The Economics of the Energy Transition: Evaluating the Impact of Renewable Power

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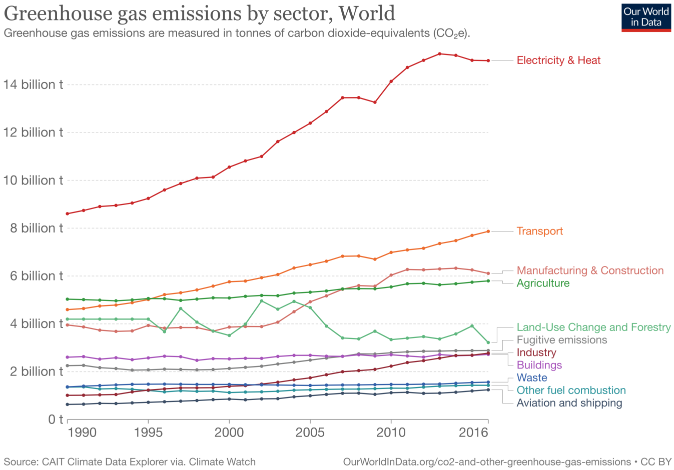
Contents

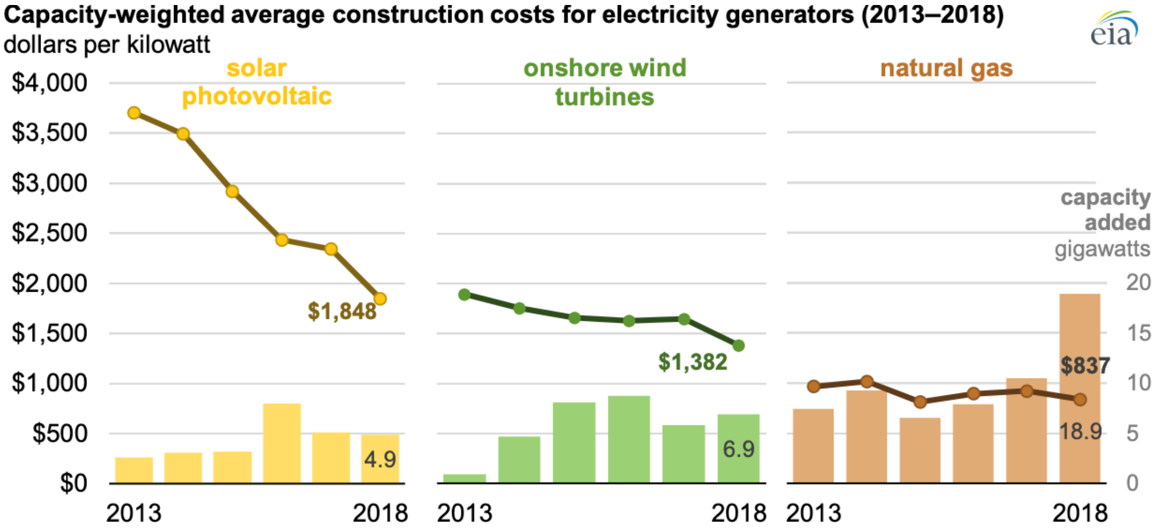
I. Introduction

Renewable expansion is key to mitigating climate change

- Electricity is a major source of GHG emissions (e.g., 25% in the US)
- Another large source is transportation, which can be electrified soon



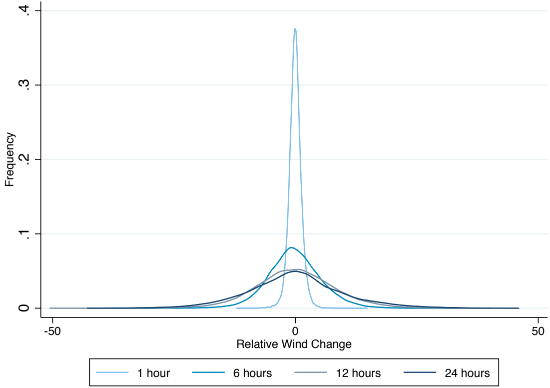
Renewables are cost effective!



Challenge 1: Intermittency

Timing

- Wind and solar power cannot be "turned on" based on demand.
- Need to adjust operations to be ready to cover when these sources are not available.
- Can increase volatility and uncertainty in the market.

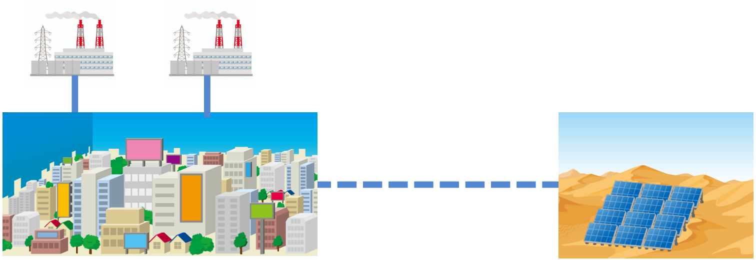


Challenge 2: Existing networks were not built for renewables

Geography

- 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



II. The cost-benefit of renewables

Renewables have become the cheapest source of energy in many countries

- Great reductions in costs, large climate benefits.
- Technological improvements that increase performance and reduce volatility.
- Very cheap, but without grid investments/batteries, it can quickly lead to saturation.
- Costs for storage and grid expansion need to be benchmarked against clear benefits of increased renewable power.

Economics can be helpful in providing a systematic cost-benefit analysis as well as in understanding how to circumvent major bottlenecks.

Costs and benefits: quantitative analysis

Costs

- Cost of panels/wind mills
- Costs to incumbents
- Intermittency
- Transmission investments

Benefits

- Price reductions
- Pollution reductions
- GHG reductions
- Resilience
- Investment spillovers

Several studies explore the benefits and costs

- Cullen (2013) and Novan (2015) measure the emissions reductions benefits from wind production.
- Bushnell and Novan (2021) measure the price impacts of solar in California.
- Abrell, Kosch, & Rausch (2019) assess impacts of wind and solar in Germany and Spain.
- Liski, M., & Vehviläinen (2020) assess impacts of wind in Nordic market.
- Gowrisankaran, Reynolds, & Samano (2016) build a structural model to analyze optimal reliability policies.
- Fell, Kaffine, and Novan (2021) look at environmental impacts of renewables with more transmission
- ...

Overall conclusion: wind and solar deployment has been a clear net benefit despite some difficulties in taking full advantage of its energy.

In my research

- ERC Consolidator grant (2021-2026) to study the energy transition.
- 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.

III. Case study from Spain: Intermittency

The Impacts of Wind Power in Spain

- **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.
- **Co-authors:** Claire Petersen and Lola Segura-Varo

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.

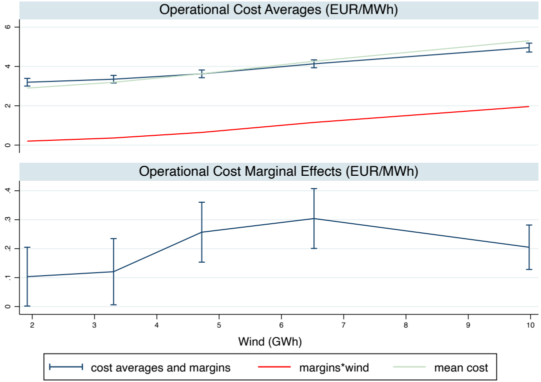
VARIABLES	(1) Wind Forecast	(2) Wind	(3) IV Forecast	(4) IV Power
Forecasted wind (GWh)	0.191			
	(0.0162)			
Final wind production (GWh)		0.152	0.182	0.188
		(0.0140)	(0.0150)	(0.0189)
Observations	83,840	83,841	83,840	81,348
R-squared	0.561	0.557	0.079	0.079

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.

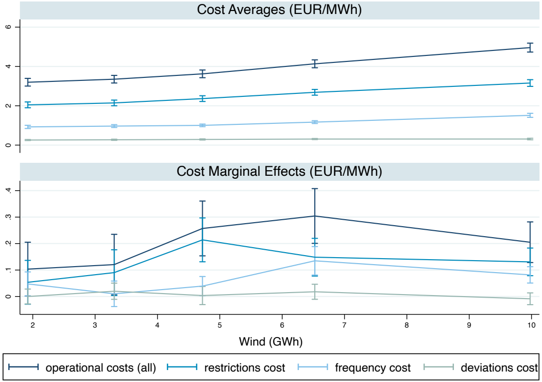
Results for operational costs

- Operational costs go up with more wind.
- However, they don't increase dramatically.
- Marginal effects don't increase.



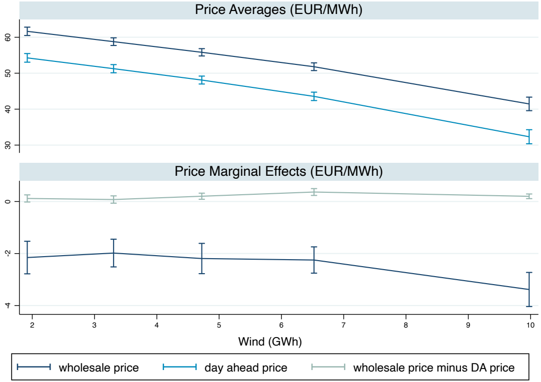
Decomposition of operational costs

- We quantify effects to different operational services.
- Congestion goes up with wind.



Results for prices

- Wind reduces prices in the market.
- Effect is one order of magnitude larger than the effect on operational costs.

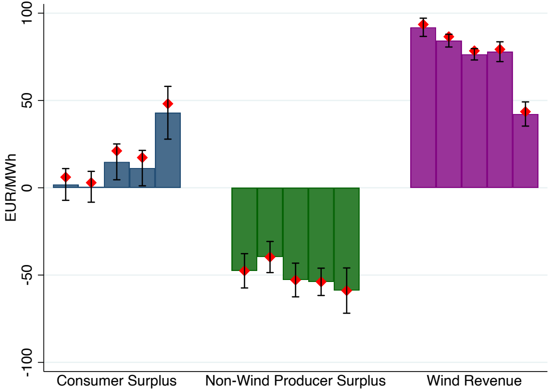


Putting all effects together for welfare

- 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 effects of wind by group

- Marginal increases in wind benefit consumers more than they hurt them, even if they have to pay subsidies.
- Biggest losers are traditional producers of electricity.
- Wind farms receive large revenues, key for welfare is how that compares with costs.
- Intermittency has modest overall effects.



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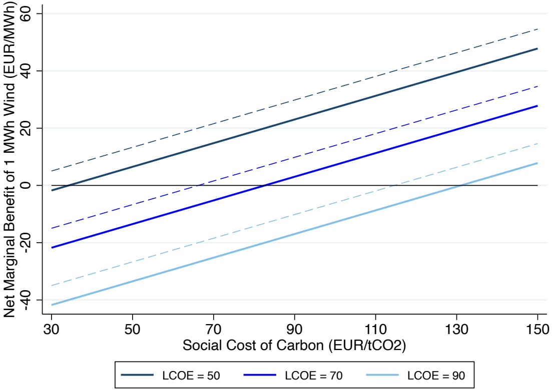
Cost-benefit for different SCC and LCOE

- Overall cost benefit sensitive to assumptions on the cost and benefits of wind power.
- LCOE = (mostly) capital costs of wind.
- SCC = social cost of carbon, global environmental benefits.
- Intermittency has some impacts, but does not affect qualitative findings.



Intermittency and the importance of market design

- There have been discussions on the value of renewables due to their intermittency and the presence of technical constraints.
- The costs of integrating wind power into the electricity market can depend on **how well-designed the market is**.
- Market design also interacts with **subsidies**.
  - E.g., negative prices in Texas or Germany, zero prices in Spain.
- Several markets have adapted their functioning to accommodate renewable power:
  - *California:* EIM market to allow for trade between regions.
  - *Germany:* half-hour markets (instead of hourly).
  - *Europe:* move towards continuous trading to have more flexibility.

Regulation change in 2014...

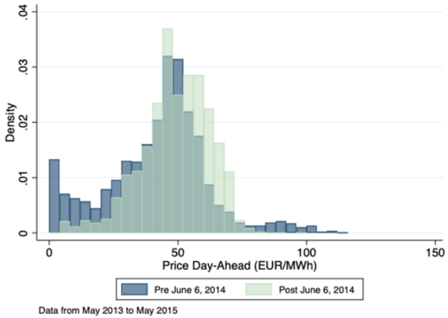
- In 2014, Spain changed how wind power plants are rewarded.
  - Moving away from output-based to capacity-based subsidy.
  - Leaving many plants without support because market price was more attractive.
  - It avoided commonly seen distortions of renewable sources bidding zero (or even negative) to obtain the subsidy.

...has substantial impact on bidding behavior...

- Prices no longer zero.
- We show that wind farms bid zero less often after policy change.
- This increases prices for consumers, increases profits for firms.
- It also avoids unnecessary reshuffling in congestion markets.

Figure 2: Price and wind outcomes before and after the 2014 policy change

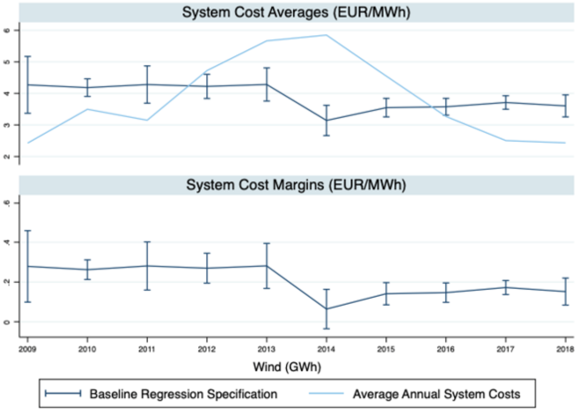
(a) Day-ahead marginal prices before and after policy change



...and leads to a reduction in system cost

- Policy change is also correlated with a reduction in system costs.
- **Disclaimer:** Not causally identified, but suggestive evidence that **market design matters**.

Figure 3: Annual Average and Marginal System Cost Effects



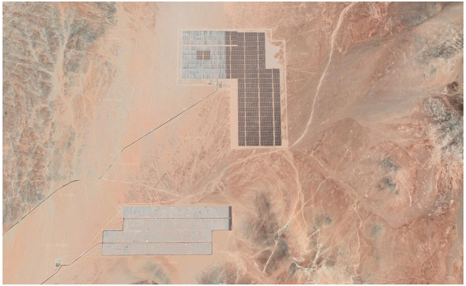
Summary

- Wind investments had a positive impact on welfare for reasonable SCC.
- On average, policy benefited both consumers and producers.
- Details on market design and compensation can substantially impact winners and losers.
- Sometimes perceived as a costly mistake, but a huge early success in climate policy has led to over 20% of generation in Spain being from the wind.
- Regulatory changes can provide useful innovations that reduce costs.

IV. Case study from Chile: Transmission

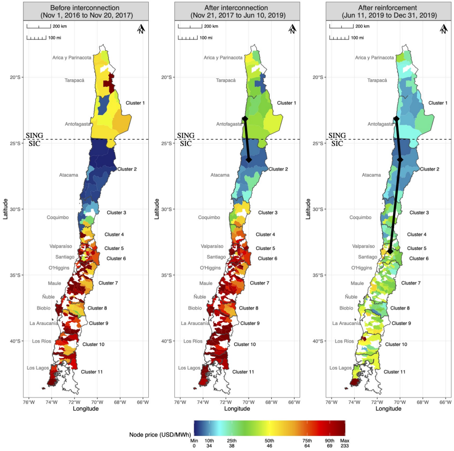
A case study from Chile

- The Chilean context provides a unique case study.
- Chile has large solar resources, but best spots disconnected from demand centers (Antofagasta and Atacama desert).
- Chile successfully connected these areas via ambitious grid projects in 2017 and 2019.
- We provide a *dynamic* quantification of the benefits.

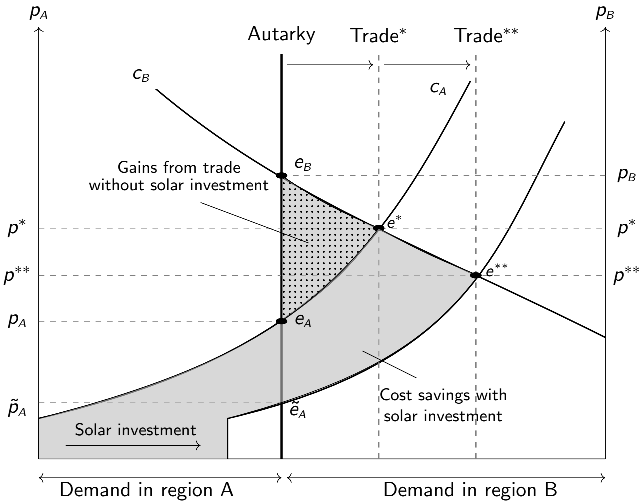


Gonzales, Ito, and Reguant (2023)

- Gonzales, Ito, and Reguant (2022) quantify the value of transmission infrastructure in Chile.
- Question: What is the cost benefit of the expansion project?
- Tools: event study + structural model of the Chilean electricity market.
- Some key findings:
  - We highlight the dynamic benefits of grid expansion, enabling increased renewable expansion.
  - The cost of transmission can be quickly recovered, even when ignoring the added climate change benefits.



Summary of the paper in a picture



Static impacts: Event study effects of the line

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

- Our method uses insights from Cicala (2022)
  - 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

Static impacts: Event study effects of the line

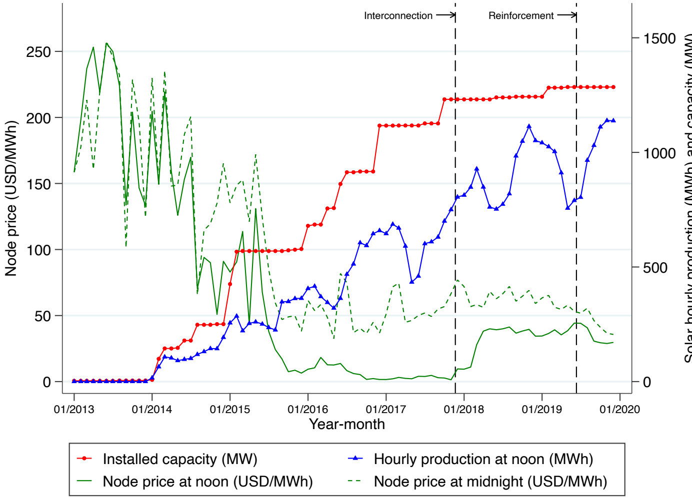
	Hour 12		All hours	
1(After the interconnection)	-2.42	(0.26)	-2.07	(0.17)
1(After the reinforcement)	-0.96	(0.58)	-0.61	(0.37)
Nationwide merit-order cost	1.12	(0.03)	1.03	(0.01)
Coal price [USD/ton]	-0.03	(0.01)	-0.01	(0.01)
Natural gas price [USD/m^3]	-10.36	(4.33)	-0.65	(3.09)
Hydro availability	0.43	(0.14)	0.00	(0.00)
Scheduled demand (GWh)	-0.51	(0.13)	-0.01	(0.00)
Sum of effects	-3.38		-2.68	
Mean of dependent variable	35.44		38.63	
Month FE	Yes		Yes	
Sample size	1033		1033	
R^2	0.94		0.97	

Does this static event study analysis get the full impact?

- Our theory suggested:
  - Yes if solar investment occurs simultaneously with integration
  - No if solar investment occurs in anticipation of integration

Solar investment occurred in anticipation of integration

- Solar investment began after the announcement of integration in 2014
- These solar entries depressed the local price to near zero in 2015-2017



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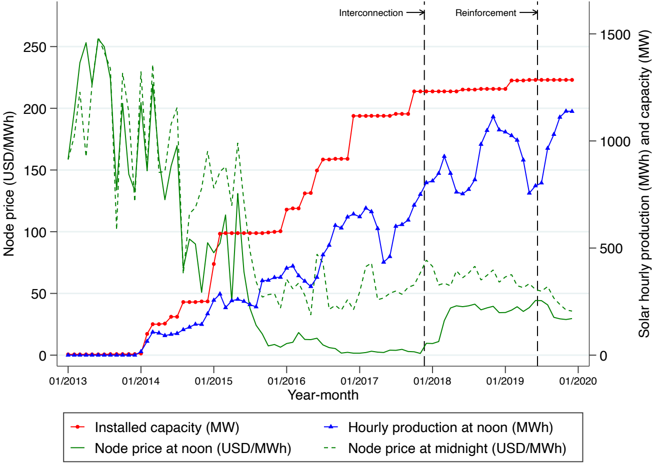
Solar investment occurred in anticipation of integration

- However, more and more new solar plants entered the market
  - Investment occurred in the anticipation of the profitable environment
  - [→] Static analysis does not capture the full impact of market integration
  - [→] We address this challenge in the next section



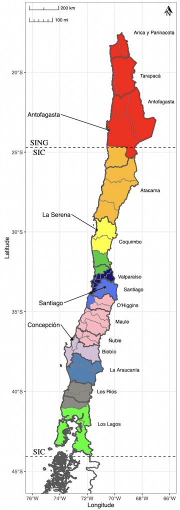
Buidling a model to get at the full effect)

- Impacts of the grid can be static and dynamic:
  - Production benefits: more solar can be sent to the demand centers, prices in solar regions go up.
  - Investment benefits: more solar power is built.

- We highlight that an event study is likely to capture only the first kind of effects (e.g., around time of expansion).
- We build a model of the Chilean electricity market to quantify the benefits of market integration including its investment effects.

A structural model to study a dynamic effect on investment

- We divide the Chilean market to five regional markets with interconnections between regions (now expanding to 11)
- 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 time period
     - Counterfactual: As if Chile did not integrate markets



The structural model solves this constrained optimization

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

- 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

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

- where:
  - 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

We calibrate the model with detailed market data

- Network model
  - k-means clustering of province prices into 5 zones, observed flows between clusters to set transmission.
- Supply curve:
  - based on observed production and/or observed reported costs.
- Demand:
  - based on nodal level data, aggregated to clusters.
- Solar potential:
  - based on days without transmission congestion.
- Cost of solar:
  - based on zero profit condition.

The cost and benefit of the transmission investments

- Cost of the interconnection and reinforcement
  - \$860 million and \$1,000 million (Raby, 2016; Isa-Interchile, 2022)
- Benefit—we focus on three benefit measures
  - Changes in consumer surplus
  - Changes in net solar revenue (= revenue − investment cost)
  - Changes in environmental externalities

Cost-benefit results

Table: Cost-Benefit Analysis of Transmission Investments

	(1)	(2)
Modelling assumptions		
Investment effect due to lack of integration	No	Yes
Benefits from market integration (million USD/year)		
Savings in consumer cost	176.3	287.6
Savings in generation cost	73.4	218.7
Savings from reduced environmental externality	-161.4	249.4
Increase in solar revenue	110.7	183.5
Costs from market integration (million USD)		
Construction cost of transmission lines	1860	1860
Cost of additional solar investment	0	2522
Years to have benefits exceed costs		
With discount rate = 0	14.8	6.1
With discount rate = 5.83%	> 25	7.2
With discount rate = 10%	> 25	8.4
Internal rate of return		
Lifespan of transmission lines = 50 years	6.95%	19.67%
Lifespan of transmission lines = 100 years	7.23%	19.67%

Assessing the cost-benefit

- With the model, we can compute the benefits of the line, with and without investment effects.
- We find that investment effects are key to justify the cost of the line.
- The line was also very attractive from a consumer welfare perspective, even at 5.83% discount rate (Chile's official rate).
- Political economy makes renewable expansion "easy" in Chile.
- How to reduce political economy challenges in other jurisdictions?

V. Conclusion

Evaluating the energy transition

- Renewable power provides a unique opportunity to decarbonize electricity generation.
- We used economics to evaluate the impacts of renewables in two countries that have experienced a tremendous transformation.
- Challenges and concerns, e.g., due to intermittency and transmission, but overall success stories.

- **More details?**
  - Measuring the Impact of Wind Power and Intermittency, with Claire Petersen and Lola Segura, *Energy Economics*.
  - The Investment Effects of Market Integration: Evidence from Renewable Energy Expansion in Chile, with Luis Gonzales and Koichiro Ito, *Econometrica*, 91(5): 1659-1693, 2023.