Reptes i èxits en la transició renovable

Dilluns de Ciència.
La transició energètica: reptes científics i oportunitats per a la innovació.

Mar Reguant

October
2024

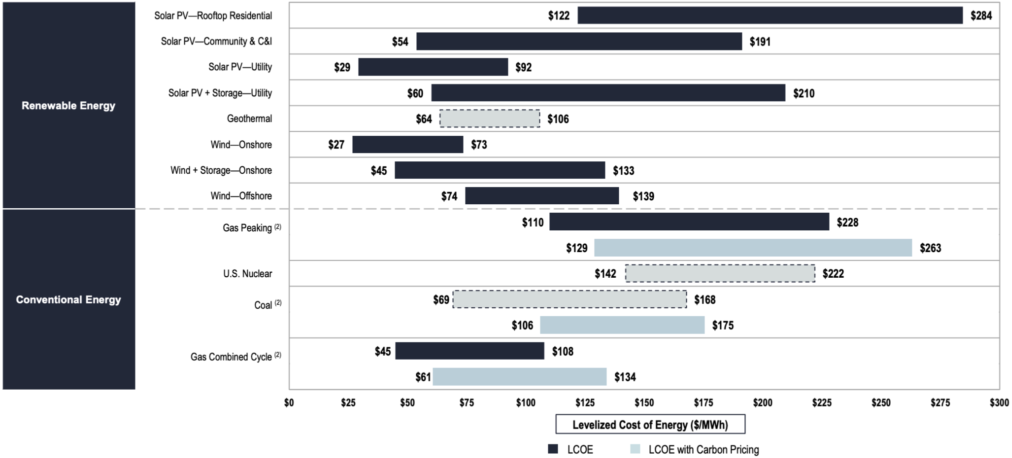
Gran impuls en el sector elèctric per descarbonitzar i electrificar

- Necessitat de reduir les emissions de gasos amb efecte d'hivernacle (GEH).
- El sector elèctric ($\approx$35-40% de les emissions de CO_2) ha estat el **més actiu** i té el major potencial per fer la transició.
- Ambició d'avançar cap a l'**electricitat lliure de carboni** per al 2035-40 a moltes regions.
- **Límits a la descarbonització**:
  - La **intermitència de les renovables** pot conduir a un possible desajustament entre l'oferta i la demanda, augmentant la necessitat de flexibilitat.
  - **Necessitat de millorar la infraestructura complementària** en alta i baixa tensió.
  - **Vulnerabilitats** a causa dels impactes climàtics.
  - **Creixents pressions** degudes a la descarbonització d'altres sectors (vehicles, calefacció, etc.).

Les renovables ja son efectives a nivell de cost

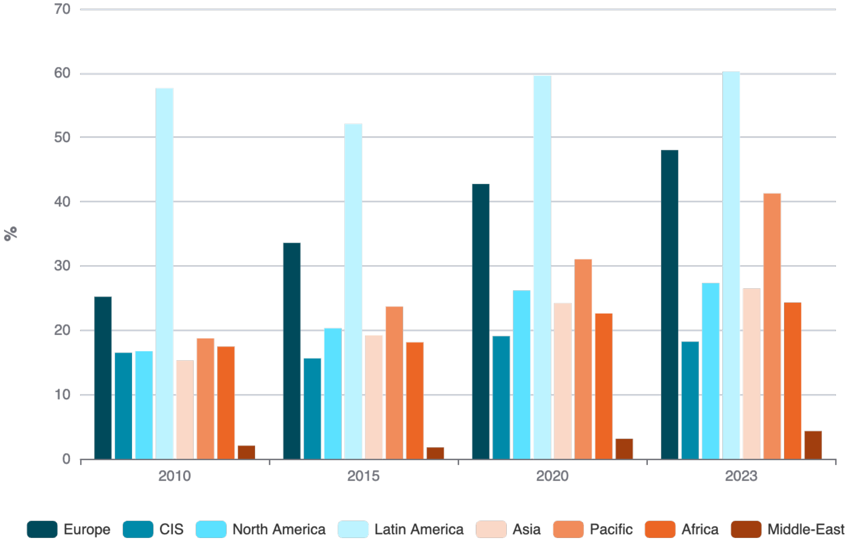
Levelized Cost of Energy Comparison—Sensitivity to Carbon Pricing

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.

Amb creixent presència, però lluny de "net-zero"



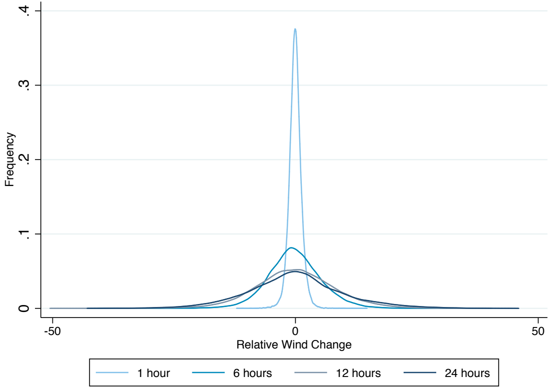
Reptes substancials continuen existint...

- Diverses preocupacions podrien frenar l'avanç de la transició energètica:
  - Intermitència i regulació de la freqüència
  - Transmissió i fiabilitat
  - Actius immobilitzats i el cost del finançament
  - Acceptabilitat i equitat, preus i transicions laborals
  - Pressió fiscal fins i tot dins de les polítiques climàtiques: adaptació & mitigació
  - Reorganització geopolítica del comerç, per exemple, amb la fixació del preu del carboni i nous aranzels.
  - Etc.
- Parlaré d'algunes d'aquestes qüestions amb exemples de la meva recerca.

Repte 1: Intermitència

Timing

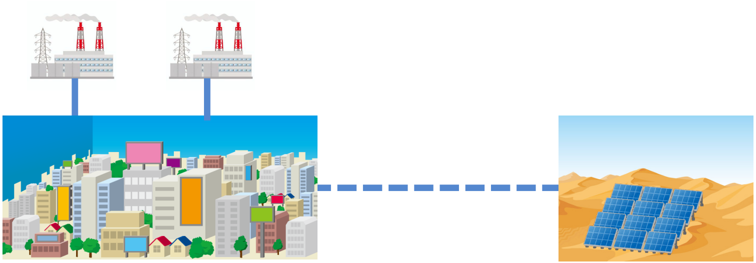
- L'energia eòlica i solar no es poden "activar" segons la demanda.
- Cal ajustar les operacions per estar preparats quan aquestes fonts no estiguin disponibles.
- L'energia eòlica i solar també redueixen la inèrcia del sistema.
- Poden augmentar la volatilitat i la incertesa en el mercat.
- Molt progrés en aquest camp.



Repte 2: La xarxa no es va construir per les renovables

Geografia

- Les centrals elèctriques convencionals es poden situar prop dels centres de demanda
  - Es necessiten poques línies de transmissió per connectar l'oferta i la demanda
- En canvi, les energies renovables sovint es generen millor en llocs remots
  - Les regions amb abundància de renovables no estan ben integrades amb els centres de demanda
- Gran inversió que requereix coordinació, amb dificultats en l'economia política i el procés regulador.



Repte 3: Els actius obsolets encallen la transició

Incentius

- Els costos de capital de les renovables són més elevats, encareix proces.
- Sense una fixació adequada del preu del carboni, el gas natural és massa barat (encara més als Estats Units).
- Els actius obsolets de carbó continuen sent utilitzats i construïts malgrat el seu avantatge comparatiu limitat.
- Els incentius dels incumbents per mantenir l'status quo (també en motor de combustió!).
- Les decisions actuals tenen conseqüències a molt llarg termini.

Union of Concerned Scientists
Science for a healthy planet and safer world

[BLOG] UNION OF CONCERNED SCIENTISTS

Coal Is No Longer a Baseload Resource, So Why Run Plants All Year?

JOSEPH DANIEL, SENIOR ENERGY ANALYST | JANUARY 15, 2020, 12:12 PM EDT

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I. Case study from Spain: Intermittency

Els impactes del vent a Espanya

- **Pregunta:** Quins han estat els impactes de la generació eòlica en l'última dècada?
- **Mètodes:** Anàlisi de regressió de les dades operatives horàries (preus, costos de congestió, beneficis d'emissions, etc.).
- **Coautores:** Claire Petersen i Lola Segura-Varo
- **Conclusions:**
  - Els consumidors han sortit beneficiats, fins i tot tenint en compte el cost de les subvencions. El disseny del mercat pot afectar aquests beneficis.
  - La innovació en el funcionament del mercat ha contribuït a augmentar els beneficis.

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.

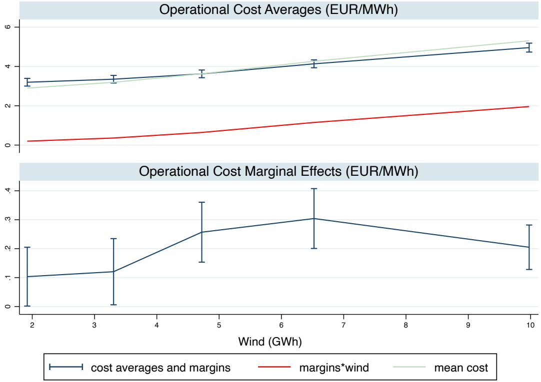
VARIABLES	(1) Wind Forecast	(2) Wind	(3) IV Forecast	(4) IV Power
Forecasted wind (GWh)	0.191			
	(0.0162)			
Final wind production (GWh)		0.152	0.182	0.188
		(0.0140)	(0.0150)	(0.0189)
Observations	83,840	83,841	83,840	81,348
R-squared	0.561	0.557	0.079	0.079

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.

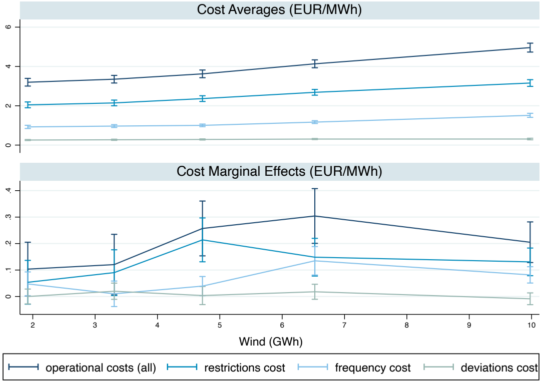
Results for operational costs

- 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.



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...

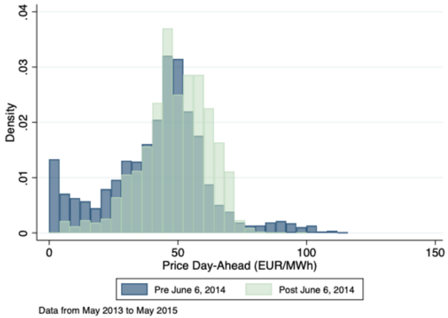
- In 2014, Spain changed how wind power plants are rewarded.
  - Moving away from output-based to capacity-based subsidy.
  - Leaving many plants without support because market price was more attractive.
  - It avoided commonly seen distortions of renewable sources bidding zero (or even negative) to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

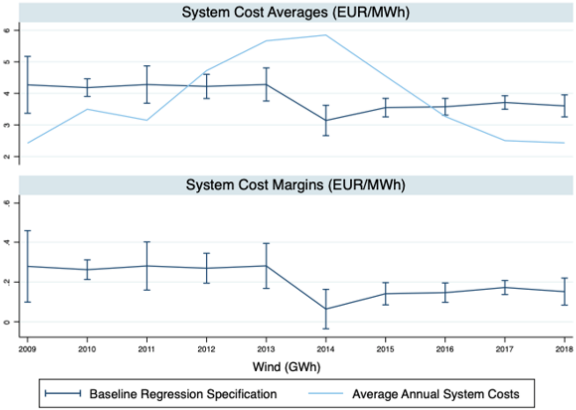
(a) Day-ahead marginal prices before and after policy change



...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



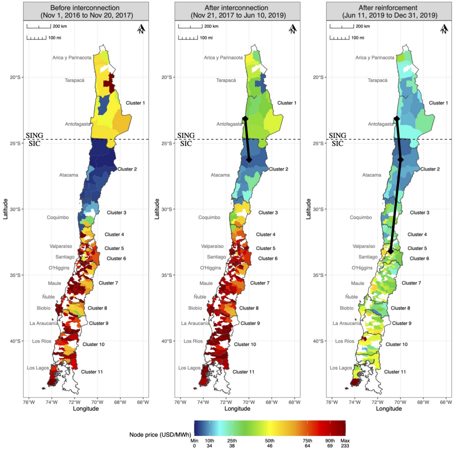
Resum

- Les inversions en energia eòlica van tenir un impacte positiu en el benestar per un cost social del carboni raonable.
- De mitjana, la política va beneficiar tant consumidors com productors.
- Els detalls sobre el disseny del mercat i la compensació poden afectar substancialment els guanyadors i perdedors.
- Sovint es percep com un error costós, però un gran èxit inicial en les polítiques climàtiques ha fet que més del 20% de la generació a Espanya provinguin de l'energia eòlica.
- Els canvis regulatoris poden proporcionar innovacions útils que redueixen costos.

II. Case study from Chile: Transmission

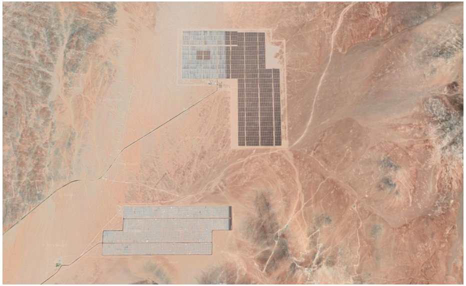
Gonzales, Ito, and Reguant (2023)

- **Pregunta**: Quin és el cost-benefici del projecte d'expansió de la transmissió a Xile?
- **Mètodes**: estudi d'esdeveniments + model estructural del mercat elèctric xilè.
- **Coautors**: Luis Gonzales i Koichiro Ito
- **Conclusions**:
  - Destaquem els beneficis dinàmics de l'expansió de la xarxa, que permeten augmentar l'expansió de les renovables.
  - El cost de la transmissió es pot recuperar ràpidament, fins i tot ignorant els beneficis afegits pel canvi climàtic.

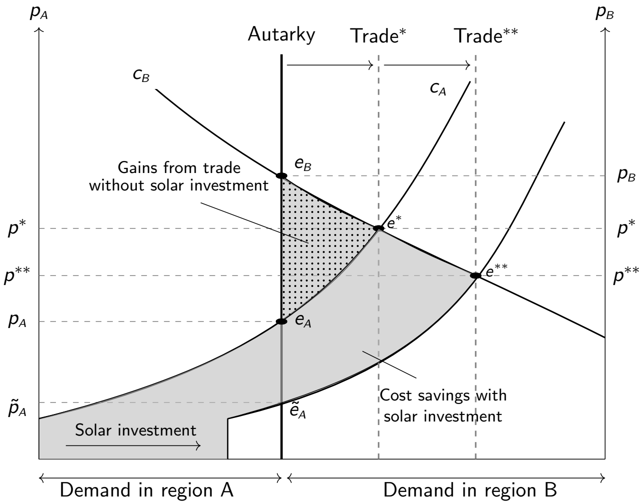


A case study from Chile

- 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

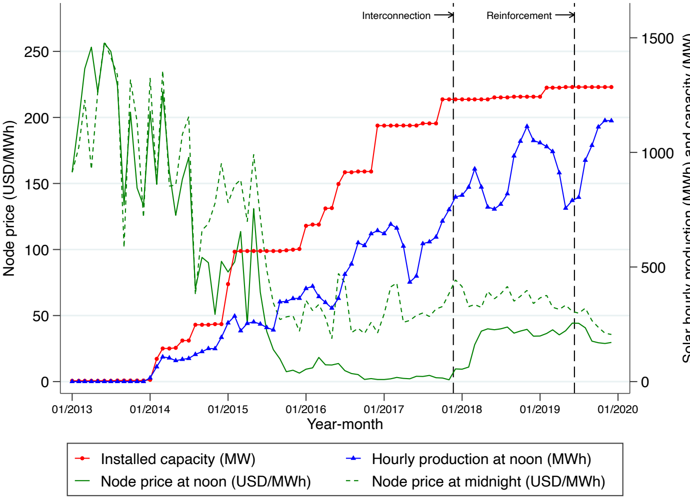
	Hour 12		All hours	
1(After the interconnection)	-2.42	(0.26)	-2.07	(0.17)
1(After the reinforcement)	-0.96	(0.58)	-0.61	(0.37)
Nationwide merit-order cost	1.12	(0.03)	1.03	(0.01)
Coal price [USD/ton]	-0.03	(0.01)	-0.01	(0.01)
Natural gas price [USD/m^3]	-10.36	(4.33)	-0.65	(3.09)
Hydro availability	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



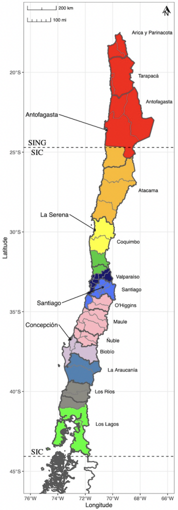
Buidling a model to get at the full effect

- 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



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%

Resum

- Amb el model, podem calcular els beneficis de la línia, amb i sense els efectes de la inversió.
- Hem trobat que els efectes de la inversió són claus per justificar el cost de la línia.
- La línia també era molt atractiva des de la perspectiva del benestar dels consumidors, fins i tot amb una taxa de descompte del 5,83% (la taxa oficial de Xile).
- L'economia política fa que l'expansió de les renovables sigui "fàcil" a Xile.
- Com podem reduir els desafiaments de l'economia política en altres jurisdiccions?

III. Case study from the US: Stranded assets

Gowrisankaran, Langer, and Reguant (2023)

- **Pregunta**: Quin és l'impacte de l'estructura reguladora en el retard de la sortida dels actius immobilitzats (actius de carbó)?
- **Mètodes**: evidència descriptiva + model estructural de regulació.
- **Coautors**: Gautam Gowrisankaran i Ashley Langer.
- **Conclusions**:
  - Destaquem que hi ha incentius per utilitzar el capital existent fins i tot si el seu cost marginal no el fa rendible.
  - Ens centrem en la transició dels EUA de carbó a gas, però també és rellevant per a la fase de gas a renovables.

Retirement of Coal Capacity by Regulatory Status in the US

- Coal exited more quickly in restructured states than in regulated ones.

Source: Authors' calculations from EIA data.

Overview of Model

- We model the regulator as having two instruments to create appropriate incentives:
  1. Offered maximum rate of return declines in utility's total variable costs, TVC.
  2. Extent to which coal enters the rate base depends on it being used and useful.
- Utility optimizes against the regulatory structure:
  - Long run: chooses coal retirement and combined-cycle natural gas investment.
  - Each hour: chooses generation mix and imports to meet load.
- Utility faces two conflicting incentives:
  1. Invests in and operates low-cost technologies to increase its rate of return.
  2. May use expensive coal generators to ensure that they are used and useful.

Empirical Approach

- Our model relies on both regulatory and cost parameters, including:
  - How much high *TVC* decreases the allowable rate of return.
  - How much usage increases coal's contribution to the rate base.
  - Operations and maintenance, ramping, and investment/retirement costs.
- Estimate regulatory and operations parameters with a nested fixed-point indirect inference approach that seeks to match important data correlations.
  - Find parameters that match key correlations in simulated model to data.
- Estimate investment/retirement costs with a GMM nested fixed-point approach.
  - Follow Gowrisankaran and Schmidt-Dengler (2024) algorithm that facilitates computation of models with many choices.

The Energy Transition Helps Identify the Model

- Consider a utility in 2006 with mostly coal capacity, but facing low-cost CCNG.
- Utility faces conflicting incentives:
  - If it invests in and uses CCNG, total variable costs fall and hence profits rise.
  - However, this reduces the usage rate of coal capacity.
  - Makes it harder to justify coal maintenance or upgrade expenditures as prudent.
- This tension will potentially lead the utility to keep and over-use legacy coal capacity.

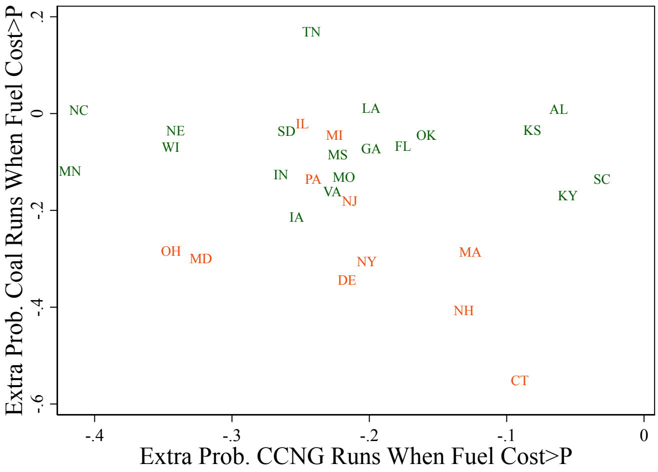
- Contrast this with a utility with higher CCNG capacity before the energy transition.
  - Relative investment in and usage of CCNG identifies regulatory parameters.

Empirical Support for Our Regulatory Model

We investigate correlations in the data that underlie our model:

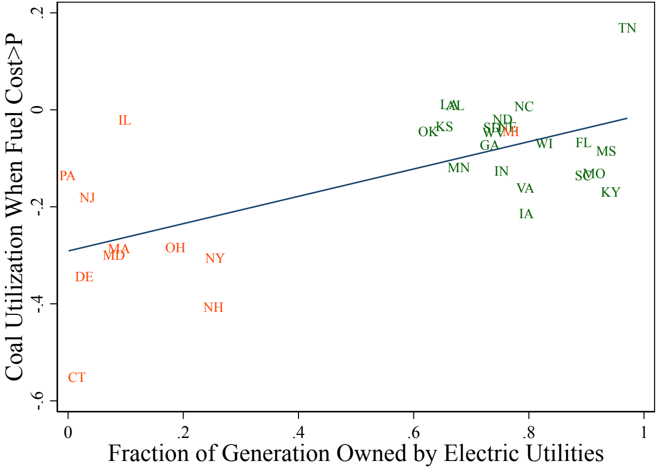
1. Relationship between observed rates of return and total variable costs.
2. Propensity for coal generators in regulated markets to run "out of dispatch order" relative to restructured markets.

Out-of-Dispatch Order Generation Varies Across States



- Most restructured states behave differently than regulated with coal but not CCNG.

Out-of-Dispatch-Order Generation vs. Utility Ownership Share



- All regulated states have high utility ownership.
- Coal's responsiveness to low wholesale prices correlates strongly with utility ownership share.

Overview of Structural Estimation

1. Estimate import supply curves following Bushnell, Mansur, and Saravia (2008).
    - Allow intercept and slope to depend on natural gas fuel price.
2. Estimate most structural parameters from utilities' hourly generation decisions by fuel/technology type.
    - O&M and ramping cost parameters.
    - Response of maximum rate of return to total variable costs.
    - Parameters governing how much coal capacity contributes to effective capital.
3. Estimate investment/retirement costs from dynamic decisions.
    - Take as an input the annual profits in each state.
    - Estimate the operations model and simulate profits across a grid of time-varying states.

Coefficient Estimates for Operations Model

Parameter	Notation	Estimate	Std. Error
Penalty for High TVC_t	γ	0.429	(0.08)
Rate Base per MW of Effective Capital (Millions $)	α	0.221	(0.06)
Coal Capacity Contribution to Effective Capital	α^{COAL}	1.117	(0.51)
Coal Usage Logit Base	μ_1	-0.589	(0.11)
Coal Usage Logit Slope	μ_2	5.641	(0.87)
NGT Contribution to Effective Capital	α^{NGT}	2.134	(1.00)
Ramping Cost for Coal (100$ / MW)	ρ^{COAL}	0.578	(0.11)
Ramping Cost for CCNG (100$ / MW)	ρ^{CCNG}	0.219	(0.31)
O&M Cost for Coal ($ / MWh)	om^{COAL}	16.350	(3.92)
O&M Cost for CCNG ($ / MWh)	om^{CCNG}	2.594	(0.10)
O&M Cost for NGT ($ / MWh)	om^{NGT}	19.767	(14.40)

Coefficient Estimates for Investment/Retirement Decisions

Parameter	Notation	Value	Std. Dev.
Fixed cost of coal retirement × 1e2	δ_0^{COAL}	-0.446	(9.79)
Linear coal cost per MW	δ_1^{COAL}	3.196	(0.44)
Quadratic coal cost per MW / 1e3	δ_2^{COAL}	0.117	(0.02)
Coal shock standard deviation per MW	σ^{COAL}	-0.430	(0.02)
Fixed cost of CCNG investment × 1e2	δ_0^{CCNG}	-0.509	(0.01)
Linear CCNG cost per MW	δ_1^{CCNG}	6.487	(0.08)
Quadratic CCNG cost per MW / 1e3	δ_2^{CCNG}	0.270	(0.05)
CCNG shock standard deviation per MW	σ^{CCNG}	-1.671	(0.06)

Note: All values in millions of 2006 dollars.

Findings

- Current regulatory structure creates unintended incentives to use more coal:
  - Cost minimizer virtually eliminates coal capacity in the 30 years after natural gas prices fell, while social planner essentially stops *using* coal immediately.
  - Current RoR regulation retires only 45% of coal capacity over this horizon.
  - Marginal adjustments to RoR regulation don't approach cost minimization.
  - RoR with CO_2 tax has 90% short-run pass through, but similar long-run effect.
- Broader takeaways:
  - Over-investment in CCNG may affect the transition to renewables above and beyond short-run marginal incentives.

Resum

- L'estructura regulatòria als EEUU allarga la vida útil de les centrals de carbó.
- Sovint aquestes estructures interactuen amb altres interessos, com els llocs de treball (Aspuru, 2024).
- Les regulacions actuals estan marcant la trajectiòria d'inversions de gas, que elevarà el problema dels actius obsolets en un futur.

Conclusions

Evaluant la transició energètica

- La transició energètica ofereix una oportunitat única per descarbonitzar la generació elèctrica.
- He avaluat els impactes i els reptes de la transició utilitzant un conjunt divers d'eines.
- Encara queden reptes i preocupacions, moltes àrees per a la recerca econòmica.

- **Més detalls?**
  - 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.
  - Energy Transitions in Regulated Markets, with Gautam Gowrisankaran and Ashley Langer, revise & resubmit at *AER*.