The Effects of Renewable Electricity Supply when Renewables Dominate: Evidence from Uruguay

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Motivation:

Figure: World map - Uruguay

Motivation:

Figure: Uruguay map

Motivation

- 94% of electricity is from renewable sources

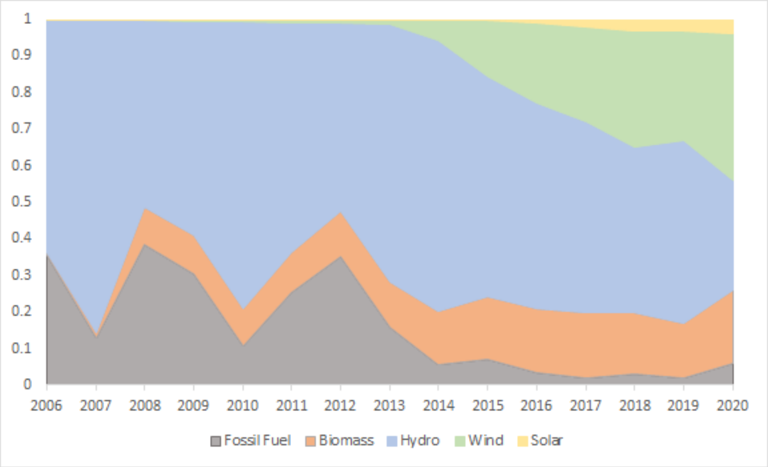

Figure: Electricity production by source. (MIEM, 2021).

Motivation

- Decarbonizing electricity production is crucial to mitigate climate change
- Large-scale production of renewables is key to stay below the 2°C target (IPCC, 2022)
- Best way to mix electricity sources on the grid? In debate

Research Questions

I analyze how wind and solar production:

1. Decreases CO_2 emissions

[2] Definition: marginal cost of increasing demand in one unit in a specific node.

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2. Substitutes thermal, hydro, and biomass production
   - Substitution patterns between sources depend on: time of the day, level of production, which production technology is the mg. source

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3. Affects electricity spot prices [2]

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3. Affects electricity spot prices [2]

- Uruguay's electricity sector has progressed further toward decarbonization than other countries

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Results

Wind and solar production have several effects:

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5. Decrease in spot prices caused by the shutting off of most costly plants (within a specific hour)

Results

Wind and solar production have several effects:

1. Reduction in the CO_2 emissions from the thermal production
2. Displacement of hydro production
3. Displacement of thermal production, especially in winter
4. Spillover effect to the region due to an increase in exports to Argentina and Brazil
5. Decrease in spot prices caused by the shutting off of most costly plants (within a specific hour)

However, the increase in wind and solar production is not enough to eradicate thermal entirely. Especially in summer, when hydro and wind production are low, solar production is not enough to satisfy electricity demand

Contributions Literature Review

My research contributes to the literature on the effect of renewables on:

- Substitution of wind on different sources in USA (Cullen, 2013), Australia (Karaduman, 2020)
- Spillover effect in Europe (Abrell & Kosch, 2022)
- Pollutants (Abrell & Kosch, 2022; Fell et al., 2021; LaRiviere & Lu, 2017; Davis & Hausman, 2016; Cullen, 2013)

Literature Review

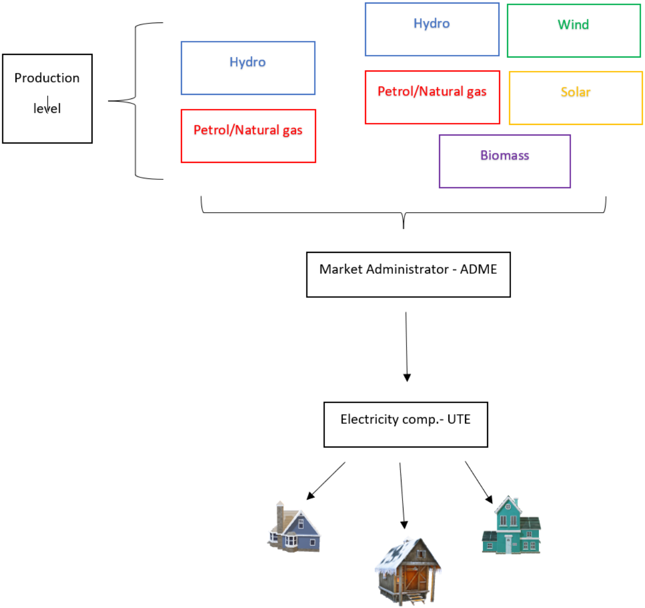
- Most of the literature in electricity markets is based on price-based sectors in developed countries, such as the United States (Cullen, 2013; Fell et al., 2021; Wolak, 2015; Mansur & White, 2012; LaRiviere & Lu, 2017; Davis & Hausman, 2016), Europe (Abrell & Kosch, 2022), or Australia (Karaduman, 2020).
- My research shed light on how renewable energy affects generation patterns in a regulated market in a middle-income country

Literature Review

- A growing literature shows the importance of electricity grid congestion[3] (Gonzales, Ito, & Reguant, 2022; Ryan, 2021; Fell et al., 2021; Wolak, 2015)
  - Calculate prices difference between regions
- I calculate congestion using another approach:
  - Need capacity of the line and how much electricity is flowing

[3] Definition: When a portion of the transmission line becomes overloaded with electric power.

Uruguayan electricity market



Uruguayan electricity market

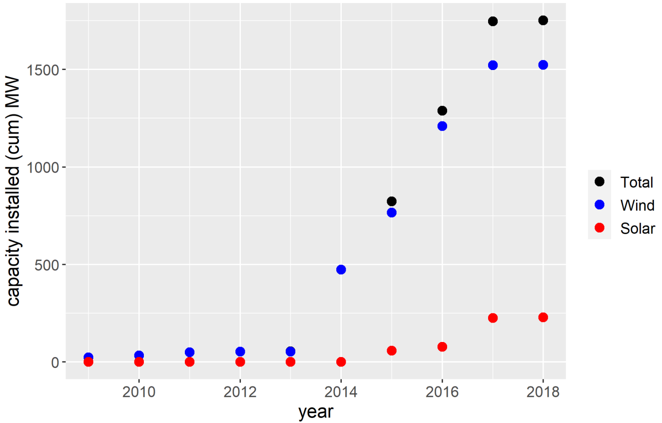


Figure: Cumulative wind and solar capacity installed

Uruguayan electricity market

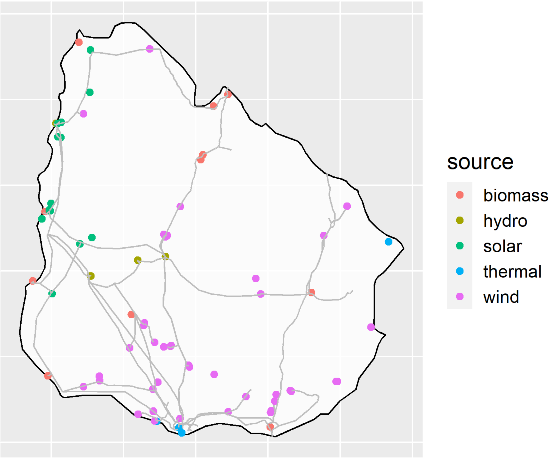


Figure: Electricity production facilities and high voltage distribution lines (MIEM, 2021).

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Data

Publicly available from “Administración del Mercado Eléctrico del Uruguay” (ADME)

- The production the market operator buys from each facility by hour (*MWh*)
- Consumption, imports, and exports to Brazil and Argentina by hour
- Spot prices by hour
- CO_2 emissions from the thermal sector by week

The data goes from the 1st of January 2009 until 31st of December 2020

Electricity production by time of day - MWh (Bs.As. 1 ; Bs.As. 2)

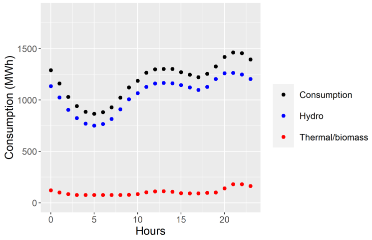


Figure: Winter 2010

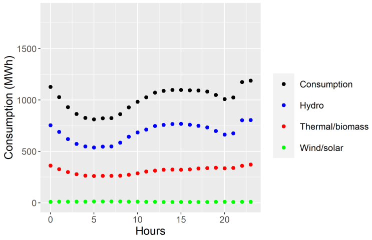


Figure: Summer 2010

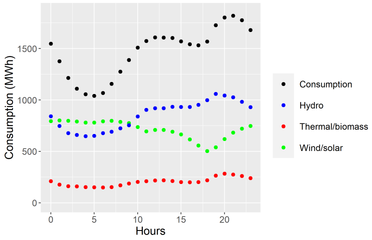


Figure: Winter 2020

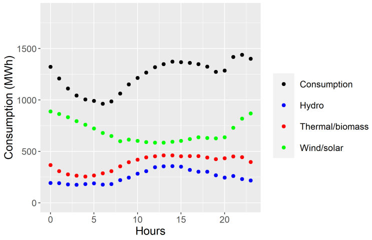


Figure: Summer 2020

Electricity production by time of day - MWh

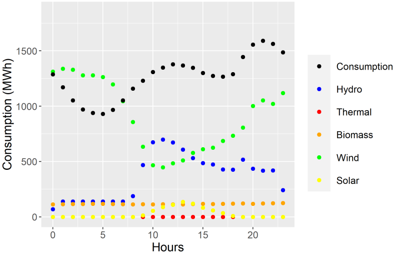


Figure: Winter - 08/10/2020

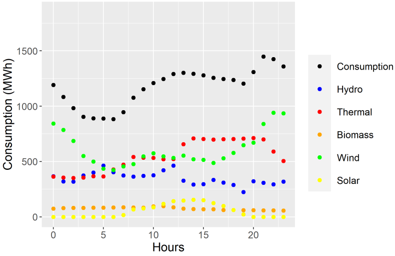


Figure: Summer - 11/10/2020

Descriptive statistics

	Mean	S.D	Min.	Max
Hydro (MWh)	755.32	344.64	0	1808.48
Wind (MWh)	236.76	314.66	0	1429.57
Thermal (MWh)	109.91	164.49	0	1040.59
Biomass (MWh)	73.37	37.65	0	206.12
Solar (MWh)	15.6	41.29	0	224.11
Demand (MWh)	1134.01	255.59	20.92	2505.68
Export (MWh)	67.04	193.33	0	1702.07
Import (MWh)	12.33	52.16	0	1000.01
Spot prices ($U\$S/MWh$)	85.27	94.06	0	275.85
Congestion	0.029	0.167	0	1
N	105,166	105,166	105,166	105,166
CO_2 emissions (Kg CO_2)	2.18M	5.63M	0	34.3M
N	1949	1949	1949	1949

Methodology - R.E substitution

$$q_{it} = \alpha + \beta W_t + \gamma S_t + \rho C_{it} + \phi D_t + \text{hour} * \text{month} + \text{month} * \text{year} + \epsilon_{it}$$

- q_{it} is the observed quantity produced by facility i at time t (hour, day, month, and year) from thermal, hydro, or biomass
- W_t - Total wind electricity produced
- S_t - Total solar electricity produced
- C_{it} - Congestion dummy Equation
- D_t - Electricity consumption (Cullen, 2013; Davis & Hausman, 2016; LaRiviere & Lu, 2017; Fell et al., 2021; Abrell & Kosch, 2022)
- hour*month fixed effects
- month*year fixed effects
- ϵ_{it} - clustered at month*year

Methodology - R.E substitution

- Use the randomness in wind and solar availability to identify the substitution patterns
- Wind and Solar have some patterns:
  - Wind: higher during early hours, especially in winter
  - Solar power is higher at noon, especially in summer
- To control for seasonal patterns, I use a rich set of time-fixed effects
- Congestion dummy - cumulative sum of electricity over the line capacity
- Consumption - also have some seasonal patterns. Depend on exogenous weather shocks, lighting, etc
- Insensitive to wholesale electricity spot prices
- No evidence: policy to decrease electricity consumption.
  - Energy efficiency

Methodology - R.E substitution: aggregate level

$$Q_t = \alpha_1 + \beta W_t + \gamma S_t + \rho C_t + \phi D_t + \text{hour} * \text{month} + \text{month} * \text{year} + \epsilon_t$$

- Q_t - Quantity produced of thermal, hydro, or biomass at hour *h*, day *d*, month *m*, and year *t*
- The rest as above

Methodology - CO_2 emission

$$\text{CO}_2\ \text{emission}_{it} = \alpha_2 + \beta W_t + \gamma S_t + \rho C_t + \phi D_t + \text{week} + \text{month} + \epsilon_{it}$$

- CO_2 emission$_{it}$ is the weekly aggregate of emissions for week w, month m, and year t for thermal facility i
- The rest as above - at weekly level

Methodology - Spot prices:

$$\sin^{-1}(\text{Spot prices}_t) = \alpha_3 + \beta W_t + \gamma S_t + \rho C_t + \phi D_t + \text{hour} * \text{month} + \text{month} * \text{year} + \epsilon_t$$

- spot price_{hdmt} is the spot prices at hour h, day d, month m, and year t
- The rest as above
- Consumption is inelastic to wholesale prices
- Spot prices - Inverse hyperbolic sine function transformation

Results: CO_2 Emissions

	kg CO_2 emissions		
Wind	-52.94**	-51.74*	-52.65**
	(24.13)	(24.86)	(23.63)
Solar	33.46 5	4.29	29.18
	(124.3)	(95.6)	(134.80)
Consumption	-38.31	-35.42	-39.33
	(31.58)	(30.37)	(31.68)
Cong. dummy	Y	Y	Y
Week	Y	N	Y
Month	N	Y	Y
N	1949	1949	1949

This table shows, the effect of wind and solar on kg CO_2 emissions. Standard errors are cluster at month*year.

Significance levels: ***0.01 **0.05 *0.1.

Results: Wind and solar substitution - Facility level

	Thermal	Hydro	Biomass
Wind	-0.0137***	-0.145***	-0.001***
	(0.0025)	(0.023)	(0.0002)
Solar	0.0058	-0.192***	0.0002
	(0.0052)	(0.028)	(0.0007)
Consumption	0.0108**	0.236***	0.0001
	(0.0038)	(0.017)	(0.0003)
Congestion	7.717	-58.56**	0
	(4.937)	(15.11)	(3.83e-09)
hour $*$ month	Y	Y	Y
month $*$ year	Y	Y	Y
N	736,162	420,664	1,051,660

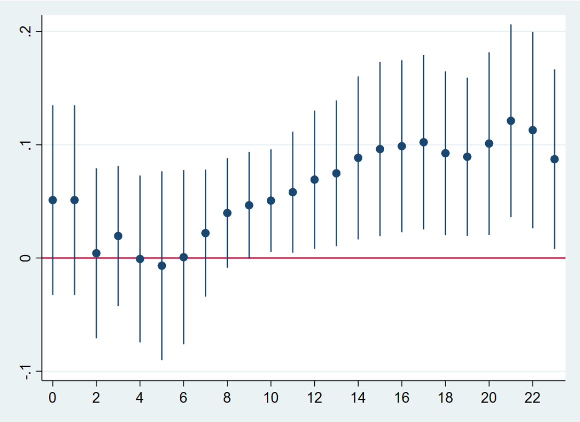
This table shows in column 2, 3, and 4, the effect of wind and solar in the production of thermal, hydro, and biomass, respectively. Standard errors are cluster at month*year. Significance levels: ***0.01 **0.05 *0.1.

Results: Wind and solar substitution - Aggregate level

	Thermal	Hydro	Biomass
Wind	-0.161***	-0.670**	-0.005***
	(0.025)	(0.067)	(0.001)
Solar	0.018	-0.755***	0.003
	(0.041)	(0.107)	(0.008)
Consumption	0.072**	0.933***	0.002
	(0.029)	(0.069)	(0.002)
Congestion	90.92***	108.25*	0
	(21.06)	(51.08)	(2.62e-08)
hour $*$ month	Y	Y	Y
month $*$ year	Y	Y	Y
N	105,166	105,166	105,166

This table shows in column 2, 3, and 4, the effect of wind and solar in the production of thermal, hydro, and biomass, respectively. Standard errors are cluster at month*year. Significance levels: ***0.01 **0.05 *0.1.

Results: Consumption on thermal production - Aggregate level



This figure presents the effect of consumption on thermal production by hour. Confidence intervals at 95%.

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Wind and solar substitution - Aggregate level by season

	Thermal	Hydro
Wind	-0.188***	-0.638***
	(0.042)	(0.008)
wind*winter	0.049	-0.06
	(0.042)	(0.066)
Solar	0.052	-0.675***
	(0.051)	(0.161)
Solar*winter	-0.11**	-0.174
	(0.059)	(0.197)
Consumption	0.07**	0.934***
	(0.026)	(0.068)
Cong. dummy	Y	Y
hour $*$ month	Y	Y
month $*$ year	Y	Y
N	105,166	105,166

Wind*winter and solar*winter shows the interaction between the sources and a dummy equal 1 if the season is winter or autumn. Winter/autumn: April to September. Summer/spring: October to March. Standard errors are cluster at month*year. Significance levels: ***0.01 **0.05 *0.1.

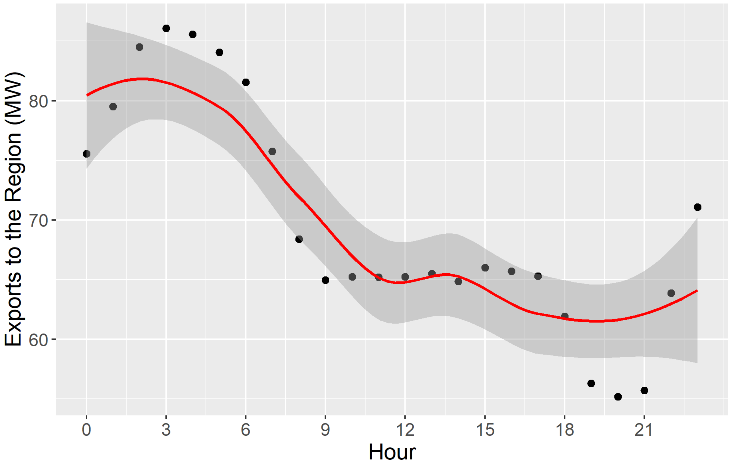
Results: Imports and Exports

	Total Exports	Total Imports
Wind	0.221**	-0.033
	(0.083)	(0.027)
Solar	0.252**	0.019
	(0.098)	(0.015)
Consumption	0.026	-0.001
	(0.064)	(0.006)
Congestion	33.14**	-3.112
	(12.84)	(3.431)
hour $*$ month	Y	Y
month $*$ year	Y	Y
N	105,166	105,166

This table shows the effect of wind and solar in the exports and imports of electricity to Argentina and Brazil.

Standard errors are cluster at month*year. Significance levels: ***0.01 **0.05 *0.1.

Results: Exports



Map

Spot prices - By season

	$\sin^{-1}$(Spot prices)
Wind	-0.0025***
	(0.0007)
wind*winter	-0.00001
	(0.0004)
Solar	0.0004
	(0.0006)
Solar*winter	-0.0017*
	(0.0009)
Consumption	0.0012**
	(0.0004)
Cong. dummy	Y
hour $*$ month	Y
month $*$ year	Y
N	105,142

This table shows the effect of wind and solar on spot prices. Spot prices are deflected using real exchange index with base 2017. Standard errors are cluster at month*year. Significance levels: ***0.01 **0.05 *0.1.

Results: Consumption on spot prices

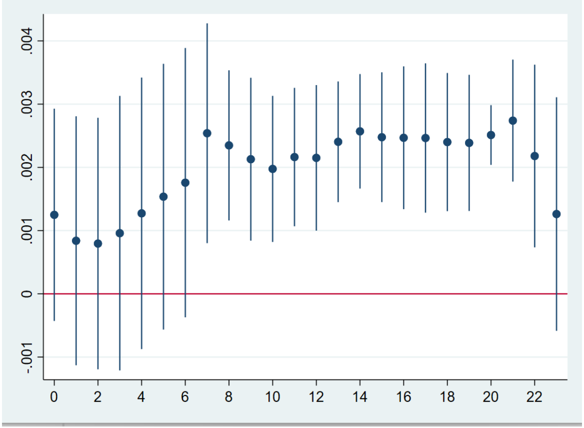


Figure: This figure presents the effect of demand on spot prices by hour. Confidence intervals at 95%.

Robustness check

1. Seemingly unrelated regression Table
   - Results are similar
2. Since hydro production is large, it could be that wind and solar are displacing hydro production in a given hour; but that hydro is then displacing some thermal production:
   - Within a day (Fell et al., 2021) Table
   - Within a week (Abrell & Kosch, 2022) Table
     - Wind estimations do not change, however I don't find the effect of solar on hydro anymore.
3. Congestion cut-off to 85% Table and 95% Table
   - Results are similar
4. Add different set of fixed effects
   - Day of the week fixed effect (Fell et al., 2021) Table
   - Hour $*$ day of the week fixed effect Table
     - Results are similar
5. Eliminate demand and congestion variable:
   - Facility level Table
   - Aggregate level Table

Conclusion

The increase in wind and solar production has several effects:

1. Displacement of thermal reduces 52 kg of CO_2

Conclusion

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1. Displacement of thermal reduces 52 kg of CO_2
2. A 1 MWh increase in wind:
   - Decreases thermal and hydro production by 0.16*** and 0.67*** MWh
   - decreases spot prices by 0.25%

Conclusion

The increase in wind and solar production has several effects:

1. Displacement of thermal reduces 52 kg of CO_2
2. A 1 MWh increase in wind:
   - Decreases thermal and hydro production by 0.16*** and 0.67*** MWh
   - decreases spot prices by 0.25%
3. A 1 MWh increase in solar:
   - Decreases hydro production by 0.76*** MWh
   - More pronounced effect on thermal in winter
   - decreases spot prices by 0.19% - winter
4. Plausible spillover effect to the region

The increase in wind and solar production is not enough to eradicate thermal entirely:

Possible Policy Implications

Countries use regulatory and fiscal policies to promote the entrance and deployment of renewable energy production:

- Another policy to increase the production of R.E
- Back-of-the-envelope calculations:
- 33.97 USD/MWh is saved for each MW*h* of wind produced
  - It cost 8 US dollars to retrieve one tonne of CO_2 (cte. 2017)
    - 1 MW*h* of wind decreases 0.052 tonnes of CO_2 emissions.
    - SCC: 185 (2020) US dollars per tonne of CO_2 (Rennert et al., 2022)
  - 25.97 USD/MWh is saved for each MW of wind produced
    - The average cost of wind is 59.30 USD/MW*h* (cte. 2017)
    - the average spot price for the whole sample is 85.27 USD/MWh (cte. 2017)
- External validity

Questions

Thank you!

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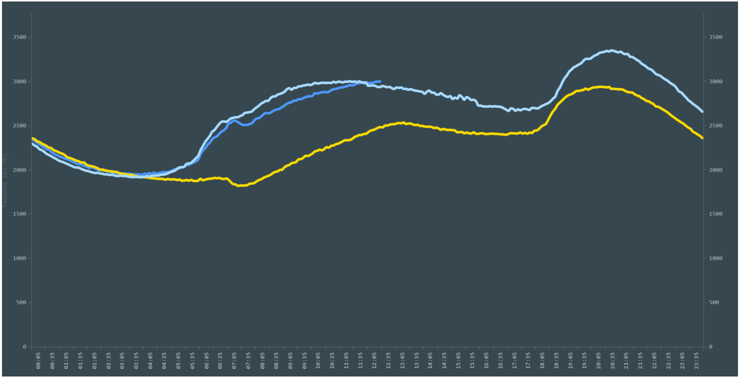
Buenos Aires - Demand electricity



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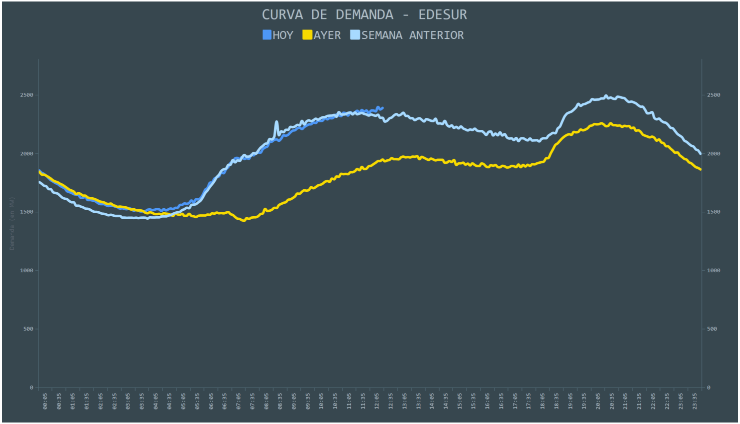
Buenos Aires - Demand electricity



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Appendix

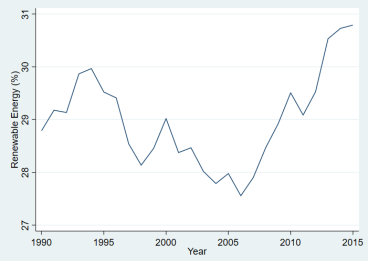

Figure: Percentage of renewable energy production for all countries. Source: WBI.b (2020).

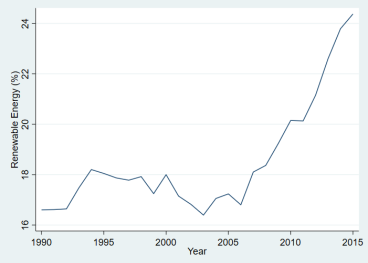

Figure: Percentage of renewable energy production for High-income countries. Source: WBI.b (2020).

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Robustness check: congestion cut-off to 85% Back

	Thermal		Hydro	
	w/a	s/s	w/a	s/s
Wind	-0.141***	-0.199***	-0.712***	-0.621***
	(0.03)	(0.044)	(0.065)	(0.082)
Solar	-0.06	0.035	-0.859***	-0.659***
	(0.033)	(0.055)	(0.127)	(0.159)
Consumption	0.038**	0.100*	0.992***	0.876***
	(0.014)	(0.045)	(0.071)	(0.072)
Cong. dummy	Y	Y	Y	Y
hour $*$ month	Y	Y	Y	Y
month $*$ year	Y	Y	Y	Y
N	52,679	52,487	52,679	52,487

This table shows the effect of wind and solar on thermal and hydro production on winter/autumn and summer/spring. The congestion cut off is set on 85%. Winter/autumn: April to September. Summer/spring: October to March. Standard errors are cluster at month*year. Significance levels: ***0.01 **0.05 *0.1.

Robustness check: congestion cut-off to 95% Back

	Thermal		Hydro	
	w/a	s/s	w/a	s/s
Wind	-0.128***	-0.183***	-0.701***	-0.621***
	(0.03)	(0.044)	(0.069)	(0.082)
Solar	-0.048	0.040	-0.856***	-0.659***
	(0.036)	(0.055)	(0.128)	(0.159)
Consumption	0.041**	0.103*	0.992***	0.876***
	(0.013)	(0.046)	(0.072)	(0.072)
Cong. dummy	Y	Y	Y	Y
hour $*$ month	Y	Y	Y	Y
month $*$ year	Y	Y	Y	Y
N	52,679	52,487	52,679	52,487

This table shows the effect of wind and solar on thermal and hydro production on winter/autumn and summer/spring. The congestion cut off is set on 85%. Winter/autumn: April to September. Summer/spring: October to March. Standard errors are cluster at month*year. Significance levels: ***0.01 **0.05 *0.1.

Robustness check: Cullen (2013) Back

	Thermal		Hydro		Biomass	
	Est.	Mg. E	Est.	Mg. E.	Est.	Mg. E
Wind	-0.061***	-0.043***	-0.19***	-0.154***	0.015***	0.009**
	(0.003)	(0.002)	(0.012)	(0.006)	(0.001)	(0.001)
$Wind^2$	3e-05 ***		6e-05***		-9.51e-06	
	(2.78e-06)		(1e-05)		(8.77e-07)	
Solar	-0.081***	-0.059**	-0.109	-0.143**	0.021***	0.0184**
	(0.025)	(0.018)	(0.09)	(0.067)	(0.007)	(0.005)
$Solar^2$	0.0005***		-0.0007		-5e-05	
	(16e-04)		(0.0005)		(4e-05)	
Consumption	-0.0052***		0.002***		0.003***	
	(0.007)		(0.007)		(0.0004)	
Cong.	Y		Y		Y	
Day	Y		Y		Y	
N	122,976		70,272		175,680	

This table shows effect of wind and solar in the production of thermal, hydro, and biomass separately. Standard errors are Newey-West with 4 lags. Significance levels: ***0.01 **0.05 *0.1.

Robustness check: Different time fixed effects Back

	Thermal	Hydro	Biomass
Wind	-0.160***	-0.672***	-0.005***
	(0.025)	(0.068)	(0.001)
Solar	0.020	-0.757***	0.003
	(0.039)	(0.108)	(0.009)
Consumption	0.058*	0.947***	0.004*
	(0.027)	(0.080)	(0.002))
day of the week	Y	Y	Y
Cong. dummy	Y	Y	Y
hour $*$ month	Y	Y	Y
month $*$ year	Y	Y	Y
N	105,166	105,166	105,166 6

This table shows the effect of wind and solar in the production of thermal, hydro, and biomass respectively, considering day of the week fixed effects. Standard errors are cluster at month*year. Significance levels: ***0.01 **0.05 *0.1

Robustness check: Different time fixed effects Back

	Thermal	Hydro	Biomass
Wind	-0.160***	-0.673***	-0.005***
	(0.025)	(0.068)	(0.015)
Solar	0.020	-0.758***	0.003
	(0.041)	(0.110)	(0.008)
Consumption	0.055	0.953***	0.004
	(0.031)	(0.085)	(0.002)
hour $*$ day of the week	Y	Y	Y
Cong. dummy	Y	Y	Y
hour $*$ month	Y	Y	Y
month $*$ year	Y	Y	Y
N	105,166	105,166	105,166

This table shows the effect of wind and solar in the production of thermal, hydro, and biomass respectively, considering hour $*$ day of the week fixed effects. Standard errors are cluster at month*year. Significance levels: ***0.01 **0.05 *0.1

Robustness check: Aggregate at day level Back

	Thermal	Hydro	Biomass
Wind	-0.157***	-0.633***	-0.005***
	(0.022)	(0.088)	(0.002)
Solar	-0.04	0.194	0.012
	(0.038)	(0.5)	(0.008)
Consumption	0.067***	1.00***	0.002
	(0.016)	(0.078)	(0.002)
day $*$ month	Y	Y	Y
N	106,166	106,166	106,166

This table shows the effect of wind and solar in the production of thermal, hydro, and biomass respectively. Aggregating at day level with day $*$ month fixed effects. Standard errors are cluster at month*year. Significance levels: ***0.01 **0.05 *0.1

Robustness check: Aggregate at week level Back

	Thermal	Hydro	Biomass
Wind	-0.159***	-0.641***	-0.005***
	(0.024)	(0.087)	(0.001)
Solar	-0.038*	0.194	0.011
	(0.02)	(0.437)	(0.007)
Consumption	0.067***	1.01***	0.004**
	(0.014)	(0.084)	(0.001)
week	Y	Y	Y
Cong. dummy	Y	Y	Y
month $*$ year	Y	Y	Y
N	106,166	106,166	106,166

This table shows the effect of wind and solar in the production of thermal, hydro, and biomass respectively.

Aggregating at week level with week. Standard errors are cluster at month*year. Significance levels: ***0.01

**0.05 *0.1

Robustness check: Facility level Back

	Thermal			
Wind	-0.0137***	-0.0108***	-0.0128***	-0.0097***
	(0.0025)	(0.002)	(0.002)	(0.002)
Solar	0.0058	0.0068	0.009	0.01
	(0.0052)	(0.005)	(0.006)	(0.006)
Consumption	0.0108**	0.011**		
	(0.0038)	(0.004)		
Congestion	7.717		7.822	
	(4.937)		(4.957)	
N	736,162	736,162	736,162	736,162

	Hydro			
Wind	-0.145***	-0.153***	-0124***	-0.131***
	(0.023)	(0.021)	(0.021)	(0.019)
Solar	-0.192***	-0.190***	-0.123***	-0.123***
	(0.028)	(0.027)	(0.034)	(0.034)
Consumption	0.236***	0.235***		
	(0.017)	(0.017)		
Congestion	-58.56**		-53.54***	
	(15.11)		(15.62)	
N	420,664	420,664	420,664	420,664
week	Y	Y	Y	Y
month $*$ year	Y	Y	Y	Y

This table shows the effect of wind and solar in the production of thermal (panel A) and hydro (panel B). Standard errors are cluster at month*year. Significance levels: ***0.01 **0.05 *0.1

Robustness check: Aggregate level Back

	Thermal			
Wind	-0.161***	-0.078***	-0.155***	-0.071***
	(0.025)	(0.015)	(0.026)	(0.015)
Solar	0.018	0.044	0.038	0.067
	(0.041)	(0.037)	(0.041)	(0.041)
Consumption	0.072**	0.081**		
	(0.029)	(0.028)		
Congestion	90.92***		92.50***	
	(21.06)		(21.59)	

	Hydro			
Wind	-0.672***	-0.613***	-0.602***	-0.525***
	(0.067)	(0.084)	(0.065)	(0.077)
Solar	-0.755***	-0.762***	-0.484**	-0.490**
	(0.107)	(0.108)	(0.130)	(0.134)
Consumption	0.933***	0.940***		
	(0.069)	(0.067)		
Congestion	108.25*		139.9*	
	(51.08)		(48.21)	
week	Y	Y	Y	
month $*$ year	Y	Y	Y	
N	106,166	106,166	106,166	

This table shows the effect of wind and solar in the production of thermal (panel A) and hydro (panel B). Standard errors are cluster at month*year. Significance levels: ***0.01 **0.05 *0.1

Robustness check: SUR Back

	Thermal	Hydro	Biomass	Exports
Wind	-0.141***	-0.64***	-0.005***	0.213***
	(0.013)	(0.026)	(0.001)	(0.025)
Solar	0.025	-0.763***	0.003	0.265***
	(0.033)	(0.084)	(0.006)	(0.088)
Demand	0.075***	0.941***	0.002	0.024
	(0.017)	(0.038)	(0.002)	(0.033)
Congestion	66.10***	27.30***	0	47.96
	(8.003)	(6.763)	-	(8,18)
N	105,166	105,166	105,166	105,166
week	Y	Y	Y	Y
month $*$ year	Y	Y	Y	Y

This table shows the seemingly unrelated regression results. Standard errors are cluster at month or year.

Significance levels: ***0.01 **0.05 *0.1

Congestion

To construct the congestion variable I:

- calculated the cumulative sum of electricity up until a facility
  - including the production of the specific facility
- Then, divided the cumulative sum production by the capacity of the line.

$$\text{Congestion} = \frac{\sum q_{i,t}}{\text{Line Capacity}} > 0.90 \qquad (1)$$

Back

Congestion over time

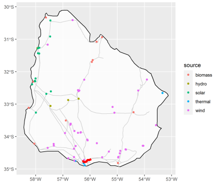

Figure: Congestion 2009

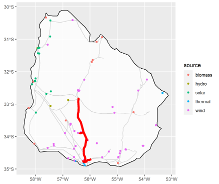

Figure: Congestion 2015

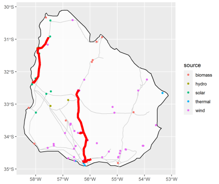

Figure: Congestion 2017

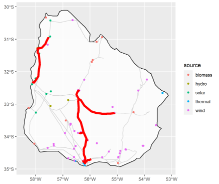

Figure: Congestion 2020

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