Challenges and Successes in the Energy Transition

EARIE 2025

Mar Reguant

August
2025

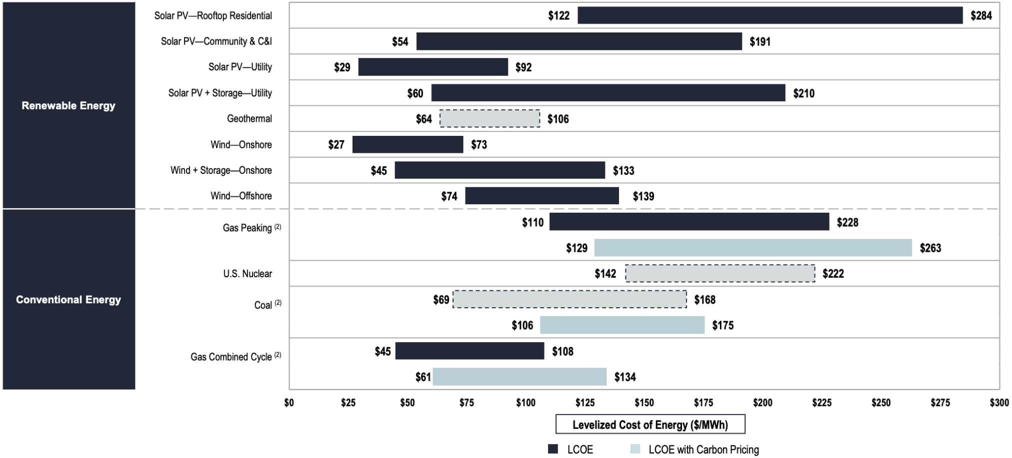
Big push in the electricity sector to decarbonize and electrify

- Need to reduce Green House Gas emissions (GHGs).
- Electricity sector (≈35-40% of CO_2 emissions) has been **most active** and has the greatest potential in making the transition.
- Ambition to move towards **carbon-free electricity** by 2050.
- **Limits to decarbonization**:
  - **Renewables' intermittency** might lead to a potential mismatch between supply and demand, increasing need for flexibility.
  - **Need to improve complementary infrastructure** in high and low voltage.
  - **Vulnerabilities** due to climate shocks.
  - **Growing pressures** due to decarbonization of other sectors (cars, heating, etc.).

Renewables are cost-effective

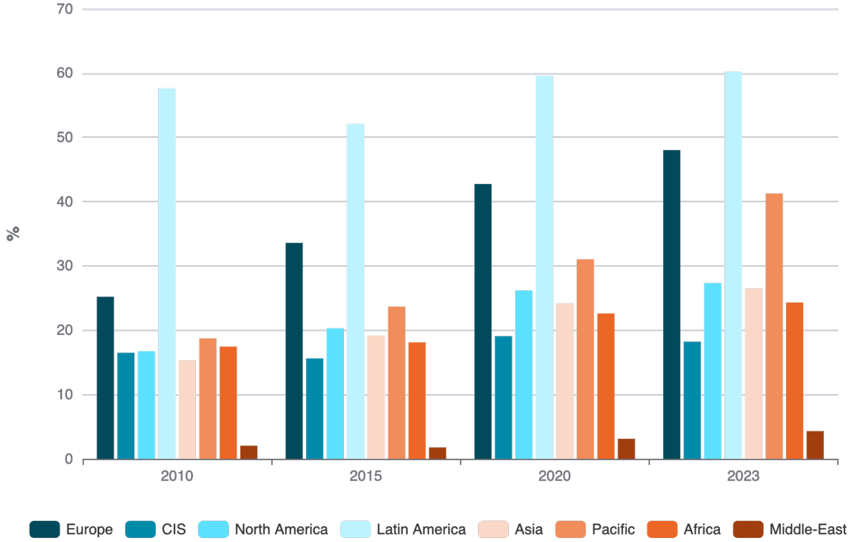
Levelized Cost of Energy Comparison—Sensitivity to Carbon Pricing

Carbon pricing is one avenue for policymakers to address carbon emissions; a carbon price range of $40 – $60/Ton[1] of carbon would increase the LCOE for certain conventional generation technologies, as indicated below



Source: *Lazard and Roland Berger estimates and publicly available information.*
Note: Unless otherwise noted, the assumptions used in this sensitivity correspond to those used in the LCOE analysis as presented on the page titled "Levelized Cost of Energy Comparison—Version 17.0".
(1) In November 2023, the U.S. Environmental Protection Agency proposed a $204/Ton social cost of carbon.
(2) The low and high ranges reflect the LCOE of selected conventional generation technologies including an illustrative carbon price of $40/Ton and $60/Ton, respectively.

With growing presence, but far from “net-zero” in most regions



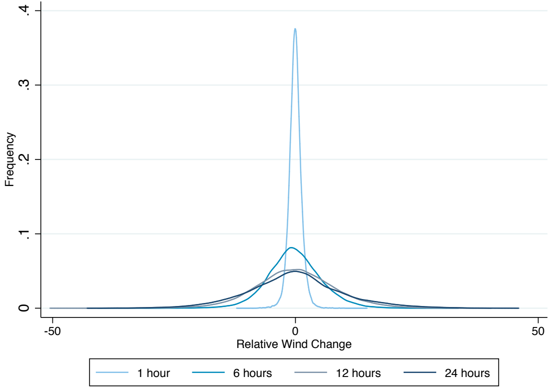
Substantial challenges remain...

- Several concerns could hinder the advancement of the energy transition:
  - Intermittency and frequency regulation
  - Transmission and reliability, infrastructure failures
  - Stranded assets and the cost of financing
  - Acceptability and equity, pricing, and job transitions
  - Fiscal pressure even within climate policies: adaptation & mitigation
  - Geopolitical reshaping of trade, e.g., with carbon pricing and new tariffs.
  - Etc.
- I will talk about two of these issues with examples from my research.

Challenge 1: Intermittency

Timing

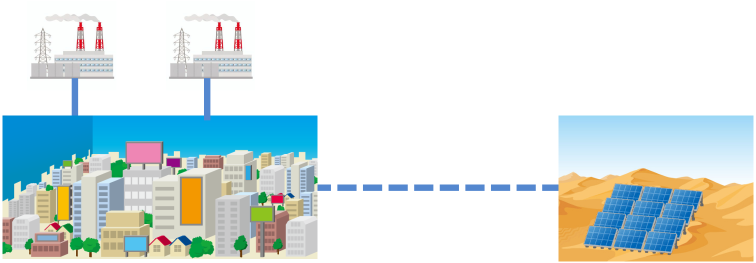
- Wind and solar power cannot be "turned on" based on demand.
- Need to adjust operations to be ready to cover when these sources are not available.
- Wind and solar also reduce the inertia of the system.
- They can increase volatility and uncertainty in the market.



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
- Large investment that requires coordination, difficulties in the political economy and regulatory process.



Contents

I. Case study from Spain: Intermittency

II. Case study from Chile: Transmission

Conclusion

I. 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?
- **Methods:** Regression analysis of hourly operational data (prices, congestion costs, emissions benefits, etc.).
- **Co-authors:** Claire Petersen and Lola Segura-Varo
- **Findings:**
  - Consumers have been better off, even after accounting for the cost of the subsidies. Market design can impact these benefits.
  - Innovation in how the market operates has contributed to increase the benefits.

Several studies explore the benefits

- 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
- ...

We focus on the **cost of intermittency** in this paper.

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.

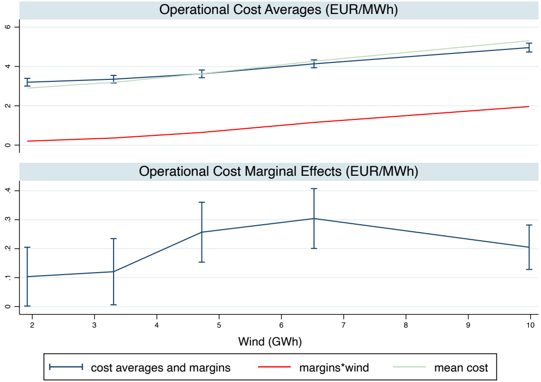
VARIABLES	(1) Wind Forecast	(2) Wind	(3) IV Forecast	(4) IV Power
Forecasted wind (GWh)	0.191			
	(0.0162)			
Final wind production (GWh)		0.152	0.182	0.188
		(0.0140)	(0.0150)	(0.0189)
Observations	83,840	83,841	83,840	81,348
R-squared	0.561	0.557	0.079	0.079

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.

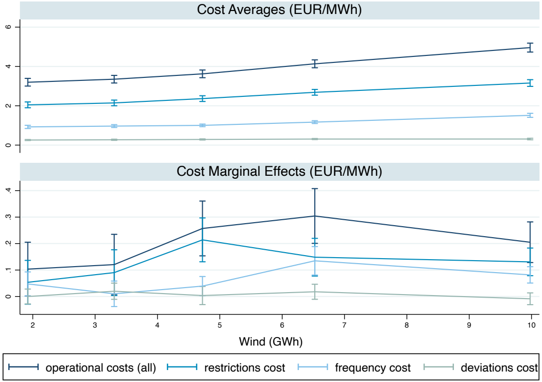
Results for operational costs

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



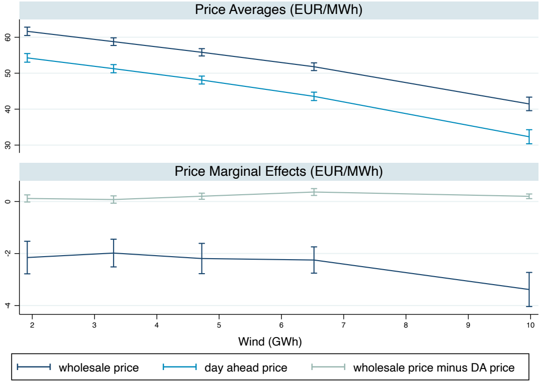
Decomposition of operational costs

- 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.

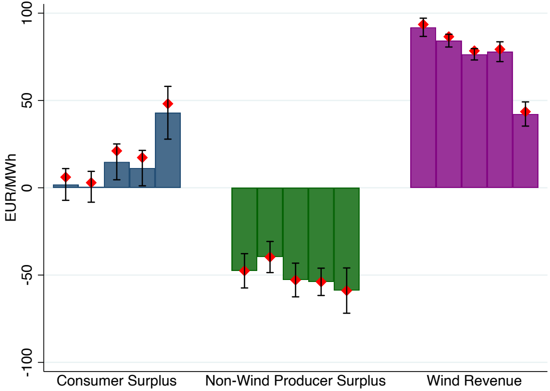


Putting all effects together for welfare

- 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.

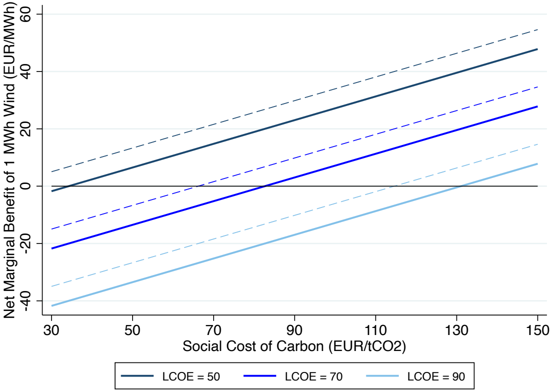
Welfare effects of wind by group

- 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.



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.

Example of a regulation change in 2014...

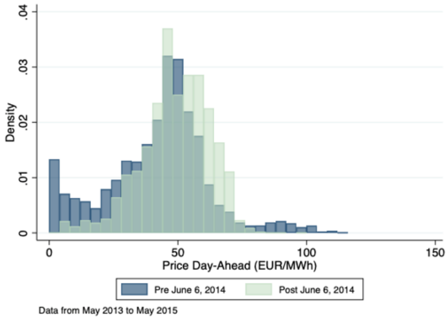
- In 2014, Spain changed how wind power plants are rewarded.
  - Moving away from output-based to capacity-based subsidy.
  - Leaving many plants without support because market price was more attractive.
  - It avoided commonly seen distortions of renewable sources bidding zero (or even negative) to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

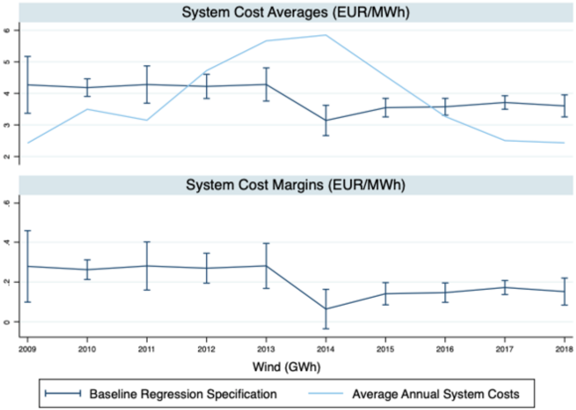
(a) Day-ahead marginal prices before and after policy change



...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**. We highlight several other improvements in the market operations during that time.

Figure 3: Annual Average and Marginal System Cost Effects

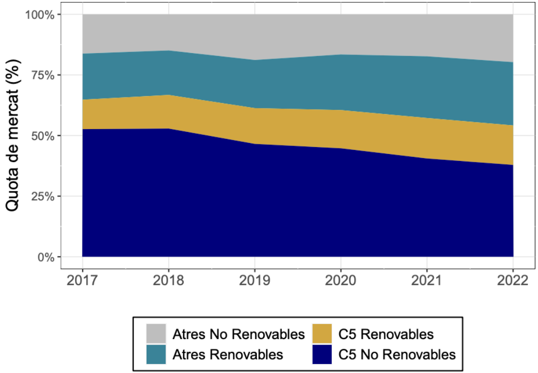


Summary

- Wind investments had a positive impact on welfare for reasonable SCC.
- On average, the policy benefited both consumers and (wind) 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.

Remaining challenges

- One result that we see in the previous paper and follow-up policy work (Enrich et al., 2024) is that renewables have also greatly increased competition in the market.
- In the previous paper, we also observed that prices for reliability products were not "out of hand."
- However, with the increasing adoption of renewables, especially solar power, Spain is now facing growing challenges in these markets.
- This is in line with other solar-heavy markets (Bushnell and Novan, 2021).

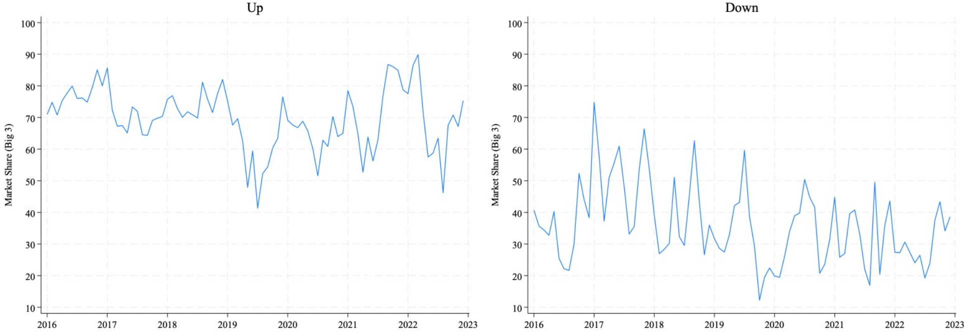


Work in progress with David Brown (U of Alberta)

- **Question:** How are reliability markets working and how do they need to be redesigned? How does the impact differ with wind and solar?
- **Methods:** Detailed analysis of bidding data at the unit level, with a combination of descriptive statistics (for now) and structural modeling (TBD).
- **Data details:**
  - Spanish data on reliability markets has an unprecedented level of detail.
  - We can examine the bidding strategies of every single firm, how they update it over time, how it interacts with the day-ahead and other energy markets, etc.

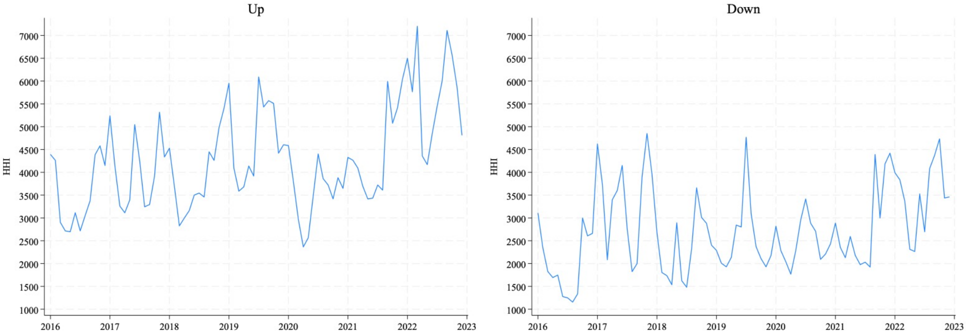
We see evidence of concern

- Back-up power is especially concentrated in the top firms, oftentimes with very few power plants offering their services in a given regulation area.
- This can make the system fragile, as observed during the blackout.



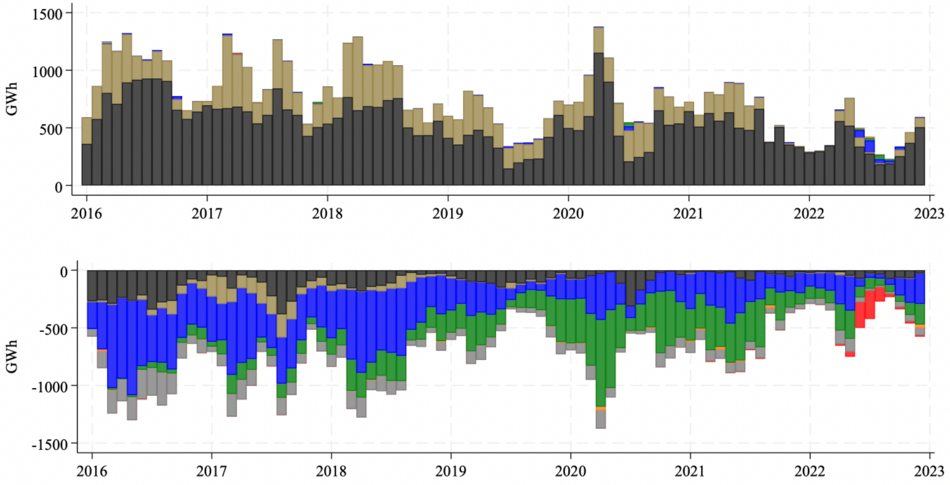
We see evidence of concern

- Standard HHI indices can be as high as 7000 in recent years, and this is without accounting for market segmentation of the regulation areas.



Competition among the Last of Them

- Competition will only increase as newer sources (e.g., batteries, hybrid renewable installations) are incorporated in the market.



The need for adaptive regulation

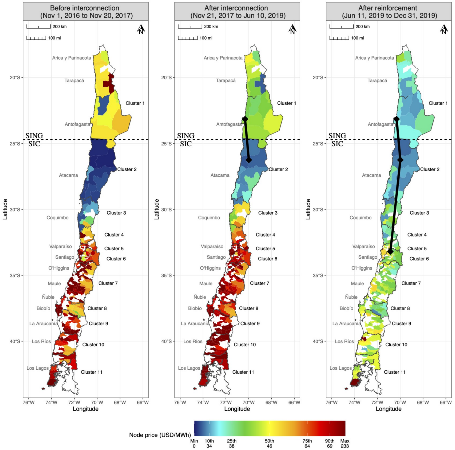
- The Spanish market is working to improve the participation of other units in these reliability markets.
- Some previous experience allowing wind farms to provide 'down' services suggests that competition can increase substantially, and some minor evidence in 2022.
- Properly pricing these services and the dispatch of resources can avoid crowding out better alternatives and should encourage the entry of batteries in the system.
- Still extremely early work: infinite data, and plenty of regulatory changes.

To be continued...

II. Case study from Chile: Transmission

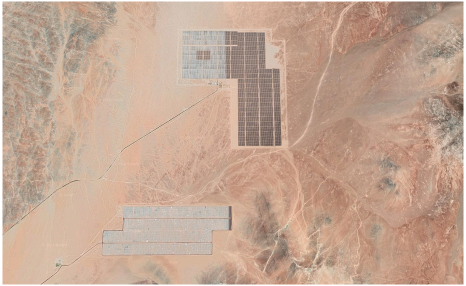
Gonzales, Ito, and Reguant (2023)

- **Question**: What is the cost-benefit of the Chilean ttransmission expansion project?
- **Methods**: event study + structural model of the Chilean electricity market.
- **Co-authors**: Luis Gonzales and Koichiro Ito
- **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.

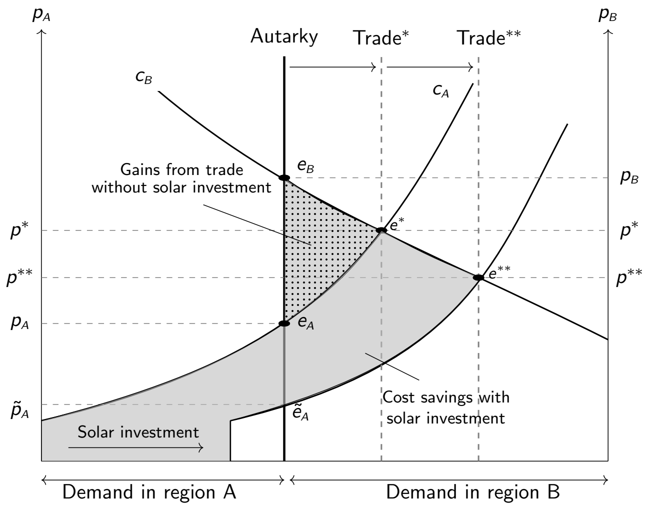


A case study from Chile

- 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.



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

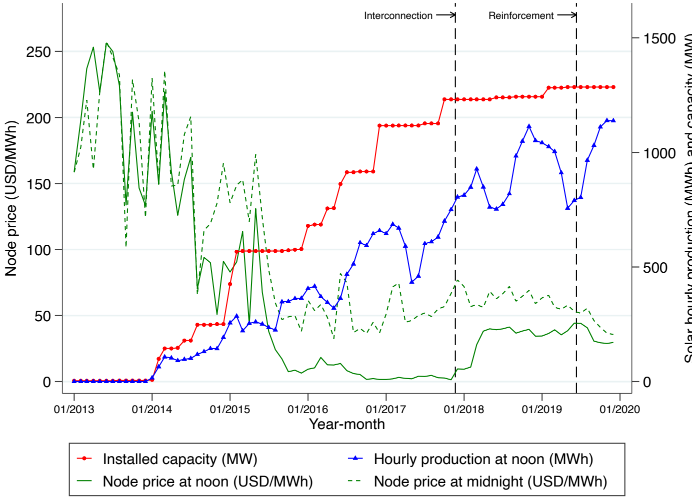
	Hour 12		All hours	
1(After the interconnection)	-2.42	(0.26)	-2.07	(0.17)
1(After the reinforcement)	-0.96	(0.58)	-0.61	(0.37)
Nationwide merit-order cost	1.12	(0.03)	1.03	(0.01)
Coal price [USD/ton]	-0.03	(0.01)	-0.01	(0.01)
Natural gas price [USD/m^3]	-10.36	(4.33)	-0.65	(3.09)
Hydro availability	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
- Plants entered “too early”.
  - [→] Static analysis does not capture the full impact of market integration
  - [→] We address this challenge in the next section



Theoretical toy model to inform the "bias"

- With anticipated investment (empirically-relevant case):
  - **Result 1** Static event study analysis understates gross cost savings
  - **Result 2** Static event study analysis understates price reductions
  - **Result 3** Static event study analysis overstates price convergence
- We use both descriptive analysis and structural estimation to:
  - Estimate the full effect of market integration
  - Quantify the impact with and with investment effects

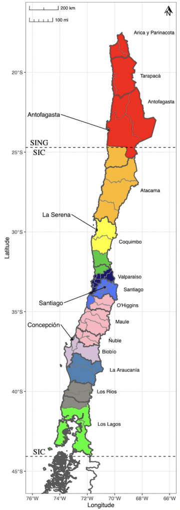
Building a model to get at the full effect

- 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



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?

In practice, political economy can indeed complicate calculation

FINANCIAL TIMES

Subscribe Sign In

US COMPANIES TECH MARKETS CLIMATE OPINION LEX WORK & CAREERS LIFE & ARTS HTSI

EU energy + Add to myFT

Sweden open to power cable project if Germany reforms, minister says

Swedish energy minister Ebba Busch prepared to move on Hansa PowerBridge project if Berlin overhauls electricity market

But, she added, “the Swedish government would be prepared to move” on the project if Germany split its internal electricity market into bidding zones that would increase the efficiency of its networks and lower prices.

Such reforms would prevent Germany from attracting as much of Sweden’s cheaper electricity, generated largely by hydropower, and avoid costs being pushed up for Swedish consumers. Electricity flows on the networks to wherever the highest price demand is.

ELSEVIER

Energy Policy
Volume 187, April 2024, 114053

What we talk about when we talk about electricity: A thematic analysis of recent political debates on Swedish electricity supply

eley Share Cite

)16/j.enpol.2024.114053 Get rights and content

ommons license Open access

HOME SHOWS NEWSFEED LIVE EN

FRANCE AFRICA MIDDLE EAST AMERICAS EUROPE ASIA-PACIFIC

HOME › LIVE NEWS

Sweden sees red over Germany's energy policy

Stockholm (AFP) – **As one of Europe's biggest suppliers of electricity, Sweden is seeing red over Germany's energy policy, which it says ends up punishing Swedish consumers.**

Issued on: 20/12/2024 - 06:31 | 3 min

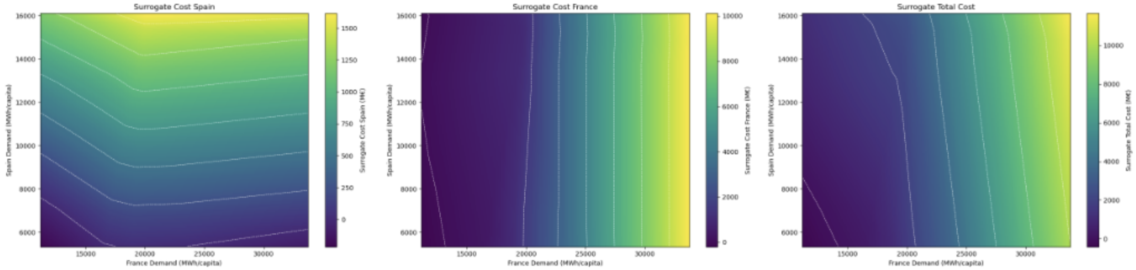
TODAY'S TOP ST

Early work in progress with David Andrés-Cerezo (UAB) and Juan Mercatante (PSE)

- **Question:** How do political interests affect the viability and shape of the network? What is the feasible set and how does it depend on the cost allocation?
- **Methods:** Detailed electricity model of the European network combined with stylized macro models of state members.
- **Computational details:**
  - Use machine learning methods to create a low-dimensional model that accurately reflects the impact of transmission investment on prices and power plant investment.
  - Embed the model into a higher-level macroeconomic model with labor, capital, and electricity as main inputs.

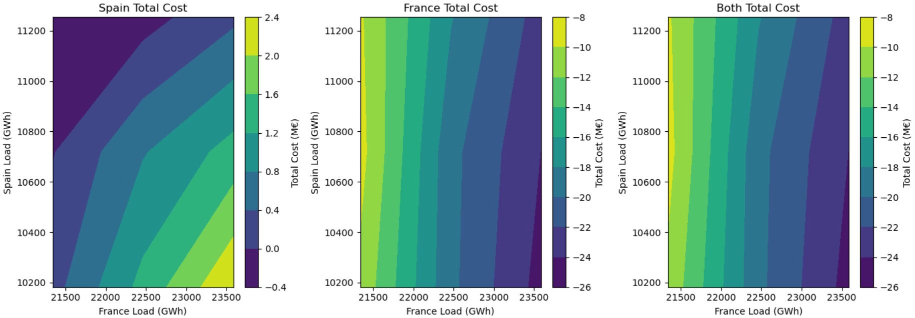
Stylized example with France and Spain

- We solve for the optimal hourly allocation and long-term investment for a given level of aggregate French and Spanish demand (for now, subject to assumptions on hourly behavior by different consumers).
- This approximated surface provides the aggregate optimal costs and the costs to each country, with relationships that can be non-linear.



Stylized example with France and Spain – buidling a line

- We can analyze the benefit of building a larger interconnection between the two.
- Spain wins or loses, but in a minor fashion. France benefits more. Other countries are also affected due to network externalities!
- This contrasts with earlier quantifications of the benefits of the line.
- In addition, it is yet shy of quantifying downstream demand effects (e.g., industrial demand).



Stylized example with France and Spain – buidling a line

- We can analyze the benefit of building a larger interconnection between the two.
- Spain wins or loses, but in a minor fashion. France benefits more. Other countries are also affected due to network externalities!
- This contrasts with earlier quantifications of the benefits of the line.
- In addition, it is yet shy of quantifying downstream demand effects (e.g., industrial demand).

TSOs' estimate

The savings in fuel costs enabled by the interconnector, coined as socio-economic welfare (SEW) in the TYNDP, represent the main part of these benefits. The TYNDP published in 2016 provides the gross estimates for these savings, which have been split between countries by the TSOs in their investment request. The figures are as follows:

Spot year	2020 EP	2030 V1	2030 V2	2030 V3	2030 V4
SEW Europe (M€/yr)	200	120	150	120	240
SEW France (M€/yr)	51	37	19	35	89
SEW Spain (M€/yr)	110	97	162	70	170

Stylized example with France and Spain – buidling a line

- We can analyze the benefit of building a larger interconnection between the two.
- Spain wins or loses, but in a minor fashion. France benefits more. Other countries are also affected due to network externalities!
- This contrasts with earlier quantifications of the benefits of the line.
- In addition, it is yet shy of quantifying downstream demand effects (e.g., industrial demand).

The project was estimated at €1,750m in 2017, half of which would be financed by each partner, with potential cost increases financed by the Spanish transmission system operator (TSO) REE (62.5%) and its French counterpart RTE (37.5%). However, due to unfavourable market context and surging component prices (cables and conversion substations), the estimated total cost has soared to €2,850m, with a risk envelope of €250m. Partners have decided to invest €1,195m each in the project; additional costs between €2,390m and €2,700m will be supported by REE (62.5%) and RTE (37.5%) and extra costs above €2,700m will be financed on a 50:50 basis. Despite rising costs, the project is still considered as beneficial for the two countries and for Europe and it should receive a €578m support from the Connecting Europe Facility (CEF), of which €350m will be granted to RTE.

The need for incorporating industrial policy in the political economy

- Cost allocation is stylized at best, and a source of active discussion.
- The benefits from the transmission line are also a moving target, as new renewable projects are adopted and latent demand shifts (e.g., cooling/heating, artificial intelligence), creating potential commitment problems given the long.
- Need to bring in detailed network analysis with more aggregate macroeconomic forces.

To be continued...

Conclusion

Evaluating the energy transition

- The energy transition provides a unique opportunity to decarbonize electricity generation.
- I evaluated the impacts and challenges of the transition using a diverse set of tools.
- Challenges and concerns remain, lots of areas for economic research.

- **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.
  - Still no working papers for the work in progress...!