The Investment Effects of Market Integration:

Evidence from Renewable Energy Expansion in Chile

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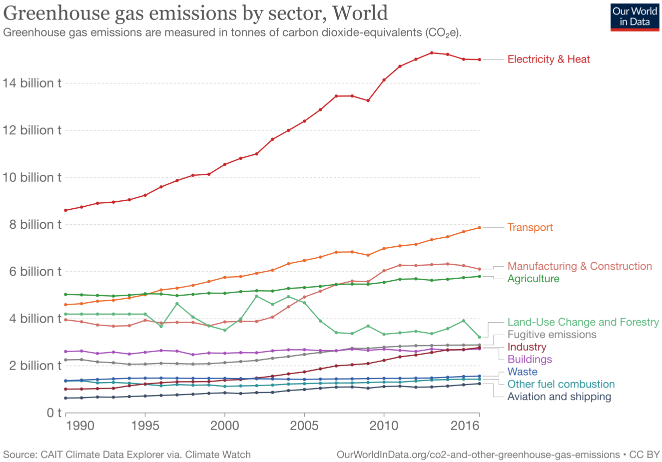
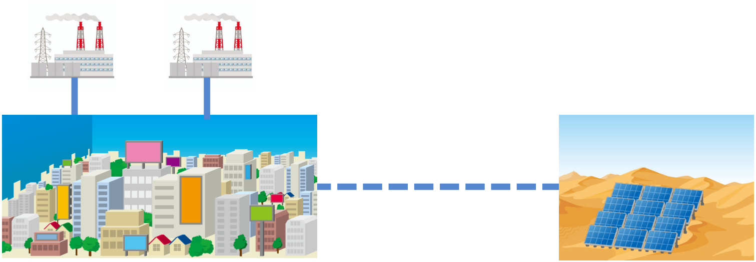
Renewable expansion is key to mitigating climate change

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



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

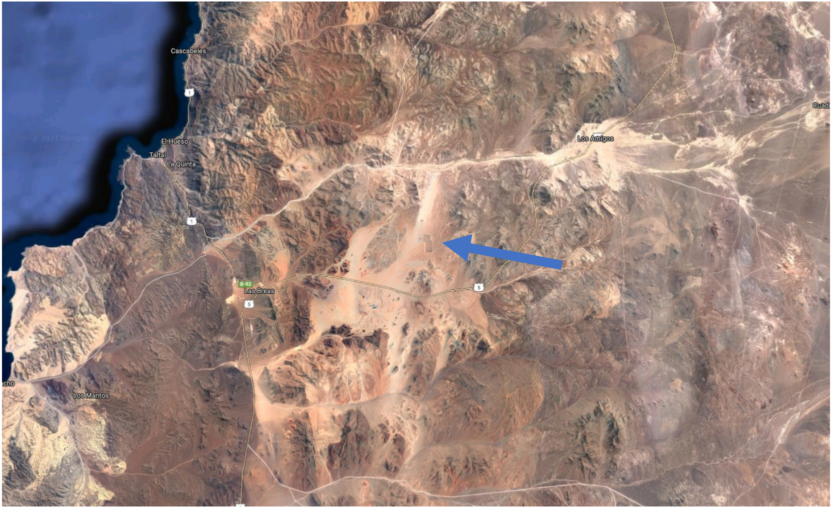
    "The Bipartisan Infrastructure Deal's more than $65 billion investment is the largest investment in clean energy transmission and the electric grid in American history. It upgrades our power infrastructure, including by building thousands of miles of new, resilient transmission lines to facilitate the 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

Atacama (1500 km from Santiago) is suitable for solar PV

An example of large-scale solar PV in Atacama



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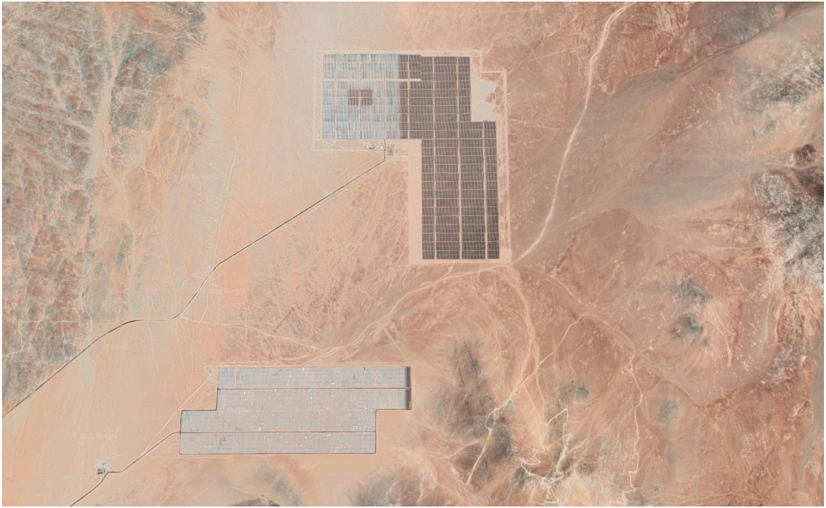
An example of large-scale solar PV in Atacama

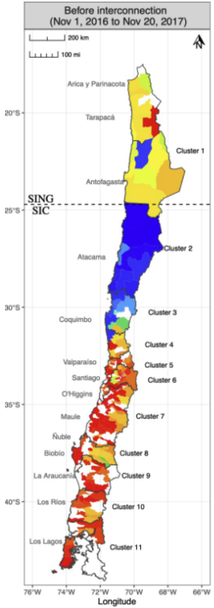


Atacama (1500 km from Santiago) is suitable for solar PV

An example of large-scale solar PV in Atacama

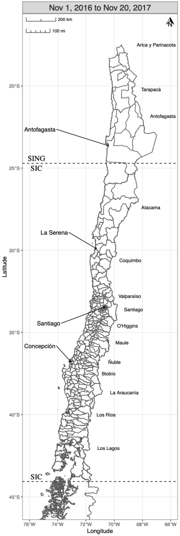
Lack of market integration created regional price dispersion

- This figure shows heat map of wholesale electricity prices <u>before</u> 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 exploit grid expansions in Chile to conduct our study

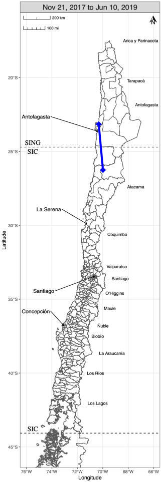
Before November 2017



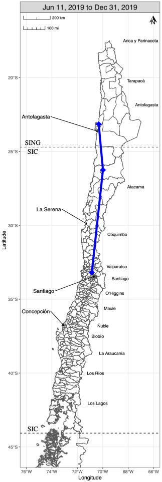
- Until 2017, there was no interconnection between SIC and SING

We exploit grid expansions in Chile to conduct our study

Interconnection (Nov. 2017)



Reinforcement (June 2019)



- In 2017, SING and SIC were integrated (via Atacama-Antofagasta line)
- In 2019, a reinforcement line was built (Atacama-Santiago line)

Road map of the talk

1. Theory
   - Characterize static and dynamic impacts of market integration
   - Highlight that a standard event study may not capture a full effect
2. Background and Data
   - Micro data on hourly market outcomes, marginal cost etc.
3. Descriptive Analysis
   - Use a standard event study analysis to estimate static effects
4. A Structural Model of Market Integration
   - Build a structural model of solar entries to estimate dynamic effects
   - Estimate the impact of market integration with & w/o investment effects
5. Cost-Benefit Analysis
   - Benefits exceed the costs of the transmission investments in 7-11 years

Related literature

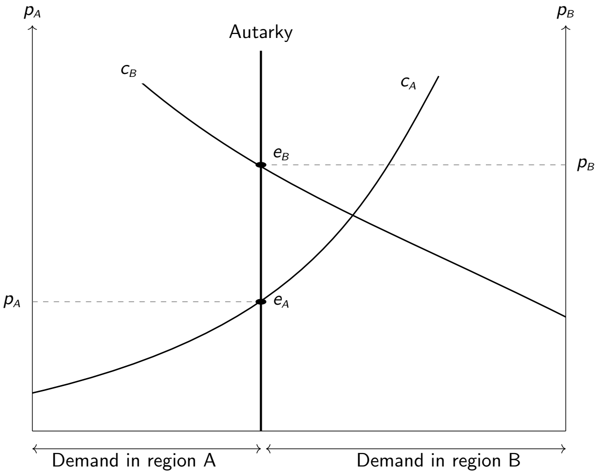
1. Economic theory of electricity transmission
   - Bushnell (1999), Joskow and Tirole (2000,2005), Borenstein, Bushnell and Stoft, (2000)
2. Efficiency gains from market-based dispatch and enhanced transmission in electricity markets
   - Mansur and White (2012), Cicala (2022), Wolak (2015), Ryan (2021)
3. Environmental impacts of transmission expansion
   - Fell, Kaffine, and Novan (2021)

Theoretical Framework

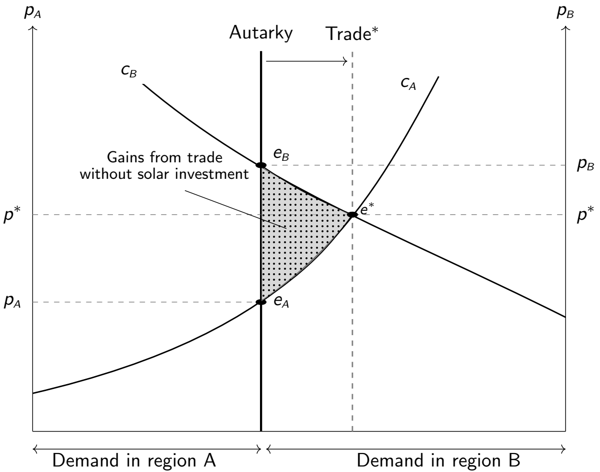
Our theory highlights two key points

1. Market integration could induce a dynamic effect on investment
   - A classical "gains from trade" abstracts from this dynamic effect
2. Event-study (before-after) analysis may not capture a full impact
   - Tempting to look at market outcomes before and after integration
   - This approach may capture a partial effect of market integration

Consider two regions, North and South

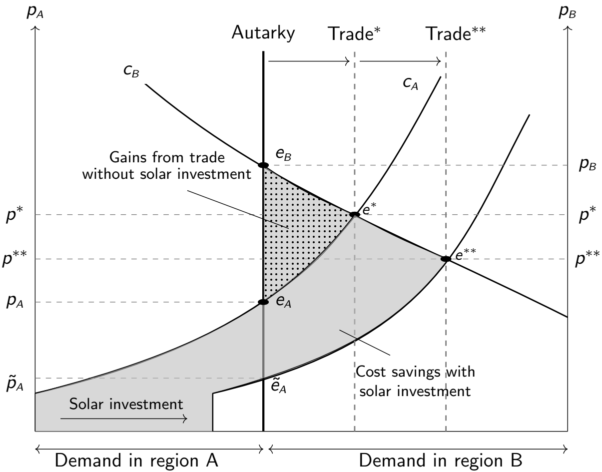


Classical gains from trade



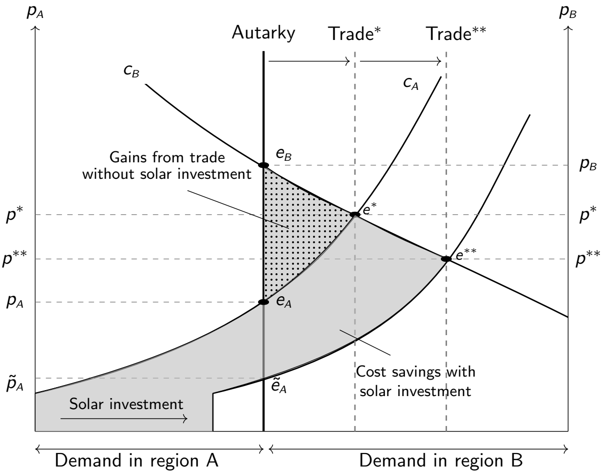
- Market integration provides classical gains from trade
- However, this figure abstracts from potential effects on investment

Gains from trade with a dynamic effect on investment



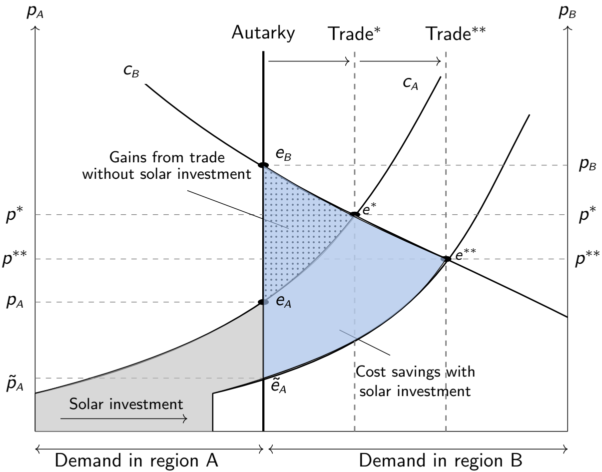
- Market integration could incentivize solar investment
- This effect shifts supply curve, resulting in a dynamic equilibrium (e^{**})

When could an event study identify the full effect?



- Suppose solar investment occurs simultaneously with integration
- In this case, event-study could get the full effect

This is not the case if investment occurs in anticipation



- Suppose solar investment occurs in anticipation of integration
- In this case, event-study gets a partial effect (the blue triangle)

We provide some guidance on the sign of 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

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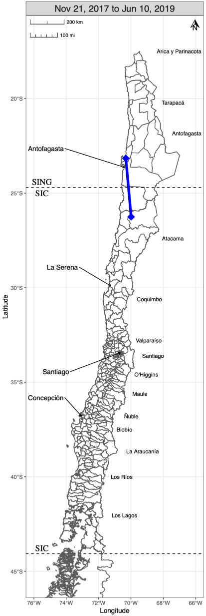
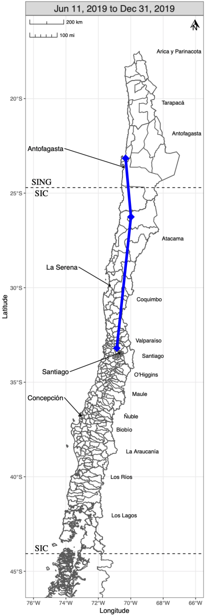
Background and Data

1) Grid expansions in the Chile

Interconnection (Nov. 2017)



Reinforcement (June 2019)



1) Grid expansions in the Chile

- February 2014: A modification to the "General Electric Services Law"
  - Government decided to built an interconnection
- August 2015: Construction of the interconnection started
- November 2017: Interconnection was opened
  - A double circuit 500kV transmission line with capacity of 1500 MW
- June 2019: Reinforcement transmission line was opened
  - Another double circuit 500kV transmission line

2) Dispatch mechanism in the Chilean electricity market

- "Cost-based" dispatch & pricing in the spot market
  - Power plants submit the technical characteristics of their units & natural gas or other input contracts with the input prices to the system operator
  - System operator uses this information with demand and transmission constraints to solve for least-cost dispatch
  - Costs are monitored and regulated. This makes it hard for firms to exercise market power compared to bid-based dispatch (Wolak, 2013)
  - In addition, firms can have bilateral long-run forward contracts
- Importantly, this mechanism was unchanged at grid expansions
  - This allows us to analyze the impact of market integration by itself

3) 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)

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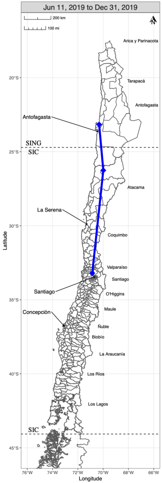
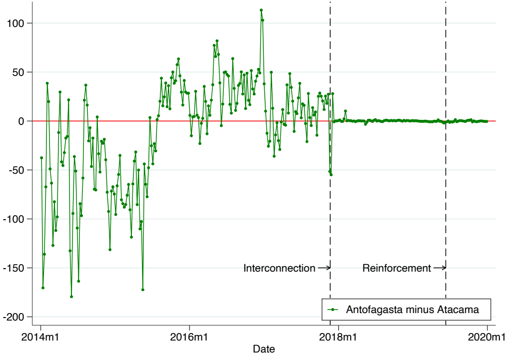
Descriptive Analysis of Market Integration

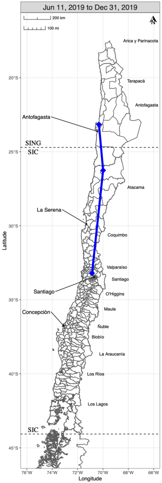
1) Price convergence btw Atacama and Antofagasta

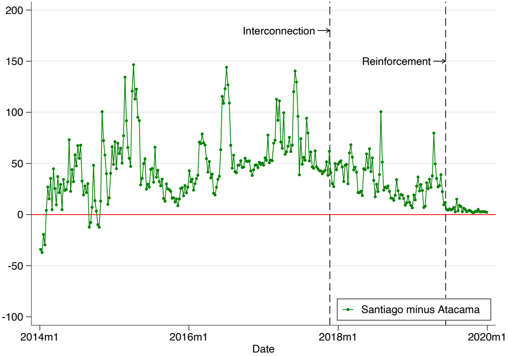




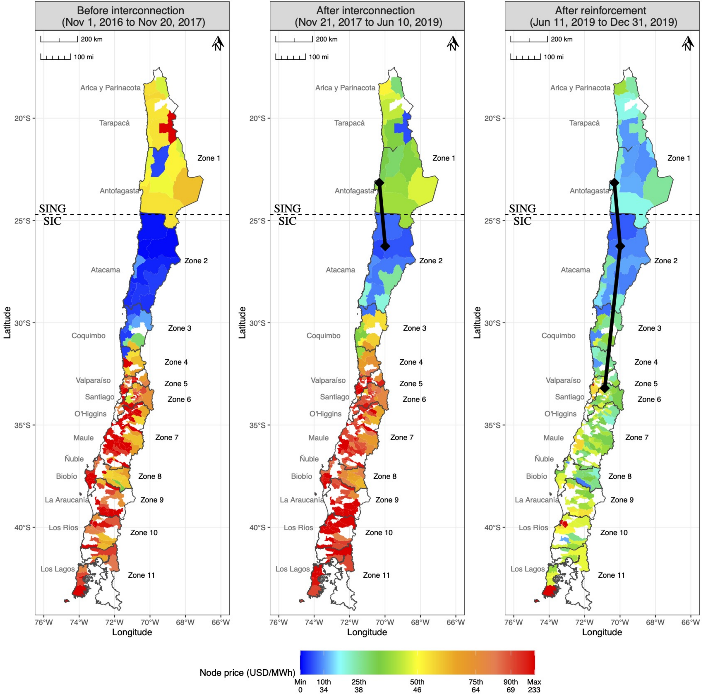
- Y = Average prices in Antofagasta − average prices in Atacama (USD/MWh)
- Finding: Price convergence after the interconnection

2) Price convergence btw Atacama and Santiago





- Y = Average prices in Antofagasta − average prices in Atacama (USD/MWh)
- Finding: Full price convergence occurred after the reinforcement


Before interconnection
(Nov 1, 2016 to Nov 20, 2017)
After interconnection
(Nov 21, 2017 to Jun 10, 2019)
After reinforcement
(Jun 11, 2019 to Dec 31, 2019)
200 km
100 mi
Arica y Parinacota
Tarapacá
Antofagasta
Atacama
Coquimbo
Valparaíso
Santiago
O'Higgins
Maule
Ñuble
Biobío
La Araucanía
Los Ríos
Los Lagos
Zone 1
Zone 2
Zone 3
Zone 4
Zone 5
Zone 6
Zone 7
Zone 8
Zone 9
Zone 10
Zone 11
SING
SIC
20°S
25°S
30°S
35°S
40°S
Latitude
76°W 74°W 72°W 70°W 68°W 66°W
Longitude
Node price (USD/MWh)
Min 0
10th 34
25th 38
50th 46
75th 64
90th 69
Max 233

Static Impacts on Generation Cost (USD/MWh)

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

- 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 on Generation Cost (USD/MWh)

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

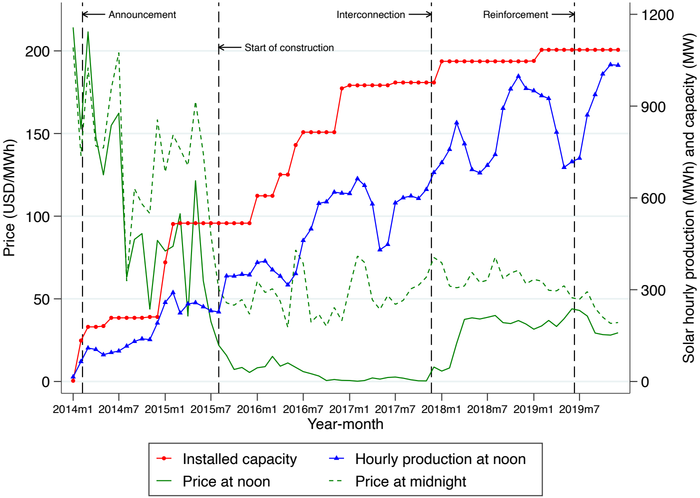
	Hour 12		All hours	
1(After the interconnection)	-2.42	(0.26)	-2.07	(0.17)
1(After the reinforcement)	-0.96	(0.58)	-0.61	(0.37)
Nationwide merit-order cost	1.12	(0.03)	1.03	(0.01)
Coal price [USD/ton]	-0.03	(0.01)	-0.01	(0.01)
Natural gas price [USD/m^3]	-10.36	(4.33)	-0.65	(3.09)
Hydro availability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

- Dependent variable: generation cost (USD/MWh)
- Market integration reduced the generation cost (gains from trade)

Does this static event study analysis get the full impact?

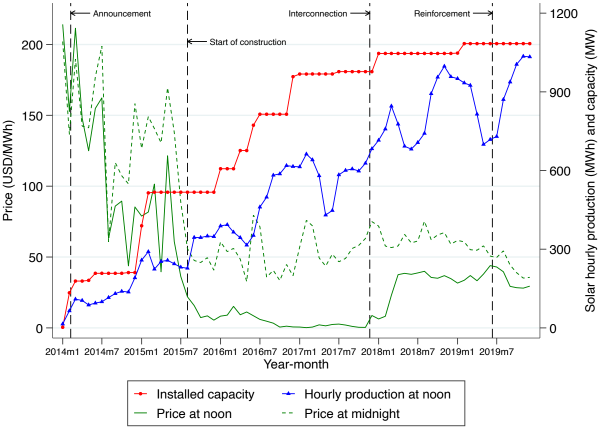
- Our theory suggested:
  - Yes if solar investment occurs simultaneously with integration
  - No if solar investment occurs in anticipation of integration

Solar investment occurred in anticipation of integration



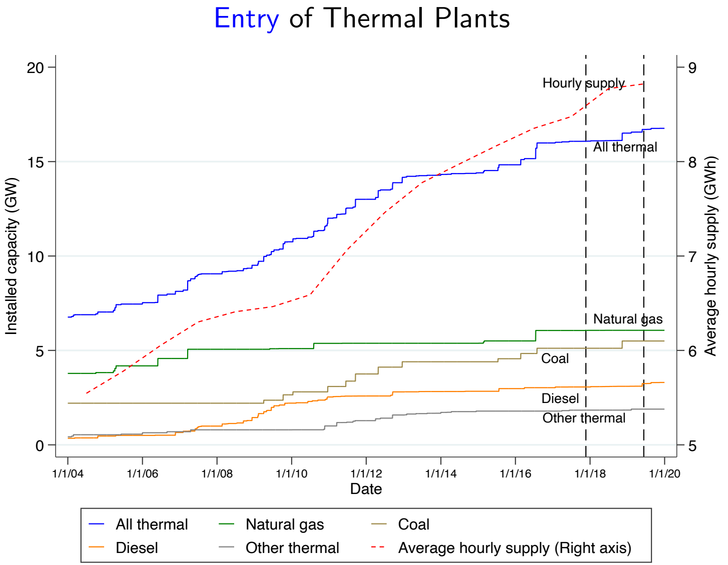
- Solar investment began after the announcement of integration in 2014
- These solar entries depressed the local price to near zero in 2015-2017

Solar investment occurred in anticipation of integration

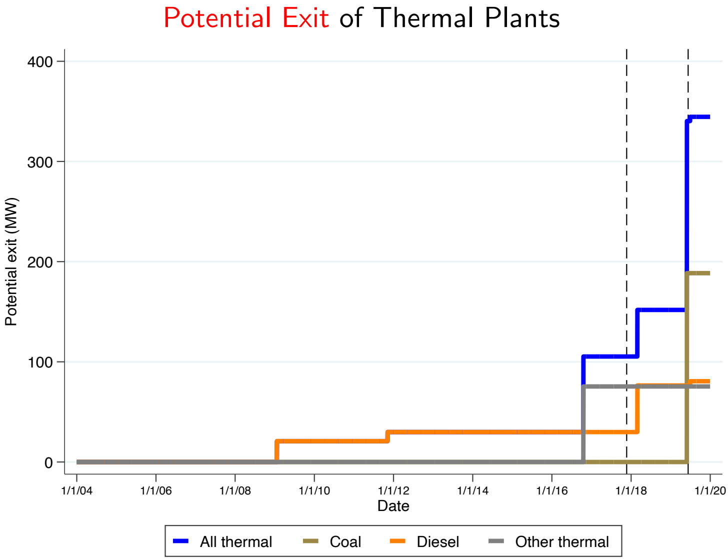


- However, more and more new solar plants entered the market
  - ▶ Investment occurred in the anticipation of the profitable environment
  - → Static analysis does not capture the full impact of market integration
  - → We address this challenge in the next section

Thermal: Entry has slowed down since 2014



Thermal: Potential Exit has increased since 2014



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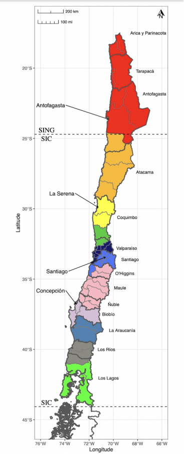
A Structural Model of Market Integration

A structural model to study a dynamic effect on investment

- We divide the Chilean market to 11 regional markets with interconnections between regions
- Our dispatch 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



Dispatch model solves this constrained optimization

$$\min_{\text{q,imp,exp}} \quad \sum_{z,t,j} C_{ztj}\left(q_{ztj}\right),$$

$$\text{s.t.} \quad (1) \quad \sum_{j} q_{ztj} + \sum_{l}\Big((1-\delta_1)\ imp_{lzt} - exp_{lzt}\Big) \geq \frac{D_{zt}}{1-\delta_2}, \quad \forall z, t,$$

$$(2) \quad 0 \leq imp_{lzt} \leq f_{lz}, \quad 0 \leq exp_{lzt} \leq f_{lz}, \quad \forall l, z, t,$$

$$(3) \quad \sum_{z}(imp_{lzt} - exp_{lzt}) = 0, \quad \forall l, t,$$

- $C_{ztj}\left(q_{ztj}\right)$: total generation cost from technology j in zone z and hour t
- q_{ztj}: production quantity
- imp_{lzt} and exp_{lzt}: imports & exports in zone z through transmission line l
- δ_1 and δ_2: transmission loss with high- and low-voltage transmission
- D_{zt}: demand
- k_i: the plant's capacity of generation
- f_{lz}: inter-regional transmission capacity

A solar investment model

$$E\left[\sum_{y\in Y}\frac{\sum_h p_{zyh}(\boldsymbol{k})\times q_{zyh}(\boldsymbol{k})}{(1+r)^y}\right] = c_z\ k_z,\quad \forall z$$

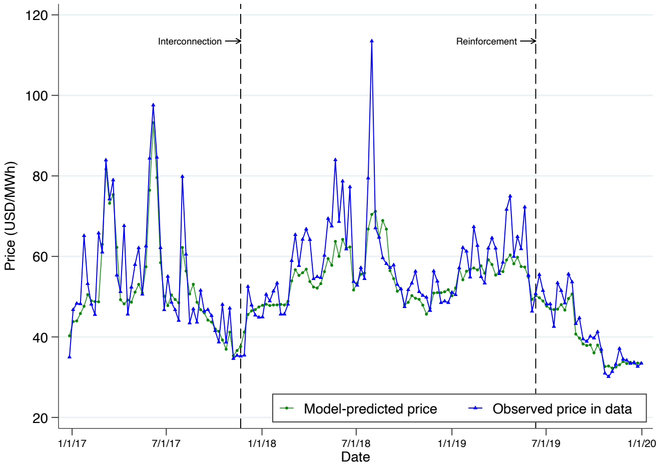
- NPV of profit (left hand side) = Investment cost (right hand side)
- y and h: year and hour
- r: discount rate
- p_{zyh}: market clearing price at zone z from the dispatch model
- c_z: solar investment cost per generation capacity (USD/MW)
- k_z: solar capacity in zone z
- $\boldsymbol{k}$: a vector of solar capacity in each zone

- Use the model to compute the profitable level of entry in each scenario

We consider three scenarios for counterfactual simulations

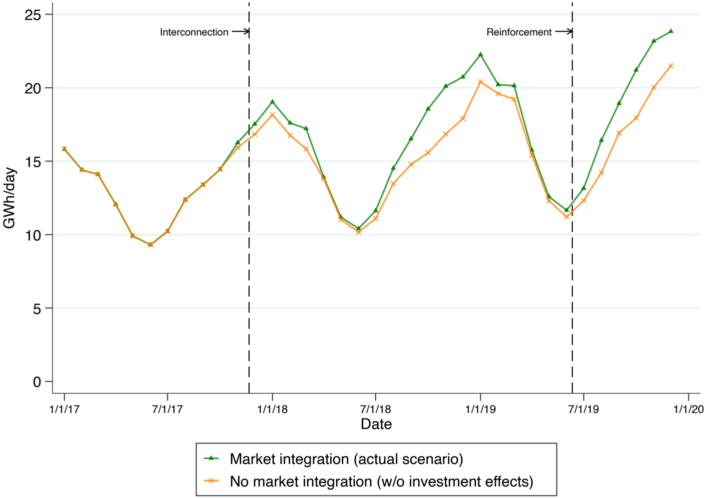
1. Actual scenario
   - Chile integrated markets by the interconnection and reinforcement
2. Counterfactual 1: No market integration (w/o investment effects)
   - Chile did not integrate markets
   - This would make some solar investment unprofitable, but we ignore it
3. Counterfactual 2: No market integration (with investment effects)
   - Chile did not integrate markets
   - We adjust for the dynamic effect by taking out unprofitable solar entries

Model fit: Observed price vs. model-predicted price



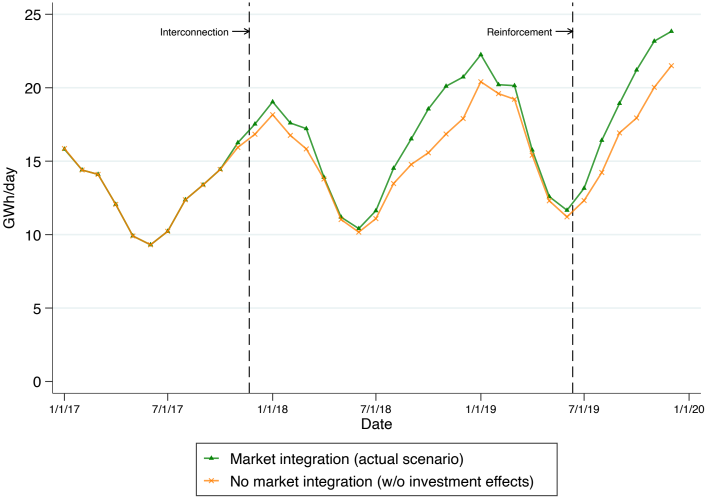
- Overall, the model well captures market outcomes

Counterfactual policy simulations: Solar generation



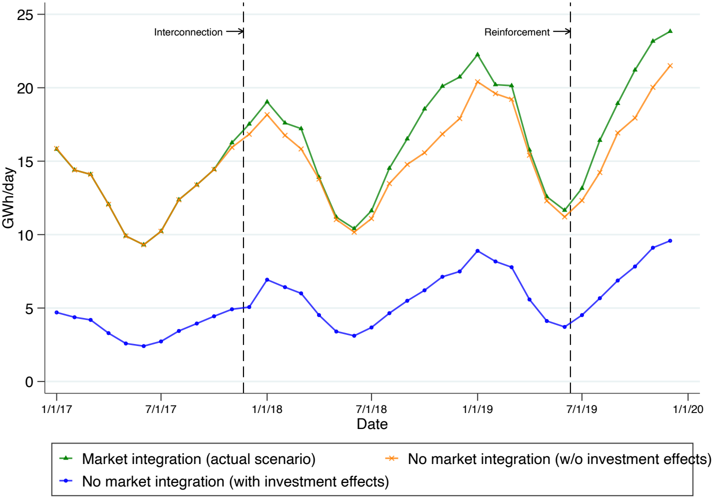
- Without market integration, solar generation would be lower because the excess solar supply cannot be exported (i.e., curtailment)

Counterfactual policy simulations: Solar generation



- In addition, large amount of solar investment would be unprofitable in the absence of integration (investment effect)

Counterfactual policy simulations: Generation cost



- Market integration lowers generation cost per MWh
- Ignoring this investment effect underestimates the cost savings

Result 1: Solar generation

	(1)	(2)	(3)	(4)	(5)
	Market Integration	No market integration (counterfactual)		Impacts of integration	
				(1)-(2)	(1)-(3)
Investment effects		No	Yes	No	Yes
Solar production (GWh/day)	17.6	16.1	6.2	1.5 (+10%)	11.4 (+185%)
Generation cost: all hours (USD/MWh)	35.9	37.1	39	-1.2 (-3%)	-3.1 (-8%)
Generation cost: hour 12 (USD/MWh)	31.3	33.7	38.4	-2.4 (-7%)	-7.1 (-18%)

- Market integration increased solar generation by 11.4 GWh/day
- Ignoring the investment effect underestimates the full effect

Result 2: Generation cost

	(1)	(2)	(3)	(4)	(5)
	Market Integration	No market integration (counterfactual)		Impacts of integration	
				(1)-(2)	(1)-(3)
Investment effects		No	Yes	No	Yes
Solar production (GWh/day)	17.6	16.1	6.2	1.5 (+10%)	11.4 (+185%)
Generation cost: all hours (USD/MWh)	35.9	37.1	39	-1.2 (-3%)	-3.1 (-8%)
Generation cost: hour 12 (USD/MWh)	31.3	33.7	38.4	-2.4 (-7%)	-7.1 (-18%)

- Market integration reduced generation cost by 3.1 USD/MWh
- Ignoring the investment effect underestimates the full effect
- This is consistent with **Result 1** in our theory section

Result 3: Price

	(1)	(2)	(3)	(4)	(5)
	Market Integration	No market integration (counterfactual)		Impacts of integration	
				(1)-(2)	(1)-(3)
Investment effects		No	Yes	No	Yes
Daily price in all regions (USD/MWh)	49.3	51	53.2	-1.7 (-3%)	-3.9 (-7%)
Price at noon in all regions (USD/MWh)	48.4	48.3	54.1	0.1 (+0%)	-5.7 (-11%)
Price at noon in Antofagasta (USD/MWh)	44.7	42	45	2.7 (+6%)	-0.3 (-1%)
Price at noon in Atacama (USD/MWh)	46	6.4	46.9	39.6 (+619%)	-0.9 (-2%)
Price at noon in Santiago (USD/MWh)	52.4	60.3	60.6	-7.9 (-13%)	-8.2 (-14%)

- Market integration reduced price by 5.7 USD/MWh
- Ignoring the investment effect underestimates the full effect
- This is consistent with **Result 2** in our theory section

Result 4: Price convergence between regions

	(1)	(2)	(3)	(4)	(5)
	Market Integration	No market integration (counterfactual)		Impacts of integration	
				(1)-(2)	(1)-(3)
Investment effects		No	Yes	No	Yes
Price difference (Antofagasta - Atacama)	-1.3	35.6	-1.9	-36.9 (-104%)	0.6 (-32%)
Price difference (Santiago - Atacama)	6.4	53.9	13.7	-47.5 (-88%)	-7.3 (-53%)

- Market integration reduced regional price
- e.g., Price converged btw Santiago and Atacama by 7.3 USD/MWh
- The static result (47.5 USD/MWh) overstates this price convergence
- This is consistent with **Result 3** in our theory section

Road map of the talk

1. Theory
   - Characterize static and dynamic impacts of market integration
   - Highlight that a standard event study may not capture a full effect
2. Background and Data
   - Micro data on hourly market outcomes, marginal cost etc.
3. Descriptive Analysis
   - Use a standard event study analysis to estimate static effects
4. A Structural Model of Market Integration
   - Build a structural model of solar entries to estimate dynamic effects
   - Estimate the impact of market integration with & w/o investment effects
5. Cost-Benefit Analysis
   - Benefits exceed the costs of the transmission investments in 7-11 years

Cost-Benefit Analysis of the Transmission Investments

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

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%

1. Ignoring investment effects would understate the benefit
2. With discount rate at 5.8%, the benefit exceeds the cost btw 7 and 11 years

Conclusion

We study market integration & renewable expansion

1. Theory
   - Characterized static and dynamic impacts of market integration
   - Highlighted that a standard event study may not capture a full effect
2. Empirical analysis:
   - We exploited grid expansions and micro data in Chile
   - We used both event study and structural estimation
3. Empirical findings:
   - Market integration increased solar entry and production
   - Substantial solar investment would be unprofitable without integration
   - Integration reduced gen. cost by 5-8% (overall) & 12-18% (hr 12)
   - Ignoring investment effects substantially underestimates these full effects
   - Benefits exceed the costs of the transmission investments in 7 years