The Value of Infrastructure and Market Integration:

Evidence from Renewable Expansion in Chile

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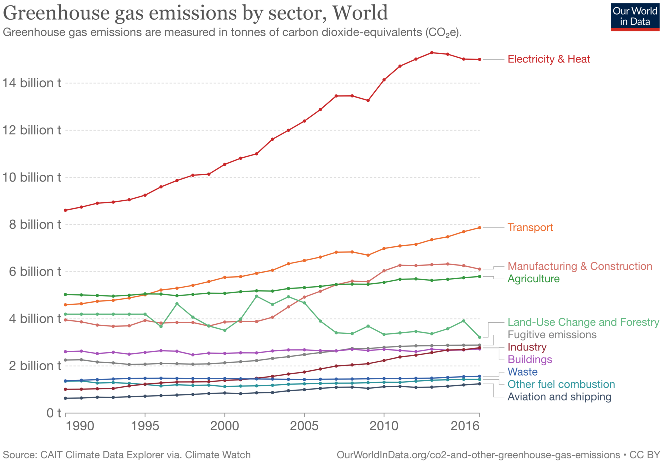
We would like to thank Andrew Smith, Tianyu Luo, and Yixin Zhou for their exceptional research assistance.

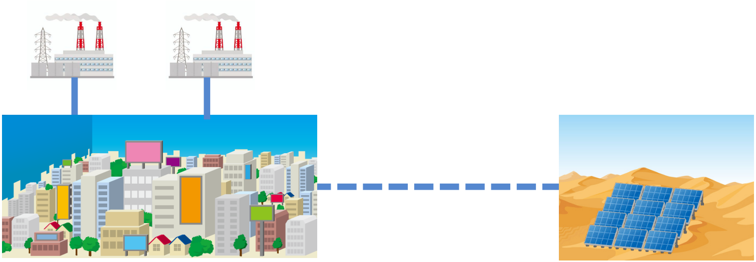
Renewable expansion is key to mitigating climate change

- 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

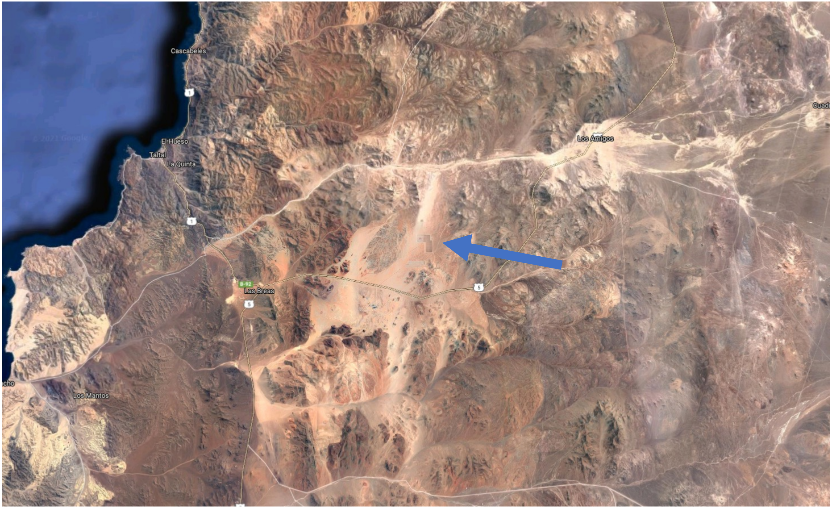
    "The Bipartisan Infrastructure Deal's more than $65 billion investment is the largest investment in clean energy transmission and the electric grid in American history. It upgrades our power infrastructure, including by building thousands of miles of new, resilient transmission lines to facilitate the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

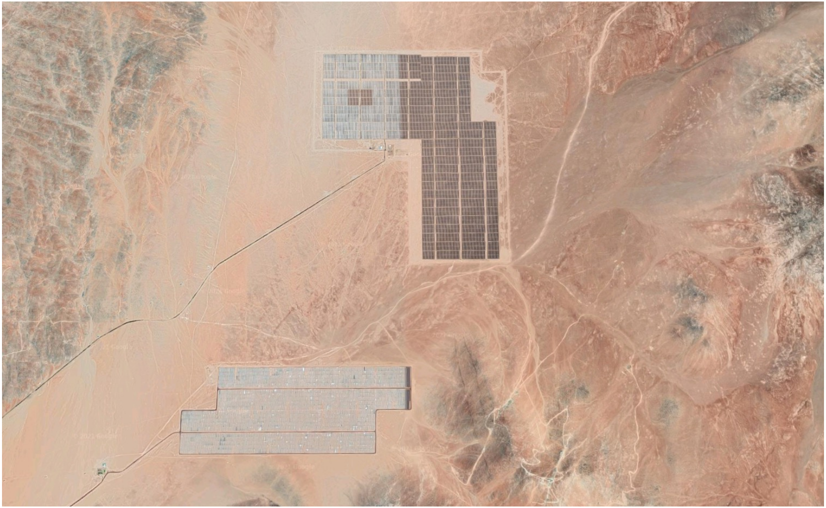
Atacama (1500 km from Santiago) is suitable for solar PV

An example of large-scale solar PV in Atacama



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

An example of large-scale solar PV in Atacama



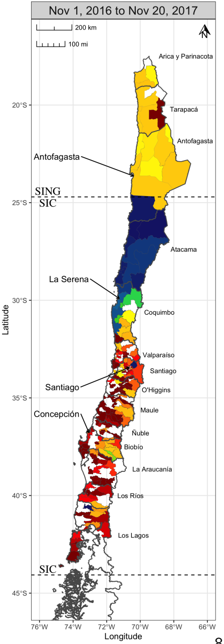
Atacama (1500 km from Santiago) is suitable for solar PV

An example of large-scale solar PV in Atacama

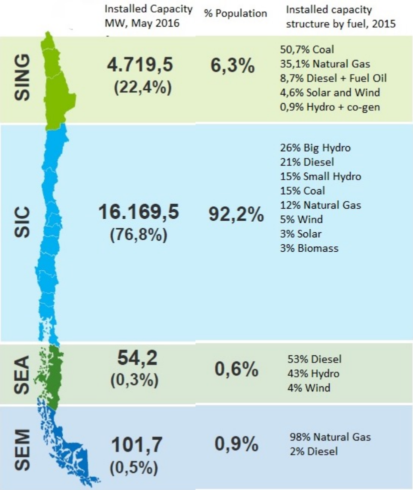
Lack of market integration created regional price dispersion

- 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)



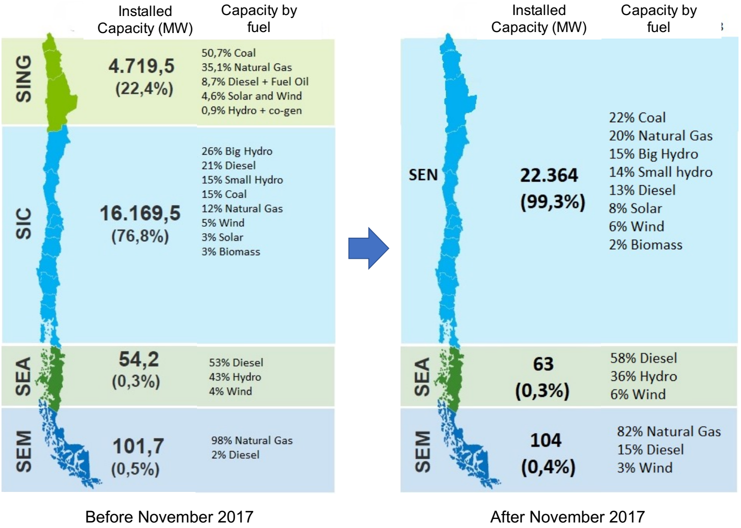
We exploit grid expansions in Chile to conduct our study



	Installed Capacity MW, May 2016	% Population	Installed capacity structure by fuel, 2015
SING	4.719,5 (22,4%)	6,3%	50,7% Coal 35,1% Natural Gas 8,7% Diesel + Fuel Oil 4,6% Solar and Wind 0,9% Hydro + co-gen
SIC	16.169,5 (76,8%)	92,2%	26% Big Hydro 21% Diesel 15% Small Hydro 15% Coal 12% Natural Gas 5% Wind 3% Solar 3% Biomass
SEA	54,2 (0,3%)	0,6%	53% Diesel 43% Hydro 4% Wind
SEM	101,7 (0,5%)	0,9%	98% Natural Gas 2% Diesel

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

We exploit grid expansions in Chile to conduct our study



- 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. Static Analysis
   - Use a standard event study analysis to estimate static effects
4. Dynamic Analysis
   - Build a structural model of solar entries to estimate dynamic effects
   - Estimate a full impact of integration and correct bias in event study
5. Cost-Benefit Analysis
   - Benefits exceed the costs of the transmission investments in 10 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)

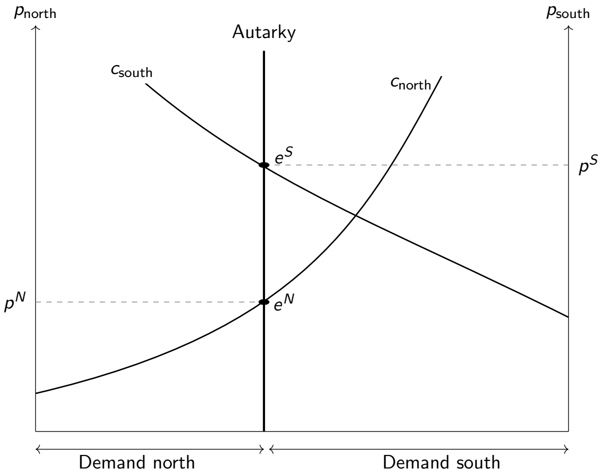
3. Environmental impacts of transmission expansion
   - Fell, Kaffine, and Novan (2021)

Theoretical Framework

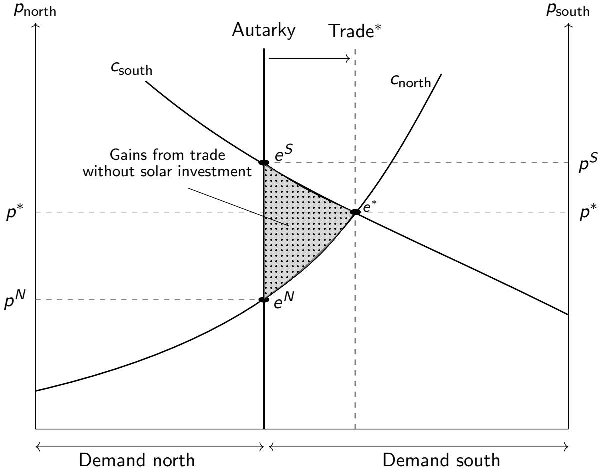
Our theory highlights two key points

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

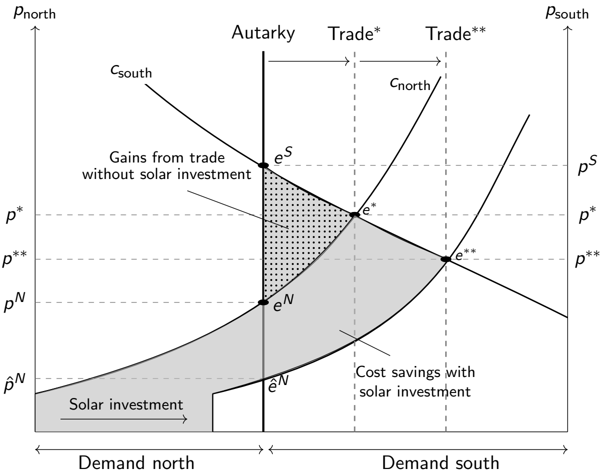


Classical gains from trade



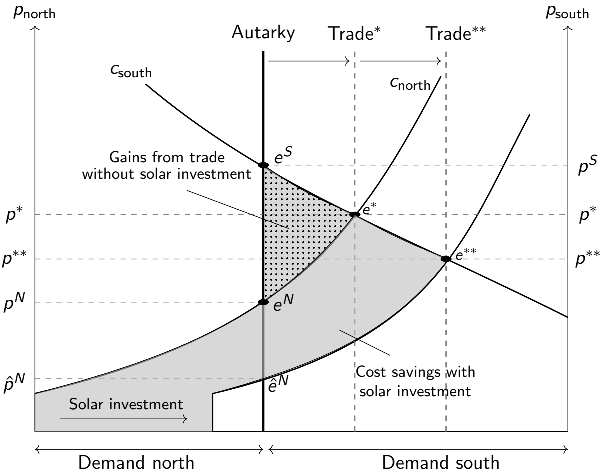
- Market integration provides classical gains from trade
- However, this figure abstracts from potential effects on investment

Gains from trade with a dynamic effect on investment



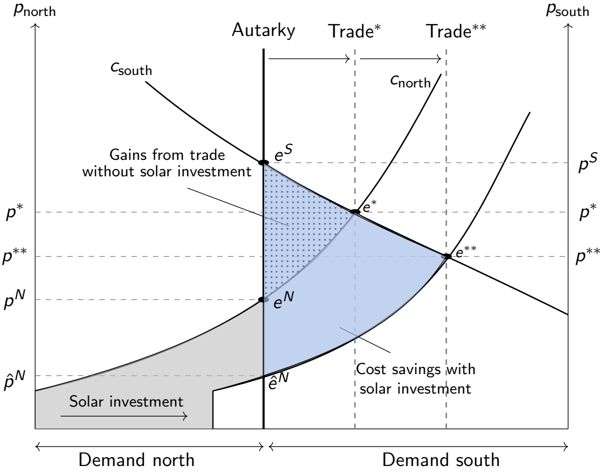
- Market integration could incentivize solar investment
- This effect shifts supply curve, resulting in a dynamic equilibrium (e^{**})

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 event study and structural estimation to:
  - Estimate the full effect of market integration
  - Quantify and correct the bias in the static event study analysis

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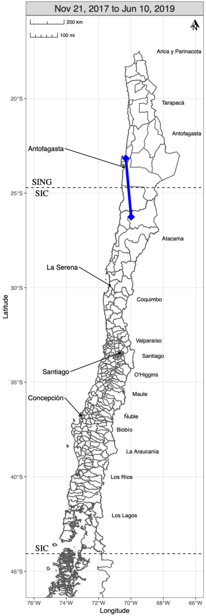
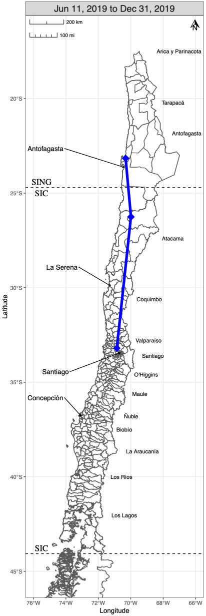
Background and Data

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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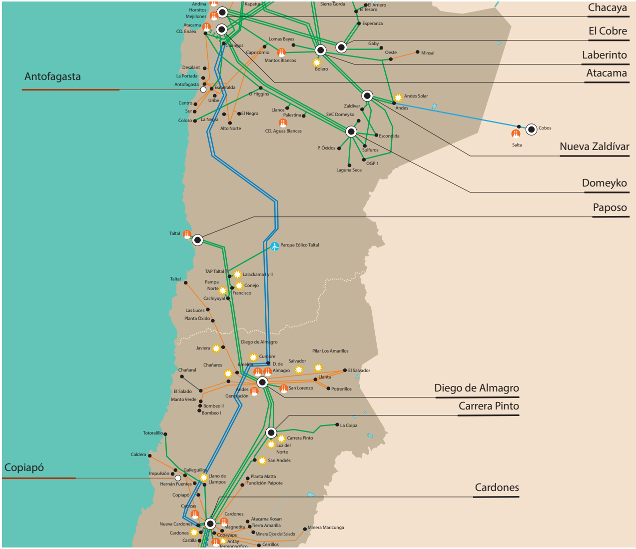
Static Analysis of Market Integration

We use event study analysis to estimate static impacts

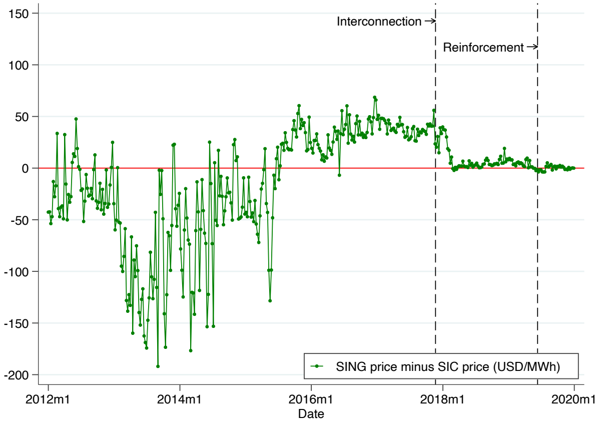
- We evaluate the impacts of two events
  - November 2017: Interconnection between Antofagasta and Atacama
  - June 2019: Reinforcement between Atacama and Santiago

1) Price convergence in the SIC-SING border regions



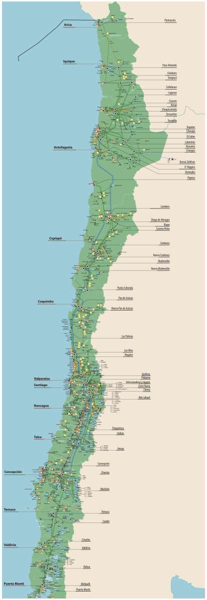
- Examine price convergence at SIC-SING border (Atacama-Antofagasta)

1) Price convergence in the SIC-SING border regions

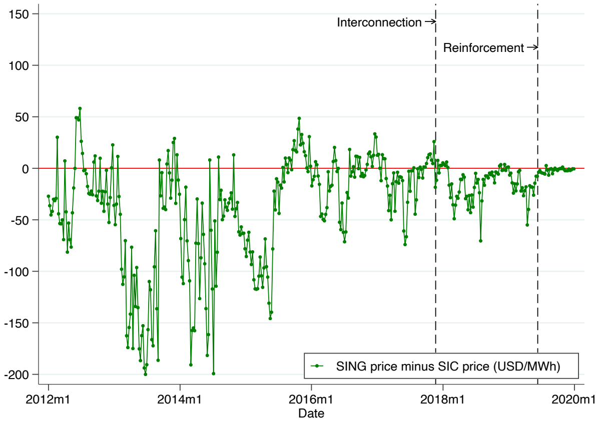


- Y = Average node prices in SING − Average node prices in SIC (USD/MWh)
- This is the result for hour 12 (other hours are in the paper)
- Finding: Price convergence after the interconnection

2) Price convergence in the entire system



Full price convergence occurred after the reinforcement



- Y = Average node prices in SING − Average node prices in SIC (USD/MWh)
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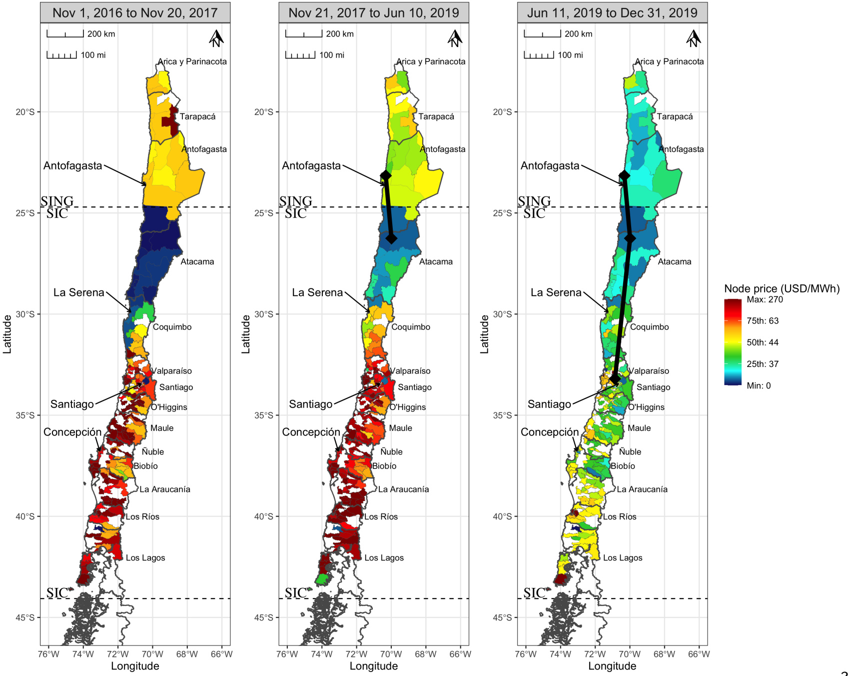
- Finding: Full price convergence occurred after the reinforcement



Nov 1, 2016 to Nov 20, 2017
Nov 21, 2017 to Jun 10, 2019
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
Antofagasta
La Serena
Santiago
Concepción
SING
SIC
20°S
25°S
30°S
35°S
40°S
45°S
Latitude
76°W
74°W
72°W
70°W
68°W
66°W
Longitude
Node price (USD/MWh)
Max: 270
75th: 63
50th: 44
25th: 37
Min: 0

Static Impacts on Generation Cost (USD/MWh)

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

- Our method uses insights from Cicala (2022)
  - c_t is the observed cost
  - c^* is the ideal (least-possible) dispatch cost under full trade in Chile
  - $c_t - c_t^*$ measures the cost relative to the ideal cost
  - $I_t = 1$ 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)

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

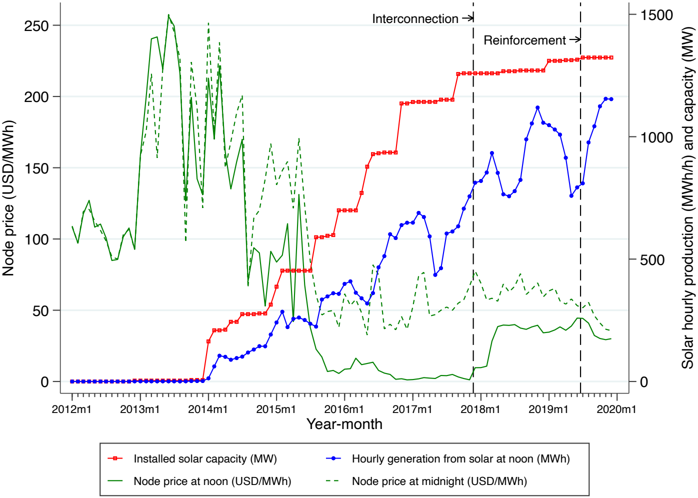
	Hour 12	All hours
1(After the interconnection)	-1.75	-0.96
	(0.19)	(0.14)
1(After the reinforcement)	-1.14	-1.04
	(0.37)	(0.27)
Coal price [USD/ton]	0.02	0.00
	(0.01)	(0.01)
Natural gas price [USD/m^3]	-4.39	0.33
	(4.20)	(3.15)
Hydro availability	-0.26	-0.43
	(0.12)	(0.10)
Scheduled demand (GWh)	0.20	0.02
	(0.10)	(0.10)
Mean of dep var	5.17	4.89
Sample size	1041	1041

- Market integration reduced the generation cost (gains from trade)

Does this static event study analysis get the full impact?

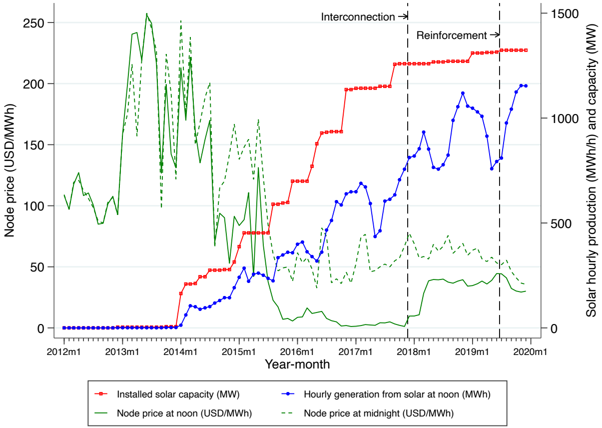
- Our theory suggested:
  - Yes if solar investment occurs simultaneously with integration
  - No if solar investment occurs in anticipation of integration

Solar investment occurred in anticipation of integration



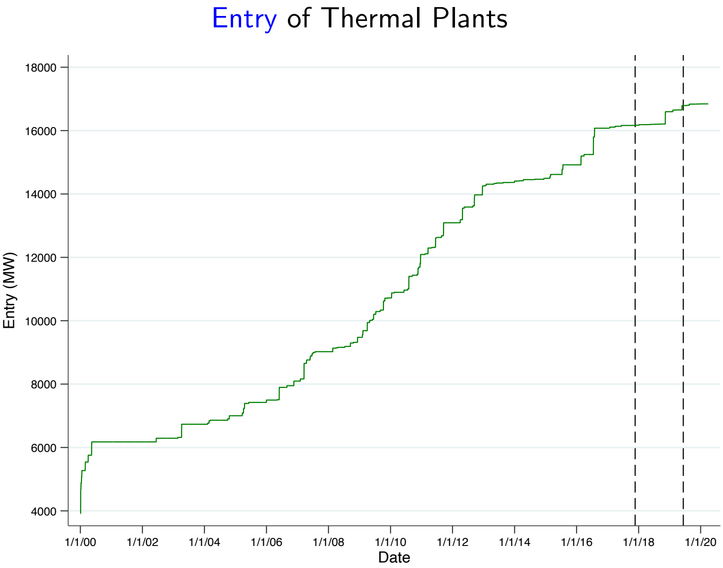
- Solar investment began after the announcement of integration in 2014
- These solar entries depressed the local price to near zero in 2015-2017

Solar investment occurred in anticipation of integration

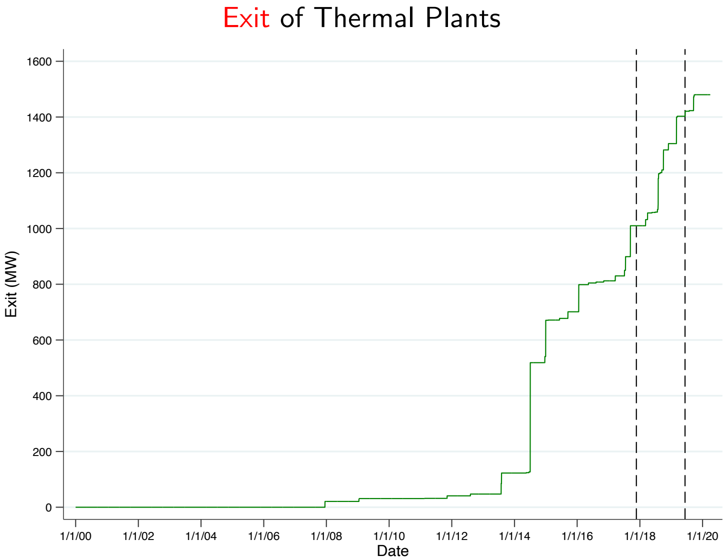


- However, more and more new solar plants entered the market
    - ▶ Investment occurred in the anticipation of the profitable environment
    - → Static analysis does not capture the full impact of market integration
    - → We address this challenge in the next section

Thermal: Entry has slowed down since 2014



Thermal: Exit has increased since 2014



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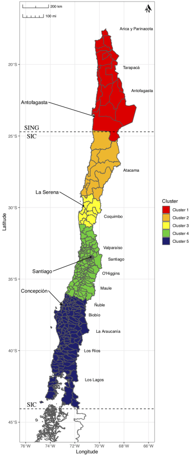
Dynamic Analysis of Market Integration

A structural model to study a dynamic effect on investment

- We divide the Chilean market to five regional markets with interconnections between regions
- 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

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

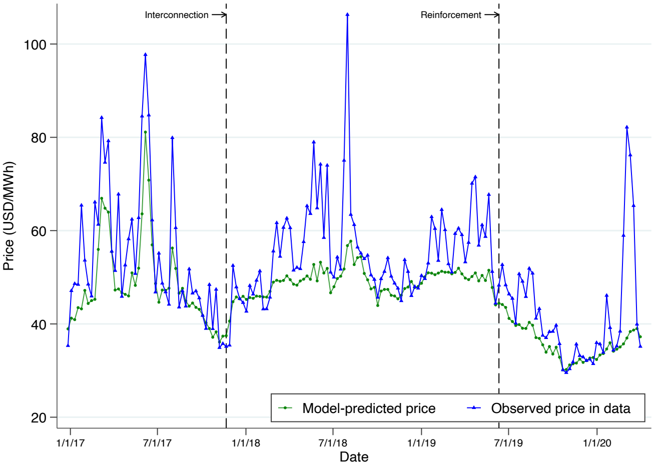
- NPV of profit (left hand side) = Investment cost (right hand side)
- ρ: solar investment cost per generation capacity (USD/MW)
- k_i: generation capacity (MW) for plant i
- p_{it}: market clearing price at time t
- q_{it}: dispatched quantify of generation at plant i
- r: discount rate

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

We consider three scenarios for counterfactual simulations

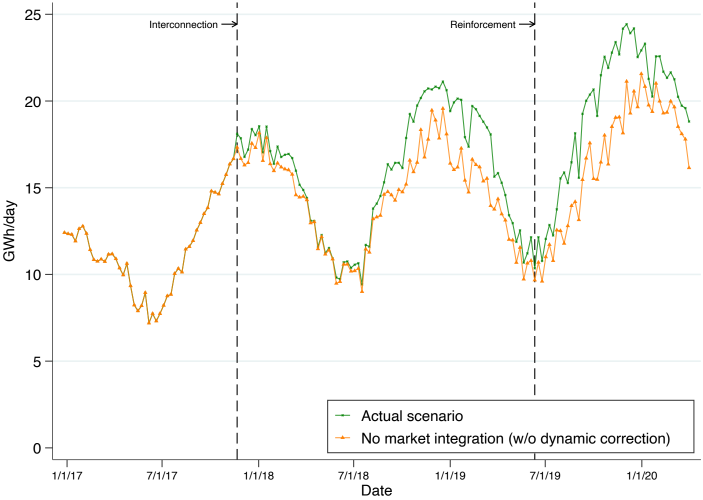
1. Actual scenario
   - Chile integrated markets by the interconnection and reinforcement
2. Counterfactual 1: No market integration (w/o dynamic correction)
   - Chile did not integrate markets
   - This would make some solar investment unprofitable, but we ignore it
3. Counterfactual 2: No market integration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



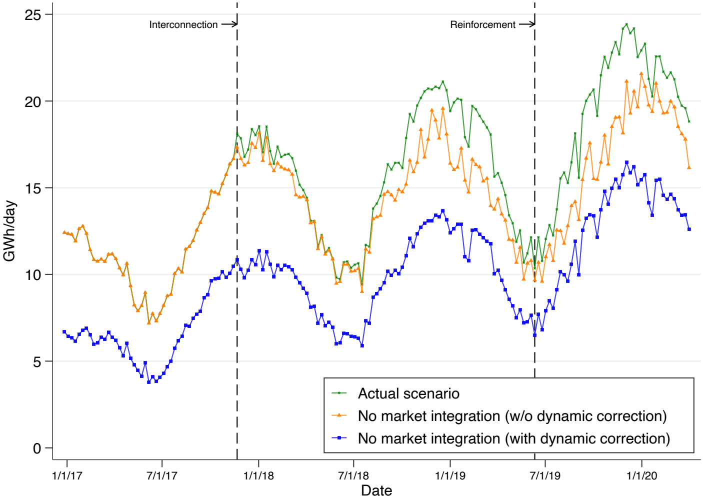
- Overall, the model well captures market outcomes
- It is still unable to capture some extremely high or low prices
- We are in the process of further improving the model

Counterfactual policy simulations: Solar generation



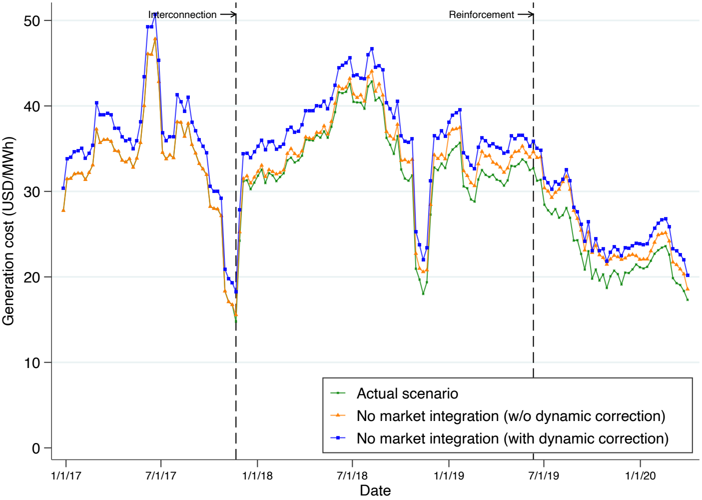
- Without market integration, solar generation would be lower because the excess solar supply cannot be exported (i.e., curtailment)

Counterfactual policy simulations: Solar generation



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

Counterfactual policy simulations: Generation cost



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

Result 1: Solar generation

	(1)	(2)	(3)	(4)	(5)
	Actual	No market integration		Impacts of integration	
	Market integration	Without dynamic correction	With dynamic correction	(1)-(2)	(1)-(3)
Solar generation (GWh/day)	19.4	16.6	12.8	2.8 (+17%)	6.6 (+51%)
Generation cost: all hours (USD/MWh)	26.4	27.5	27.9	-1.0 (-4%)	-1.5 (-5%)
Generation cost: hour 12 (USD/MWh)	23.1	25.3	26.4	-2.2 (-9%)	-3.3 (-12%)

- Market integration increased solar generation by 6.6 GWh/day
- The static result (2.8 GWh/day) underestimates the full effect

Result 2: Generation cost

	(1)	(2)	(3)	(4)	(5)
	Actual	No market integration		Impacts of integration	
	Market integration	Without dynamic correction	With dynamic correction	(1)-(2)	(1)-(3)
Solar generation (GWh/day)	19.4	16.6	12.8	2.8 (+17%)	6.6 (+51%)
Generation cost: all hours (USD/MWh)	26.4	27.5	27.9	-1.0 (-4%)	-1.5 (-5%)
Generation cost: hour 12 (USD/MWh)	23.1	25.3	26.4	-2.2 (-9%)	-3.3 (-12%)

- Market integration reduced generation cost by 1.5 USD/MWh
- The static result (1.0 USD/MWh) underestimates the full effect
- This is consistent with **Result 1** in our theory section

Result 3: Price

	(1)	(2)	(3)	(4)	(5)
	Actual	No market integration		Impacts of integration	
	Market integration	Without dynamic correction	With dynamic correction	(1)-(2)	(1)-(3)
Daily price in all regions (USD/MWh)	36.3	38.2	38.9	-1.8 (-5%)	-2.5 (-7%)
Price at noon in all regions (USD/MWh)	35.5	37.3	39.2	-1.8 (-5%)	-3.7 (-9%)
Price at noon in Atacama (USD/MWh)	33.9	1.6	28.8	32.3 (+2,040%)	5.1 (+18%)
Price at noon in Santiago (USD/MWh)	36.7	43.6	43.6	-6.9 (-16%)	-6.9 (-16%)
Price difference (Santiago - Atacama)	2.8	42.0	14.8	-39.2 (-93%)	-12.0 (-81%)

- Market integration reduced price by 3.7 USD/MWh
- The static result (1.8 USD/MWh) underestimates the full effect
- This is consistent with **Result 2** in our theory section

Result 4: Regional price difference

	(1)	(2)	(3)	(4)	(5)
	Actual	No market integration		Impacts of integration	
	Market integration	Without dynamic correction	With dynamic correction	(1)-(2)	(1)-(3)
Daily price in all regions (USD/MWh)	36.3	38.2	38.9	-1.8 (-5%)	-2.5 (-7%)
Price at noon in all regions (USD/MWh)	35.5	37.3	39.2	-1.8 (-5%)	-3.7 (-9%)
Price at noon in Atacama (USD/MWh)	33.9	1.6	28.8	32.3 (+2,040%)	5.1 (+18%)
Price at noon in Santiago (USD/MWh)	36.7	43.6	43.6	-6.9 (-16%)	-6.9 (-16%)
Price difference (Santiago - Atacama)	2.8	42.0	14.8	-39.2 (-93%)	-12.0 (-81%)

- Market integration reduced regional price difference by 12.0 USD/MWh
- The static result (39.2 USD/MWh) overstates this price convergence
- This is consistent with **Result 3** in our theory section

Can we use our model to correct bias in event study?

1. Shift the timing of solar investment
   - Let solar investment occur simultaneously with integration
2. Solve the model to obtain market outcomes
3. Run the event study regression with these outcome variables

- First, we use our model to reproduce the static event study result

	Hour 12			All hours		
	Event study		Simulation	Event study		Simulation
	(1)	(2)	(3)	(4)	(5)	(6)
Dynamic correction:	No	Yes	Yes	No	Yes	Yes
1(After the interconnection)	-1.32 (0.07)	-2.62 (0.09)	-2.36	-0.60 (0.04)	-1.18 (0.05)	-1.05
1(After the reinforcement)	-0.61 (0.14)	-1.89 (0.17)	-1.58	-0.25 (0.07)	-0.72 (0.09)	-0.64

- Second, we let solar investment occur simultaneously with integration
- This illustrates how static event study underestimates the effects

	Hour 12			All hours		
	Event study		Simulation	Event study		Simulation
	(1)	(2)	(3)	(4)	(5)	(6)
Dynamic correction:	No	Yes	Yes	No	Yes	Yes
1(After the interconnection)	-1.32	-2.62	-2.36	-0.60	-1.18	-1.05
	(0.07)	(0.09)		(0.04)	(0.05)	
1(After the reinforcement)	-0.61	-1.89	-1.58	-0.25	-0.72	-0.64
	(0.14)	(0.17)		(0.07)	(0.09)	

Road map of the talk

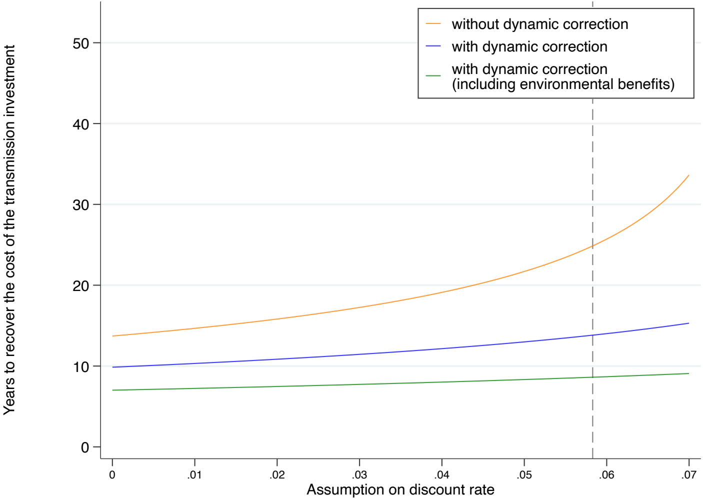
1. Theory
   - Characterize static and dynamic impacts of market integration
   - Highlight that a standard event study may not capture a full effect
2. Background and Data
   - Micro data on hourly market outcomes, marginal cost etc.
3. Static Analysis
   - Use a standard event study analysis to estimate static effects
4. Dynamic Analysis
   - Build a structural model of solar entries to estimate dynamic effects
   - Estimate a full impact of integration and correct bias in event study
5. Cost-Benefit Analysis
   - Benefits exceed the costs of the transmission investments in 10 years

Cost-Benefit Analysis of the Transmission Investments

The costs and benefits of the transmission investments

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

Benefits exceed the costs roughly in 10 years



- The Chilean government's official discount rate is 5.83%
- Ignoring the dynamic impact would underestimate the benefit

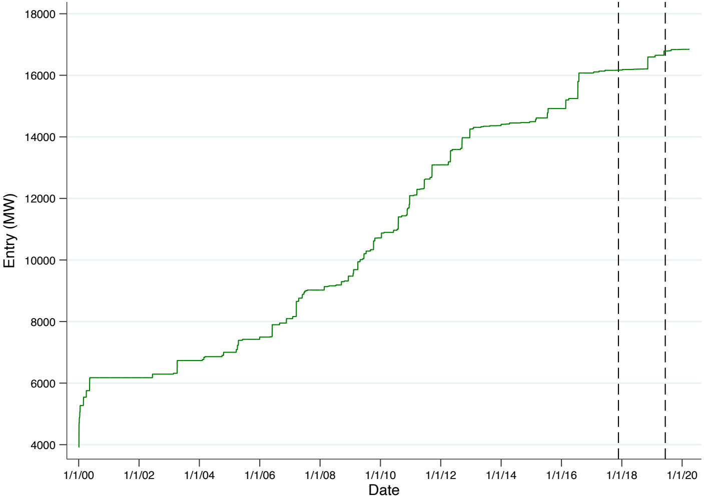
Conclusion

We study market integration & renewable expansion

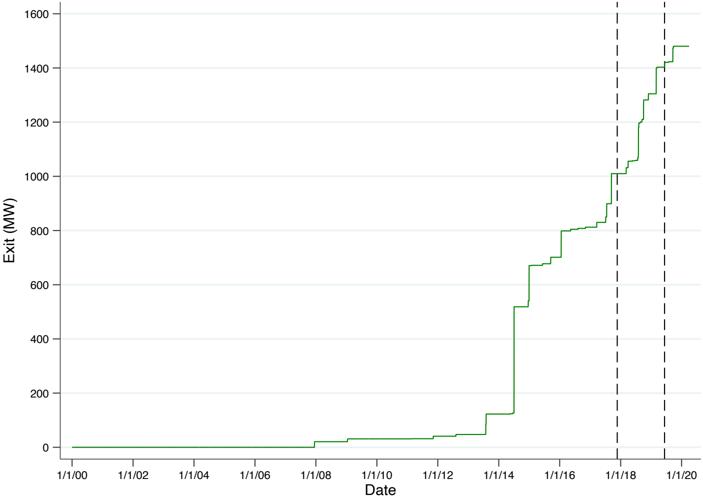
1. Theory
   - Characterized static and dynamic impacts of market integration
   - Highlighted that a standard event study may not capture a full effect
2. Empirical analysis:
   - We exploited grid expansions and micro data in Chile
   - We used both event study and structural estimation
3. Empirical findings:
   - Substantial solar investment would be unprofitable without integration
   - Market integration increased solar generation by 51%
   - Market integration reduced gen. cost by 5% (overall) & 13% (hr 12)
   - We showed how static analysis underestimates these full effects
   - Benefits exceed the costs of the transmission investments in 10 years

Appendix

Entry of Thermal Plants



Exit of Thermal Plants



Carbon emission

	Renewable	Hydro	Coal	Natural gas	Other thermal	Total
Generation ratio						
Actual scenario	16.0%	27.1%	37.4%	13.2%	6.4%	100.0%
No mkt integration (static)	14.3%	27.3%	36.0%	15.6%	6.7%	100.0%
No mkt integration (dynamic)	12.9%	27.3%	37.5%	15.6%	6.7%	100.0%
Generation level (GWh)						
Actual scenario	34.0	57.6	79.9	28.2	13.6	213.3
No mkt integration (static)	30.3	57.9	76.8	33.3	14.3	212.6
No mkt integration (dynamic)	27.3	57.9	79.8	33.3	14.3	212.6
Emission level (tons of CO2)						
Actual scenario	0.0	0.0	66332.0	9598.7	0.0	75930.7
No mkt integration (static)	0.0	0.0	63709.0	11326.8	2.9	75038.8
No mkt integration (dynamic)	0.0	0.0	66221.4	11336.9	2.9	77561.2
Non-carbon externality (1000 USD)						
Actual scenario	0.0	0.0	2717.2	56.5	0.0	2773.7
No mkt integration (static)	0.0	0.0	2609.8	66.6	0.0	2676.4
No mkt integration (dynamic)	0.0	0.0	2712.7	66.7	0.0	2779.4