy transition using high-frequency data and machine learning tools.
- A focus on how to adapt and design markets for the upcoming changes and how to actively prepare for the uneven impacts of climate change in the electricity sector.

Examples of broad topic categories

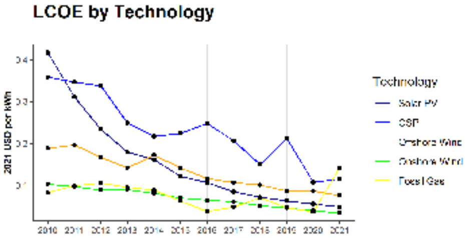
Most of the focus is on electricity markets, with work on:

- **Supply side**: impacts of renewables, entry/exit, transmission expansion, etc.
- **Demand side**: distributional impacts of transition, retail competition, consumer responses, etc.

Today, I will talk about some of the supply side papers.

Examining the renewable expansion

- Technological innovations and cost reductions in **renewable energy** are among the few good news around climate efforts.
- Initial concerns that intermittency of renewable power could hinder its economic and environmental value (Joskow, 2011; Borenstein, 2012).
- **Innovation** is important not just for the technologies in the vacuum but also for how we *integrate* them: physical infrastructure, market design, complementary tech like batteries, etc.



Innovations in renewable integration

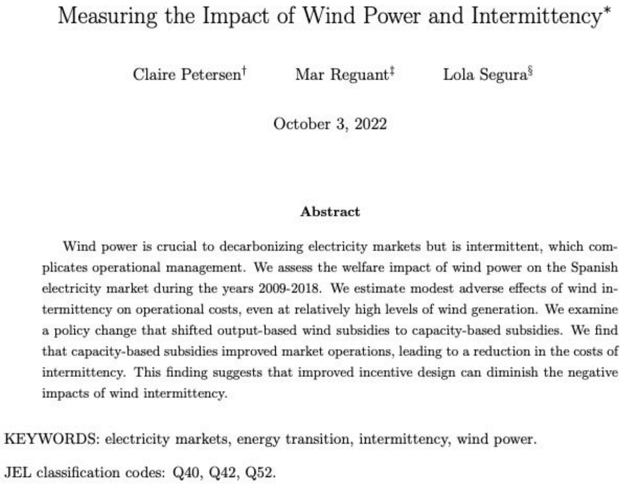
- Markets with a large share of renewable power have been **actively innovating** to better integrate renewable power.
- For example (not exhaustive):
    - Texas with improved forecasting, grid expansions (CREZ), and changes in ancillary services.
    - California with improved market coordination and design (IEM), expansion of batteries.
    - Germany with increased trading to accommodate for renewable volatility and uncertainty.
    - Spain with improved market design, frequency regulation, improved use of pumped hydro.
    - Chile with public efforts in grid expansion.

I present highlights from two current projects

Paper	Co-Authors	Data	Tools
Measuring the Impact of Wind Power and Intermittency	C. Petersen, L. Segura	Hourly electricity market operations data, Spain, 2009-2019	Regression analysis, flexible splines
The Dynamic Impact of Market Integration: Evidence from Renewable Energy Expansion in Chile	L. Gonzales, K. Ito	Hourly electricity market operations data, Chile, 2016-2020	Event study, K-mean clustering, structural modeling

Petersen, Reguant and Segura (2022)

- **Question:** What have been the impacts of wind generation in the last decade?
- **Methodology:** Regression analysis of hourly operational data (prices, congestion costs, emissions benefits, etc.).
- **Finding:** Consumers have been better off, even after accounting for the cost of the subsidies. Market design can impact these benefits.



Measuring the Impact of Wind Power and Intermittency*

Claire Petersen[†] Mar Reguant[‡] Lola Segura[§]

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Abstract

Wind power is crucial to decarbonizing electricity markets but is intermittent, which complicates operational management. We assess the welfare impact of wind power on the Spanish electricity market during the years 2009-2018. We estimate modest adverse effects of wind intermittency on operational costs, even at relatively high levels of wind generation. We examine a policy change that shifted output-based wind subsidies to capacity-based subsidies. We find that capacity-based subsidies improved market operations, leading to a reduction in the costs of intermittency. This finding suggests that improved incentive design can diminish the negative impacts of wind intermittency.

KEYWORDS: electricity markets, energy transition, intermittency, wind power.

JEL classification codes: Q40, Q42, Q52.

Data

- We get hourly data from the Spanish electricity market (2009-2018). Data from REE and OMIE.
- Data include: market prices, intermittency costs, congestion, and other reliability services, emissions data (tons/CO2), subsidies received (millions), etc.
- We **quantify the impact of wind** on these variables:
  - Benefits: emissions reductions, reduced use of fuels, price reductions for consumers.
  - Costs: increased costs of intermittency (paid by consumers and by wind farms), price reductions for consumers.

Identification strategy

- Given randomness in wind forecasts, we run a regression of the impacts of wind on these variables.
- **Spline approach** to look at the impact at different quintiles:

$$Y_t = \beta_0 + \sum_{q=1}^{5} \beta_q W_{qt} + \gamma X_t + \epsilon_t \ ,$$

  where W_{qt} are spline bins according to the quintiles of the wind variable.
- Examine *average* predicted costs as well as *marginal effects*.

Note on endogeneity

- Wind production can be endogeous due to:
    - Curtailment.
    - Strategic behavior.
- Use forecasted wind either directly or as an instrument to actual production.

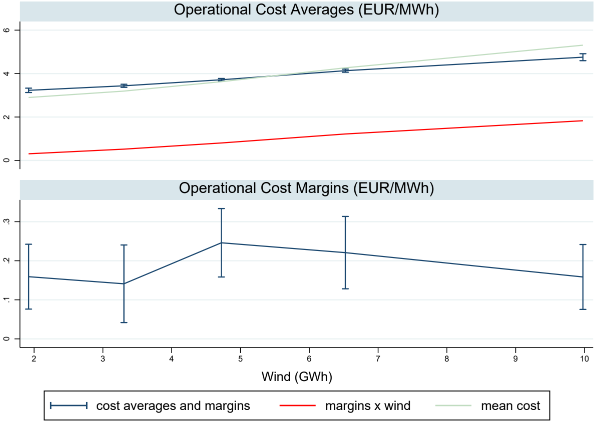
VARIABLES	(1) Wind Forecast	(2) Wind	(3) IV Forecast	(4) IV Power
Forecasted wind (GWh)	0.191			
	(0.0162)			
Final wind production (GWh)		0.152	0.182	0.188
		(0.0140)	(0.0150)	(0.0189)
Observations	83,840	83,841	83,840	81,348
R-squared	0.561	0.557	0.079	0.079

Emphasis on operational costs

- In the literature, often large emphasis on the costs of intermittency from renewable resources.
- Focus on the paper to quantify intermittency costs in the market.
- *Has wind contributed to large increases in operational costs?*
- We identify intermittency costs as the (accounting) costs of providing congestion management, reliability services, balancing, etc.

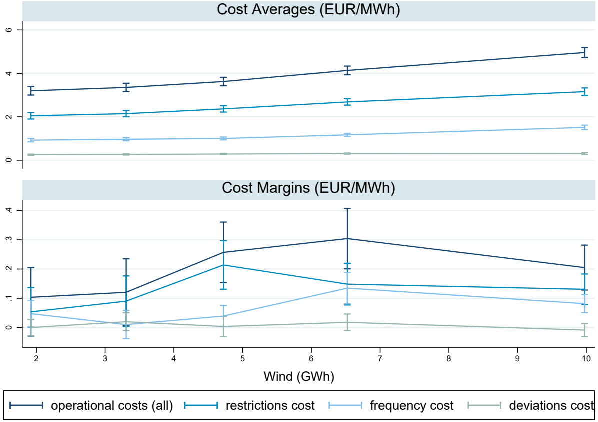
Results for operational costs

- System costs increase with wind, but not exponentially.



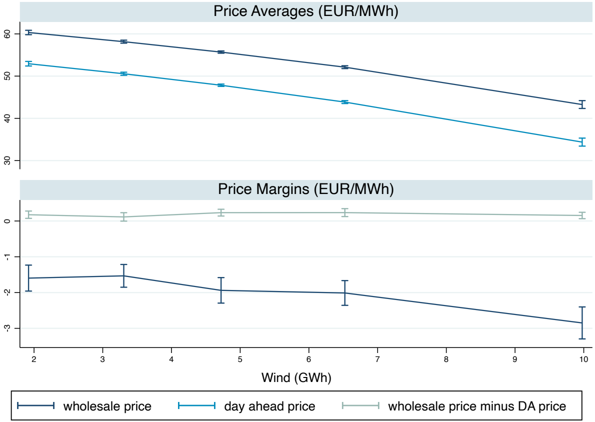
Decomposition of operational costs

- Largest impacts concentrated on congestion costs.



Results for prices

- Full price still decreasing with the presence of wind.

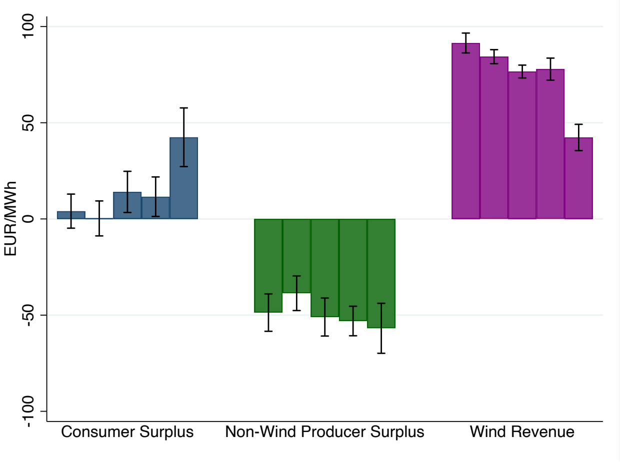


Putting all effects together for welfare

- Consumer surplus
  - Benefit: reduced price.
  - Cost: subsidy, costs of intermittency paid by consumers.
- Producer surplus
  - Benefit: subsidy, reduced fossil fuel costs.
  - Cost: reduced price, costs of intermittency paid by wind farms.
- Emissions reductions
  - Above and beyond what is already internalized by EU-ETS.
  - For alternative values of SCC.
- Cost of investment.
  - For alternative LCOE values.

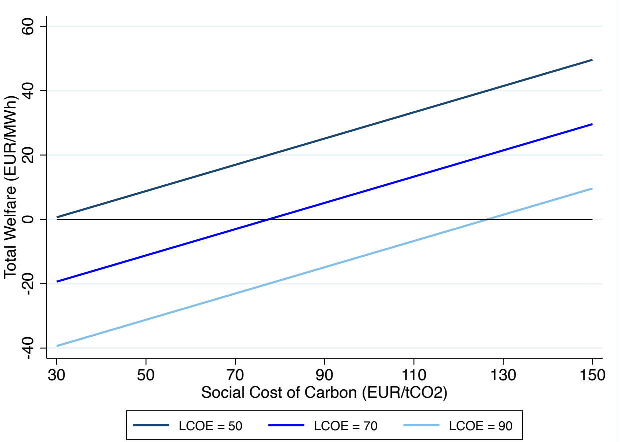
Welfare impacts by sector

- Gross rents go to consumers and wind producers, positive due to reductions in production costs.



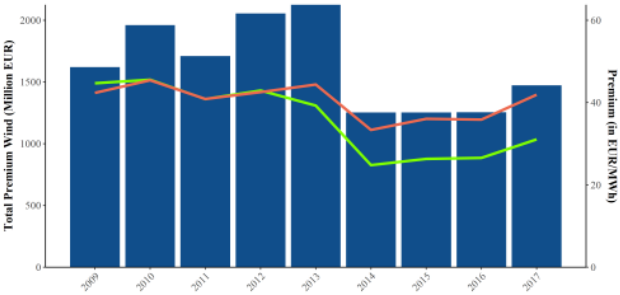
LCOE vs emissions reductions

- Net benefits from the policy for reasonable valuations of LCOEs and emissions reductions.



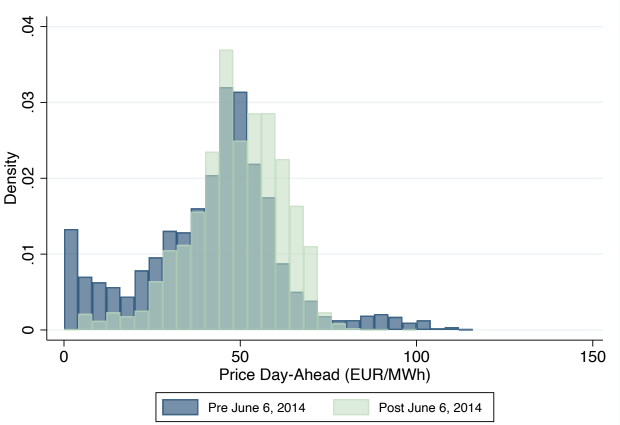
How does the impact depend on the market design?

- We examine the role of subsidy policy changes in Spain in explaining our results.
- In 2014, Spanish regulator changed subsidies:
    - From production-based to investment-based.
    - Unattractive for many installations, which opted for market compensation.



Zero prices disappeared...

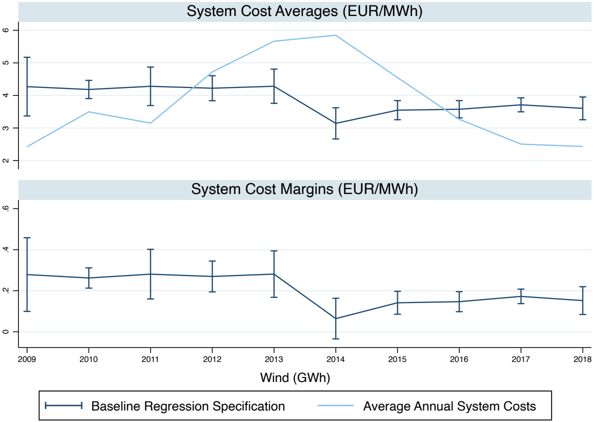
- Policy change had a first-order effect in the reduction of "zero price" events.



Data from May 2013 to May 2015

...system operational costs decreased...

- Anomalous congestion outcomes to circumvent zero prices were largely reduced.



...but consumers were worse off.

- We estimate a decreased value of wind production of 10 EUR/MWh to consumers.
- Even if subsidy payments were reduced, higher prices hurt consumers.
- The **overall sign effect** of the policy is nosily estimated due to to countervailing forces:
  - Transfer of rents between producers and consumers.
  - Reduced operational costs (+).
  - Decrease in wind production (-).

Some broader conclusions (Paper 1)

- Early adoption of wind was perceived as expensive, but gains are positive and growing (e.g., due to natural gas crisis).
- Active innovation in how wind farms operate and how the market is designed has significantly reduced renewable integration costs.
- These innovations are *hard to predict*, but we should expect some lowering of integration costs alongside the lowering of production costs.

Gonzales, Ito and Reguant (2022)

- **Question:** What are the impacts of large renewable infrastructure expansions?
- **Methodology:** Event study + structural model.
- **Finding:** Transmission expansion was a net gain to consumers.

The Dynamic Impact of Market Integration:
Evidence from Renewable Energy Expansion in Chile*

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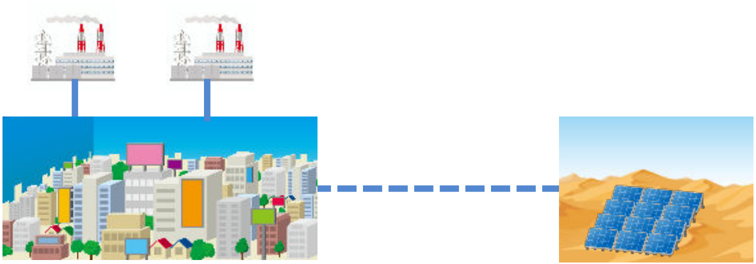
Abstract

We study the static and dynamic impacts of market integration on renewable energy expansion. Our theory highlights that statically, market integration improves allocative efficiency by gains from trade, and dynamically, it incentivizes new entry of renewable power plants. Using two recent grid expansions in the Chilean electricity market, we empirically test our theoretical predictions and show that commonly-used event study estimation underestimates the dynamic benefits if renewable investments occur in anticipation of market integration. We build a structural model of power plant entry and show how to correct for such bias. We find that market integration resulted in price convergence across regions, increases in renewable generation, and decreases in generation cost and pollution emissions. Furthermore, a substantial amount of renewable entry would not have occurred in the absence of market integration. We show that ignoring this dynamic effect would substantially understate the benefits of transmission investments.

Challenge: Existing networks were not built for renewables

- Conventional power plants can be placed near demand centers
    - Minimal transmission lines were required to connect supply and demand

- By contrast, renewables are often best generated in remote locations
    - Renewable-abundant regions are not well integrated with demand centers



Two problems arise from the lack of market integration

1. Curtailment
   - Excess renewable supply cannot be exported to demand centers
   - Renewable producers cannot sell electricity even though their MC ≈ 0
2. Depression of local prices
   - Renewables lower regional wholesale price toward 0 (b/c MC ≈ 0)
   - Without integration, profit can be low even if there is no curtailment

These two issues discourage renewable investment/entries

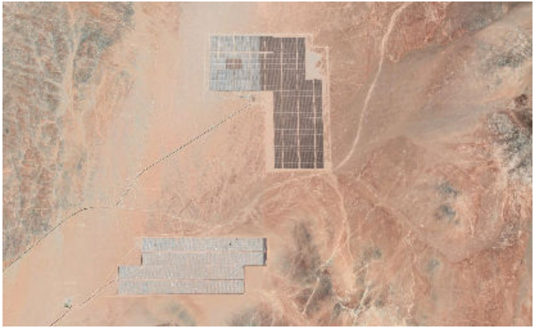
Many countries now recognize this as a first-order problem

- United States
  - Investment in transmission lines and renewable energy is a key part of the Biden Administration's infrastructure bill

    "The Bipartisan Infrastructure Deals more than $65 billion investment is the largest investment in clean energy transmission and the electric grid in American history. It upgrades our power infrastructure, including by building thousands of miles of new, resilient transmission lines to facilitate the expansion of renewable energy." (White House, 2021)

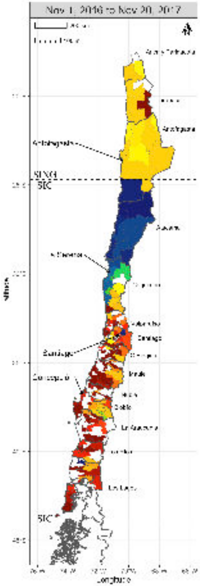
- Chile
  - Already has done such transmission expansions in 2017 and 2019

Demand center (e.g. Santiago) is distant from renewables



Lack of market integration created regional price dispersion

- This figure shows heat map of wholesale electricity prices before market integration
    - Blue: price ≈ 0
    - Red: price > 70 USD/MWh
- This motivated Chile to build new transmission lines
    - 2017: Atacama (solar)—Antofagasta (mining)
    - 2019: Atacama (solar)—Santiago (city)



We combine event study and structural modeling methodologies

- We evaluate the impacts of two events
  - November 2017: Interconnection between Antofagasta and Atacama
  - June 2019: Reinforcement between Atacama and Santiago

- We use two methodologies:
  - **Event study** to look at the effects of transmission at impact.
  - **Structural model** to quantify investment steering effects.

Data

We collected nearly all of the market data at the unit or node level:

1. Daily marginal cost at the plant-unit level:
2. Hourly demand at the node level (there are over 1000 nodes in Chile)
3. Hourly market clearing prices at the node level
4. Hourly electricity generation at the plant-unit level
5. Power plant characteristics (capacity, heat rate etc.)
6. Power plant investment data (i.e. construction cost of each plant)

Static Impacts on Generation Cost (USD/MWh)

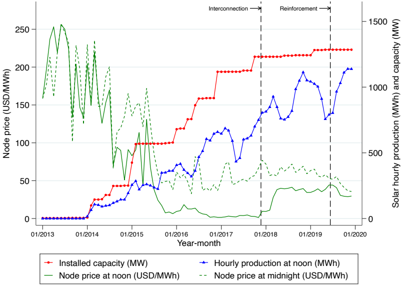
$$c_t = \alpha_1 I_t + \alpha_2 R_t + \alpha_3 c_t^* + \alpha_4 X_t + \theta_m + u_t$$

- c_t is the observed cost
- c_t^* is the nationwide merit-order cost (least-possible dispatch cost under full trade in Chile)
- $I_t = 1$ after the interconnection; $R_t = 1$ after the reinforcement
- X_t is a set of control variables; θ_t is month fixed effects
- α_1 and α_2 are the impacts of interconnection and reinforcement

	Hour 12	All hours
1(After the interconnection)	-1.72	-0.97
	(0.22)	(0.17)
1(After the reinforcement)	-1.12	-1.07
	(0.49)	(0.38)
Nationwide merit-order cost	1.02	0.99
	(0.02)	(0.02)
Coal price [USD/ton]	0.02	0.01
	(0.01)	(0.01)
Natural gas price [USD/m^3]	-4.59	0.51
	(3.63)	(2.69)
Hydro availability	-0.27	-0.43
	(0.12)	(0.11)
Scheduled demand (GWh)	0.17	0.04
	(0.10)	(0.09)
Mean of dependent variable	36.12	38.87
Sample size	1041	1041

Does this static event study analysis get the full impact?

- We develop a theory that suggests:
  - Yes if solar investment occurs simultaneously with integration
  - No if solar investment occurs in anticipation of integration
- In our case:
  - Solar investment began after the announcement of integration in 2014
  - These solar entries depressed the local price to near zero in 2015-2017



A structural model to study a dynamic effect on investment

- We divide the Chilean market into five regional markets with interconnections between regions (11 in the new version to improve fit!)

- Model solves constrained optimization to find optimal dispatch that minimizes generation cost

- Constraints:
  1. Hourly demand = (hourly supply - transmission loss)
  2. Supply function is based on plant-level hourly cost data
  3. Demand is based on node-level hourly demand data
  4. Transmission capacity between regions:
     - Actual transmission capacity in each period.
     - Counterfactual: As if Chile did not integrate markets.

The structural model solves this constrained optimization

$$\begin{aligned} \underset{q_{it} \geq 0}{\text{Min}} \quad C_t &= \sum_{i \in I} c_{it} q_{it}, \\ \text{s.t.} \quad \sum_{i \in I} q_{it} - L_t = D_t, &\quad q_{it} \leq k_i, \quad f_r \leq F_r. \end{aligned} \tag{1}$$

- Variables:
  - C_t: total system-wise generation cost at time $t \in T$
  - c_{it}: marginal cost of generation for plant $i \in I$ at time t
  - q_{it}: dispatched quantify of generation at plant i
  - L_t: Transmission loss of electricity
  - D_t: total demand
  - k_i: the plant's capacity of generation
  - f_r: inter-regional trade flow with transmission capacity F_r

Dynamic responses are solved as a zero-profit condition

$$E\left[\sum_{t\in T}\left(\frac{p_{it}(k_i)q_{it}(k_i)}{(1+r)^t}\right)\right]=\rho k_i \tag{2}$$

- NPV of profit (left hand side) = Investment cost (right hand side)
- ρ: solar investment cost per generation capacity (USD/MW)
- k_i: generation capacity (MW) for plant i
- p_{it}: market clearing price at time t
- q_{it}: dispatched quantify of generation at plant i
- r: discount rate

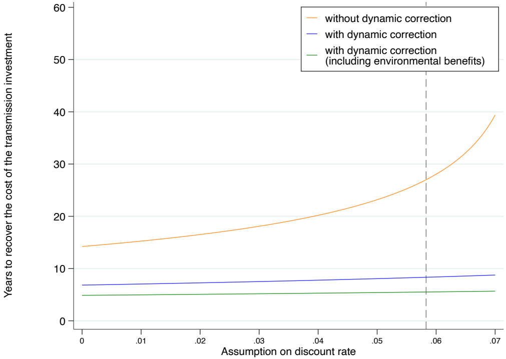
- This allows us to solve for the profitable level of entry for each scenario

The costs and benefits of the transmission investments

- Cost of the interconnection and reinforcement
    - \$860 million and \$1,000 million (Raby, 2016; Isa-Interchile, 2022)
- Benefit
    - Counterfactual simulations: “Market integration” vs. “No integration”
    - Calculate (the net present value of) the change in consumer surplus
        - Note: We consider that the fixed costs of the new entries (power plant construction cost) will be paid by cumulative producer surplus

Benefits exceed the costs roughly in 6 years

- The dashed line is 5.83% (Moore et al. 2020), which is nearly identical to the Chilean government's official discount rate 6%
- Ignoring the dynamic impact would underestimate the benefit



Some broader conclusions (Paper 2)

- Expansion of renewable power requires large infrastructure.
- This is a difficult coordination problem that often runs into jurisdictional/support problems.
- Cost allocation of transmission lines can also be difficult.
- Publicly funded projects (and even consumer-funded projects) can be cost-effective and still bring net consumer surplus.

Thank you.

Questions? Comments?

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