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

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Abstract

The benefits of expanding wind and solar electricity generation depend on their effect on the electricity production mix. Using hourly production data, I study the electricity transition to renewables in Uruguay, a country that currently has 94% of its grid green. First, I quantify how an increase in wind and solar production substitutes hydro, biomass, and fossil fuel electricity production. Second, I analyze how this transition reduces CO_2 emissions in the context of large hydropower production. Third, I analyze how this affects spot prices. I find that the increase in wind and solar production has the following effects: (i) a displacement of hydro and fossil fuel production, especially in winter, with no effect on biomass; (ii) a reduction in CO_2 emissions; (iii) a decrease in spot prices caused by the shutting off of the most (marginally) costly plants; and (iv) a spillover effect to the region due to an increase in exports to Argentina and Brazil. I find, however, that the increase in wind and solar production is insufficient to eradicate fossil fuels. These results show the effect of increasing renewables, how they interact with each other - particularly in hydro-dependent countries -, and their effect on emissions and spot prices.

Keywords: Energy economics, climate change, applied microeconomics

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1 Introduction

Decarbonizing electricity production is crucial to mitigate climate change and large-scale investments in renewables are vital to stay below the 2°C target (IPCC, 2022). The most reliable way to mix electricity sources in the grid is, however, subject to debate. This is particularly significant for renewables, as they are non-dispatchable, weather-dependent, and produced at long distances from consumption centers. These inherent characteristics increase their uncertainty at the production level. Furthermore, developed countries have led the expansion of renewables; however, given the worsening climate conditions, developing countries also need to increase their production of renewables. In this study, I analyze the electricity transition of Uruguay, a country that transitioned to a 94% green grid in 12 years by fostering a policy that reduced uncertainty at the firm level (BEN, 2022; CAF, 2022).

The government regulates the Uruguayan electricity market and until 2007, electricity was generated from two state-owned sources: hydropower and fossil fuels. To reduce exposure to droughts and to decouple electricity prices from crude oil and natural gas prices - Uruguay imports all of its gas oil, fuel oil, and natural gas (see Table A2 for more details) - the government fostered investment in renewable sources such as wind and solar. Such investments have led to a rapid transition to renewable energy over the last two decades. Furthermore, the market operator decides which sources to buy electricity from based on a merit order; from facilities with the lowest to the highest marginal costs.

This study focuses on several aspects of Uruguay's transition to a green grid. First, I quantify the substitution of wind and solar with other electricity sources, namely hydropower, biomass, and fossil fuels. Second, I examine the effect of this transition on CO_2 emissions in the context of large hydropower production. Finally, I analyze the effect on the spot price, which reflects the marginal cost of increasing the demand by one unit at a given node.[1] Shifts in the spot prices show how the marginal cost of producing electricity changes in response

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[1] Uruguay has a unique node for the entire country.

to an increase in wind and solar production, helping to determine which source is likely to be used at the margin. The displacement of renewables from other sources depends on several factors: the temporal patterns of production from different sources, the demand for electricity, the composition of electricity production, and the intermittency of renewables. Consequently, the substitution effect of renewables on other sources and their effect on CO_2 emissions and spot prices is an empirical question. [2]

I collect facility-level data for the hourly production of wind, solar, fossil fuel, hydro, and biomass for the period 2009-2020 from the Uruguayan market operator "Administración del Mercado Eléctrico del Uruguay" (ADME). I also obtain hourly data on consumption (i.e., load), spot prices, imports, and exports for the same period and from the same source. I exploit the randomness of wind and solar production to identify their substitution effect on hydro, biomass, and fossil fuel production. However, as wind and solar exhibit some predictable patterns (wind is higher in the early morning, especially in winter, while solar power is higher at noon, especially in summer), I control for these seasonal patterns using an extensive set of time-fixed effects.

The results can be summarized as follows. First, wind production displaces hydro and fossil fuels, with a more pronounced effect on hydropower. Specifically, a 1 $\mathrm{MW}h$ increase in wind displaces hydro and fossil fuel production by 0.69 and 0.17 $\mathrm{MW}h$, respectively. Solar, on the other hand, only significantly affects hydro. An additional $\mathrm{MW}h$ in solar reduces hydro production by 0.84 $\mathrm{MW}h$. I find no substitution effect of wind and solar on biomass, which is consistent with biomass being a baseload source (i.e., not used at the margin). I also consider heterogeneity by season, analyzing spring and summer separately from autumn and winter. Wind has the same substitution effect across the seasons while solar substitutes fossil fuels only in the autumn and winter. I propose two possible mechanisms to explain the latter: first a change in the baseload (Holland & Mansur, 2008; Holladay & LaRiviere, 2017; Abrell et al.,

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[2] This holds despite the fact that the market operator has a minimization problem in mind. For more information, see Section 3.

2019). Wind and hydro production are at their lowest in spring and summer and consequently, fossil fuels are used because solar power is insufficient to satisfy consumption. In contrast, in autumn and winter fossil fuel facilities are mostly used at the margin. The other plausible explanation is that wind and solar are exported: a 1 MWh increase in wind and solar increases exports by 0.13 and 0.22 MWh, respectively. These results are consistent with renewable electricity being a heterogeneous good (Novan, 2015), especially when understanding its substitution effect on non-renewables. In renewables, however, wind and solar have the same substitution rate.

Second, the results indicate that wind production reduces CO_2 emissions: a 1 MWh increase in wind reduces 17 kg of CO_2 emissions from fossil fuel production. This effect is smaller than expected because, although wind substitutes for fossil fuels significantly, its effect for hydro is larger.

Finally, wind and solar production decreases spot prices: an additional MWh in wind and solar reduces spot prices by 0.22% and 0.17%, respectively. Note that the effect of solar is only observed in winter, this is consistent with solar only substituting fossil fuels in autumn and winter, as mentioned previously. Because the spot price equals the marginal cost of producing an additional unit of electricity and the market administrator satisfies consumption using a merit order approach (from the lowest to the highest marginal cost), these results show that the increase in wind and solar production shuts off the facilities with the highest marginal cost (i.e. fossil fuel facilities) at a specific hour. Moreover, I study the effect of a one-unit increase in consumption on spot prices. Consumers do not respond to spot prices; they pay a fixed and known amount, as specified in the electricity contract. [3] On average, I find that consumption has a positive effect on spot prices, however the impact differs depending on the time. From 11 p.m. to 6 a.m., when wind production peaks, a one-unit increase in consumption has no effect on spot prices, whereas from 7 a.m. to 10 p.m., when wind is low

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[3] For further details see section 5.

and solar is not enough to displace fossil fuels, consumption has a positive and significant effect on spot prices.

This study contributes to the literature in several ways. First, I analyze how an increase in wind and solar production interacts with other renewable sources. While many countries are pursuing a transition to renewables, how these renewables interact with each other has yet to be fully explored. The Uruguayan case is, therefore, particularly useful in analyzing how renewables substitute each other, as Uruguay has always had a large share of hydro and a moderate share of biomass in its grid. This is particularly relevant for upper-middle and middle-income countries, which generate 21% and 19% of their electricity from hydropower (WB, 2023), respectively. Second, I contribute to the growing literature on the spillover effects of an increase in renewable production on other countries. Third, I present an alternative approach to calculating congestion in which only the capacity of the line, the electricity sold into the grid from the facilities, and the facilities' locations are required. Fourth, this study contributes to the literature on the effect of renewables on CO_2 emissions in a new context, one with large hydropower production - a feature shared by many countries and where the substitution effect for fossil fuels is complex. Finally, in contrast to other studies that have focused on price-based electricity markets in developed countries, I examine the expansion of renewable energy in a regulated market; a setting that has been scarcely explored.

The remainder of this paper is organized as follows. Section 2 presents the literature review. Section 3 describes the Uruguayan electricity market. Section 4 presents the data and descriptive statistics. Sections 5 and 6 present the identification strategy and results. In section 7, different robustness checks are presented. Finally, the conclusion is presented in Section 8.

2 Literature Review

This study makes several contributions to the existing literature. First, it expands the analysis of the substitution of renewable electricity for different energy sources. Cullen (2013), for example, estimates the substitution of wind for fossil fuels in Texas from 2005 to 2007, and finds that a 1 MWh increase in wind reduces coal and gas production between 0.1 to 0.18 MWh and 0.85 to 0.92 MWh, respectively. Following this groundbreaking paper, other important papers incorporated hourly or seasonal heterogeneity, focused on other regions and years, and/or changed the scope of analysis. For instance, Carson and Novan (2013) analyzes the impact of storage on the increase in wind and solar production and its effect on wholesale prices and emissions in Texas between 2007 and 2009. The authors find that electricity arbitrage affects renewable production substitution and spot prices differently, depending on whether the arbitrage happens during the on-peak or off-peak demand periods. Novan (2015) contributes to the previous literature by including heterogeneity by source and analyzing how wind and (potential) solar production substitutes fossil fuels in Texas from 2007 to 2011. The author finds that wind and solar are heterogeneous goods, with wind having a larger substitution effect for fossil fuels than solar. Holladay and LaRiviere (2017) use wind and potential solar production to analyze the substitution effect on natural gas after the fracking boom in the United States and its effect on CO_2 emissions. They find that the natural gas boom changed the merit order of supply, rendering the effect of renewables on marginal emissions time-, season-, and context-dependent. Callaway et al. (2018) evaluate how a simulated increase in wind and solar production, as well as the implementation of energy-efficiency improvements, reduces emissions, taking into account technological, spatial, and temporal variation for the United States between 2010 and 2012. The authors find large regional differences in the substitution of renewables for fossil fuels. A key difference in this study is the use of actual solar production rather than potential production, as used in these previous studies.

In the European market, Abrell et al. (2019) examine how an increase in wind and solar production affects CO_2 emissions, prices, and abatement costs by comparing Germany and Spain's electricity markets. Results vary depending on the resource and subsidy type, ultimately representing differences in market conditions, production costs, and availability of natural resources. Similarly, Gugler et al. (2021) analyzes how an increase in wind and solar production displaces fossil fuels and the effect on CO_2 emissions, exploiting the difference in carbon prices for Britain and renewable subsidies for Germany. In concordance with Abrell et al. (2019), they find that the effect of wind and solar on fossil fuels, and consequently on CO_2 emissions, depends on the context. In Germany, the reduction in emissions is greater because coal is being displaced, while in Britain, natural gas is the source in the margin, dampening the effect on emissions.

While all previous studies mentioned employ methodologies similar to the one used in this paper, in that the short-run substitution is analyzed, Bushnell and Novan (2021) differs. Specifically, they study the long-run substitution of renewable electricity production for fossil fuels, their effect on prices, and on CO_2 emissions in California from 2013 to 2017, including hourly and seasonal heterogeneity. The authors find that an increase in renewables substitutes for fossil fuels and affects spot prices differently depending on the time of day. [4]

The main contribution of this study to the existing literature is to examine the substitution effect of wind and solar on other renewables (such as hydro and biomass) and their effect on fossil fuels. While previous studies have only examined the substitution effect of renewables on non-renewables, this study broadens the scope by analyzing the effect on renewables as well. Understanding how renewables interact with each other is an important step towards decarbonizing the electricity sector, especially considering that the goal is for all countries' grids to be primarily powered by renewable sources.

This study also contributes to the expanding body of literature on the spillover effects

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[4] See a summary of these papers in Table A1 in the Appendix.

of renewables on other countries. For example, Abrell and Kosch (2022) study the spillover effect of an increase in renewable energy production in Germany on other European countries from 2015 to 2020. They find that an increase in renewable energy from Germany not only substitutes for fossil fuels, but also for hydro, the latter of which is aligned with my findings. Similarly, Yang (2022) studies how an increase in wind and solar affects the trade between two different grids. In conclusion, interconnection decreases (increases) investment in renewables and consequently increases (decreases) emissions when carbon prices are low (high).

Next, a growing body of literature shows that electricity grid congestion poses a crucial obstacle to the expansion of renewable energy generation. For example, Fell et al. (2021) find that accounting for congestion increases non-market wind value by 30%, using data from Texas between 2011 and 2015. Similarly, Ryan (2021) finds that congestion in India limits interregional trade, ultimately raising prices and exacerbating power market. Within this context, Wolak (2015), LaRiviere and Lu (2017), and Gonzales et al. (2022) study the effect of transmission line expansion in Alberta, Canada; Texas, USA; and Chile, respectively. All of these studies show a decrease in energy prices following the completion of electricity transmission lines. These studies either obtained the congestion measure from the market operator or calculated it by analyzing price differences between regions[5] As my research focuses on a regulated market where price differences between regions are not observable, another contribution is the development of a different approach for calculating congestion, requiring the line capacity, the electricity sold into the grid from facilities, and the facility's location.

Transitioning to a greener grid directly affects air pollution. Multiple studies find that an increase in renewable production reduced pollution, including Abrell and Kosch (2022); Bushnell and Novan (2021); Fell et al. (2021); Gugler et al. (2021); LaRiviere and Lu (2017); Kaffine et al. (2013). However, Holladay and LaRiviere (2017) find that the natural gas

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[5] For example, if there is a distinguishable price difference between nodes, the lines are congested.

fracking boom in the United States changed the baseload, making the effect of an increase in wind and solar production on CO_2 emissions region- and time-dependent. From the consumer perspective, Holland and Mansur (2008) explore how short-run changes in load affect emissions in the United States from 1997 to 2007 and conclude that shifts in demand change the baseload variance distribution, making the effect on emissions context-dependent. Zivin et al. (2014) expands on the previous study by introducing temporal heterogeneity and reaches a similar conclusion, finding that the effect of load on emissions varies between locations and hours of the day. Similarly, Holland et al. (2016) analyzes how an increase in electricity consumption due to a rise in electric vehicle use between 2010 and 2012 substitutes local emissions for global emissions, arguing that most of these vehicles are charged using natural gas or coal. However, these results are spatially dependent and therefore, my fourth contribution is to expand the extensive literature on the effects of renewables on CO_2 emissions, focusing especially on highly hydro-dependent countries. In addition, I explore how changes in load affect the production of hydro, biomass, and fossil fuels.

Finally, most of the literature on 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), European countries (Abrell & Kosch, 2022; Yang, 2022; Gugler et al., 2021; Abrell et al., 2019), and Australia (Karaduman, 2020). Furthermore, most renewable energy production currently occurs in developed countries such as Iceland, Norway, New Zealand, and Austria, with the exception of Brazil and Chile.[6] This research, however, examines a different setting that has not yet been thoroughly explored. Specifically, I study the increase in renewable electricity production in a regulated market. However, from a policy perspective, the same model used in the Uruguayan market can be applied to both regulated and unregulated markets. This is because, even though the Uruguayan electricity market is regulated, it is based on a least-cost

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[6] Source: Our World in Data.

dispatch model, as is the case in unregulated markets. Plants with the lowest marginal cost are dispatched first (e.g. renewables and hydro),[7] followed sequentially by the plants with the higher marginal cost (e.g. fossil fuels).

3 Electricity Market in Uruguay

To avoid blackouts, countries with an unregulated electricity market typically operate as follows: electricity firms submit bids of electricity production and price, which are then ordered by the dispatcher until the market clears. This approach is implemented in several countries, including the United States, Spain, (Reguant, 2014), and Australia (Karaduman, 2020). The Uruguayan electricity market, however, operates differently as it is a state-regulated market. The market operator (ADME) decides the quantity of electricity to buy from each plant based on a merit order, from the lowest to the highest marginal cost, and then a large state-owned electric company distributes the electricity to consumers. Until 2007, all electricity was generated from two sources: hydropower and fossil fuels, both owned entirely by the government. To reduce exposure to droughts and detach electricity prices from crude oil and natural gas prices (Uruguay imports the entity of its gas oil, fuel oil, and natural gas consumption, see Table A2 for more details), the government incentivized investment in renewable sources, such as wind, solar, and biomass. Through public auctions, companies submitted bids based on power capacity and price, and the government then authorized the installation and production of renewable energy to the companies with the best offers. This arrangement is distinctive in that the government agrees by contract to buy all the renewable electricity produced at the bidding price. While wind, solar, and biomass prices are all stipulated by contract, hydropower and fossil fuels participate in the spot market.

The market operator's minimization problem is stated in Equation 1,[8] where $T \exists in$ (fossil fuels(f), hydr

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[7] Nuclear is also in this category. In this case, it is omitted because Uruguay has no nuclear production.

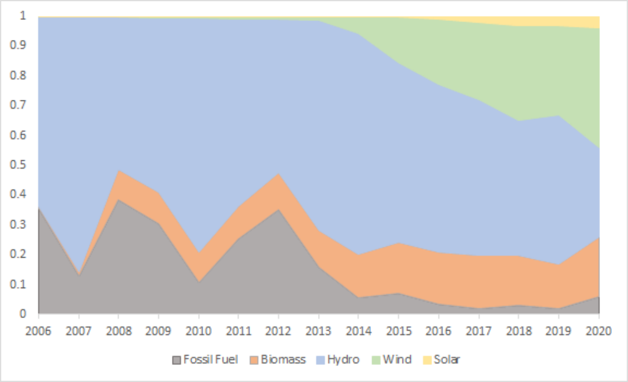
[8] Special acknowledgment to the anonymous reviewer that raised this concern.

M, X, where M refer to imports and X to exports. C_T is the cost of obtaining a unit of electricity from the source T; q_T is the total units of electricity from source T; and k_T is the total capacity from source T. The first constraint states that the supply equals the demand, and the second restriction shows the capacity constraint of each source.

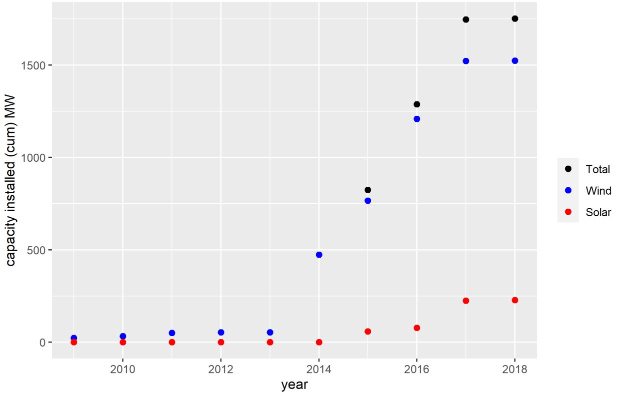
$$\begin{aligned} \min \ & \sum_T C_T q_T \\ S.T \ & \sum_T q_T + M - X = Demand \\ & q_T \leq k_T, \forall T \end{aligned} \tag{1}$$

Ideally, the market operator would solve Equation (1) at every hour. However, there are several factors that are beyond the dispatcher's control, including the demand for electricity, the composition of electricity production, and the intermittency of renewables, which ultimately depends on the stochastic nature of sunlight and wind. Consequently, the dispatcher does not know the exact substitution pattern between sources, requiring the empirical approach specified in Section 5.

Uruguay has encouraged investment in renewable electricity over the past two decades by exclusively allowing only the installation and production of renewables. Furthermore, the government has agreed to purchase all electricity generated by renewable farms at the bidding price, participating outside the spot market. This policy resulted in renewable sources accounting for 94% of the grid capacity (BEN, 2022; CAF, 2022). Panel (a) in Figure 1 shows the composition of electricity consumption and how it changes over time. In 2009, the main source dispatched to satisfy electricity demand was hydropower, followed by fossil fuels, while in 2020, wind and hydro were the main sources, followed by biomass. Panel (b) shows the growth in wind and solar cumulative capacity installed in megawatts (MW) over time. Since 2018, Uruguay's wind and solar capacity has remained stable at 1500 MW of wind and 250 MW of solar.



(a) Electricity production by source. Source: (BEN, 2022)



(b) Wind and solar capacities installed (MW). Source (ADME, 2022; UTEi, 2022)

Panel (a) presents the different sources that satisfy consumption over the years, source: (BEN, 2022). Panel (b) shows the cumulative installed capacity of wind and solar power over the years (MW), source (ADME, 2022; UTEi, 2022).

Figure 1: Electricity evolution

4 Data and Descriptive Statistics

The data used is publicly available from the Uruguayan market operator ADME. (ADME, 2022). I collect hourly production data (what the market operator buys from each facility in megawatt-hours MWh) ranging from January 1st, 2009, to December 31st, 2020[9] I also obtain hourly consumption, imports and exports to Brazil and Argentina, and spot prices.

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[9] The 31st of August, 2016 is omitted due to unreliable data.

As shown in Figure 1, since 2018, the wind and solar capacity has stabilized at 1500 and 250 MW, respectively. Therefore, from 2009 to 2020 the entirety of investments in wind and solar production are considered. Moreover, data from 2020 onward was discarded because of COVID-19 and its disruption to electricity consumption patterns (Santiago et al., 2021; García et al., 2021).

Uruguay has five main sources of electricity: wind, solar, biomass, fossil fuels, and hydro. The source with the most establishments is wind with 41 facilities; followed by solar with 17 facilities; biomass with 11 facilities; fossil fuel with 9 facilities; and finally hydro with 4 facilities. The main fuel used in fossil fuel facilities is gas oil, followed by natural gas and fuel oil; for more information, see Table A2 in the Appendix. Hydro has 4 facilities that are run-of-river generation[10] Figure 2 shows the locations of these facilities, color-coded by source, along with the main electricity lines in gray. These facilities have produced electricity at least once since 2009. Wind and solar farms are strategically located near the main power lines.[11] The yellow area in the figure represents the capital city, where the majority of the population lives and most of the fossil fuel plants are located.

Figure 3 presents the average electricity consumption and production in July and December for 2010 and 2020, before and after the increase in wind and solar production. Unlike countries in the northern hemisphere, in Uruguay, autumn and winter are from April to September, while spring and summer are from October to March. The black line represents the electricity consumption, the blue line the hydro dispatch, the red line the biomass and fossil fuel dispatch, and the green line the wind and solar dispatch. All units are in MWh. Figure 3 demonstrates that electricity consumption has increased between 2010 and 2020. Second, it shows that peak demand occurs after 8 p.m. (20 hrs), while the off-peak hour is around 5 a.m. Third, fossil fuel and biomass production in winter is relatively low, given

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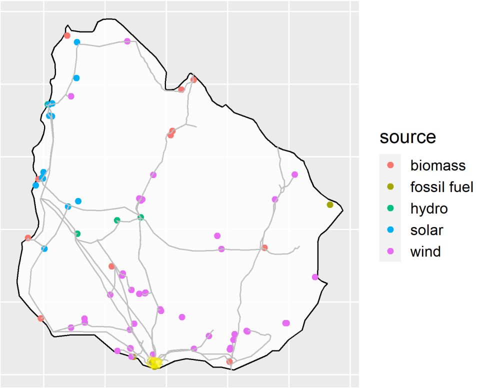
[10] They have some reservoir capacity, but only up to 3 days. Therefore, as a robustness check, the data is aggregated at weekly level.

[11] Unfortunately installation timing of the electricity line was unavailable.



This figure shows the location of the different facilities, color-coded by source, and the main electricity lines shown in gray. The yellow area represents the capital city. All the facilities have produced electricity at least once since 2009. Source (UTEi, 2022).

Figure 2: Electricity facilities and lines.

that hydro in 2010 and hydro, and wind and solar together in 2020 are the primary sources that satisfy the consumption (see panels (a) and (c)). Fourth, wind and solar have considerably displaced hydro production in winter. Finally, in summer, fossil fuels are still being dispatched at the same level as in 2010.

Figure 4 shows the behavior of each source on a specific day in winter (August 10th) and summer (November 10th) in 2020. In both graphs, the biomass dispatch remains nearly constant and solar dispatch occurs only between 10 a.m. and 7 p.m. (19 hrs.). Hydro and wind mirror each other in winter and fossil fuel dispatch is close to zero. In summer, however, fossil fuel production increases. Fossil fuel technologies include gas oil, natural gas, and fuel oil. It takes between 5 and 35 minutes to start generating electricity and therefore these facilities can quickly respond to changes in consumption. [12]

As discussed in Section 2, congestion is a key factor that can bias the results if not accounted for. To construct the congestion variable, I first calculate the cumulative sum of electricity production up to a facility, including the specific plant's production. The cumulative production is then divided by the capacity of the line. Additionally, since the capital and

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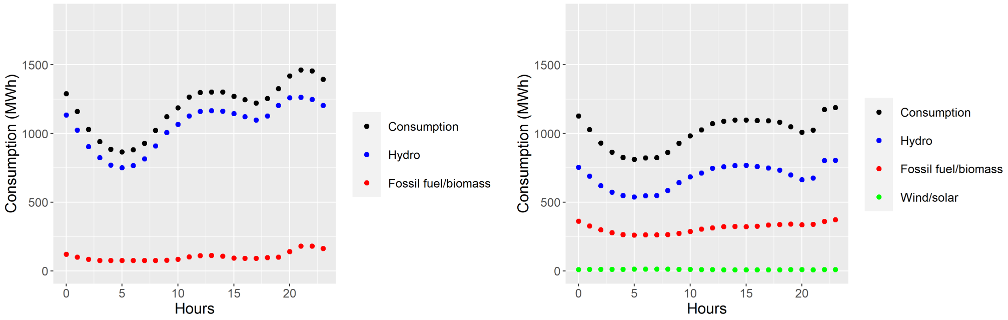
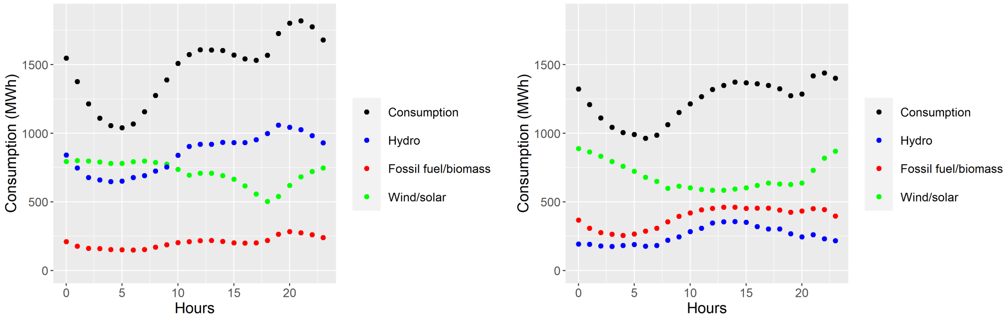
[12] More precisely, it takes 5, 15, 25, or 35 minutes to turn on, depending on the technology.



(a) Winter 2010 MWh (b) Summer 2010 MWh

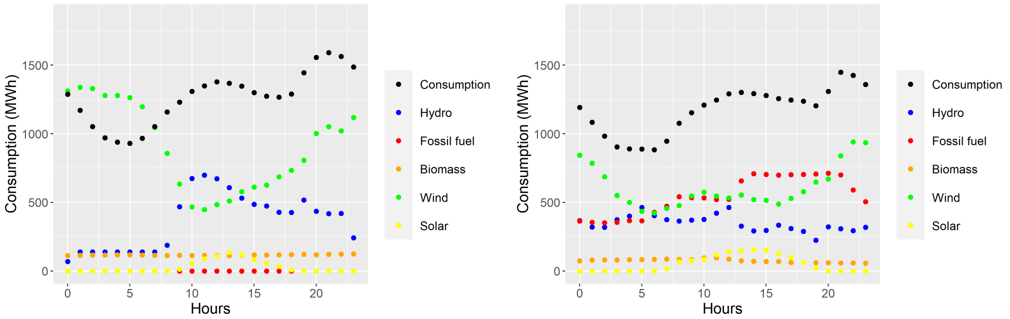


(c) Winter 2020 MWh (d) Summer 2020 MWh

Panels (a) and (b) show the evolution of the average consumption and which sources were used to satisfy it in July (winter) and December (summer) of 2010. Panels (c) and (d) show the evolution of the average consumption and which sources were used to satisfy it in July and December of 2020, after the increase in wind and solar production. All units are in MWh. The black line represents electricity consumption, the blue line represents hydro dispatch, the red line represents biomass and fossil fuel dispatch, and the green line represents wind and solar dispatch. Source: ADME (2022).

Figure 3: consumption of electricity and which sources are used to satisfy it

the second-largest city in Uruguay are adjacent and together consume approximately 55% of all electricity produced (BEN, 2022; INE, 2022), I assume that only 55% of the purchased electricity flows to these cities. Figure A1 in the appendix shows the evolution of congestion. This variable takes the value of 1 if the electricity load at a specific hour (h), day (d), month (m), and year (y) exceeds 90% of the line's capacity. As a robustness check, I also consider different cut-off values. Figure A1 shows that new power lines become congested over the years. From 2009 to 2014, before wind and solar penetration began, the only congested electricity line was near the capital city (see panel (a)), but as new wind and solar farms were



(a) Winter - 08/10/2020 (b) Summer - 11/10/2020

Panels (a) and (b) show how consumption behaves and which sources were used to satisfy it for a specific day in winter - August 10th - and in summer - November 10th- in 2020. All units are in MWh. The black line represents electricity consumption, the blue line represents hydro dispatch, the red line represents fossil fuel dispatch, the orange line represents biomass dispatch, the green line represents wind dispatch, and the yellow line represents solar dispatch. Source: ADME (2022).

Figure 4: consumption of electricity and which sources are used to satisfy it by day

installed, other electricity lines also became congested.

To calculate the CO_2 emissions from fossil fuel electricity generation, I collect daily data on consumption of gas oil, fuel oil, and natural gas UTEi (2022). Then, using the CO_2 emission factor from the IPCC (2006), I compute daily emissions from the fossil fuel sector in kilograms (kg) of CO_2. The data is constructed on a daily basis from 2:00 a.m. to 2:00 a.m.;[13] between January 1st, 2009 and January 1st, 2021.

Figure 5 shows the evolution of the spot prices over time. Each point represents a monthly average in $U\$S/MWh$, adjusted for inflation using the real exchange rate index based on 2017 (Xavier, 2022). As renewable electricity production increases, the average spot prices decrease. However, spot prices show a high level of variability, ranging from 0 to 100 $U\$S/MWh$.

The descriptive statistics are presented in Table 1. On average, hydro produces the most electricity, followed by wind and fossil fuels. Solar production is relatively low, however, the standard deviation is high, with the maximum solar production almost reaching the total

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[13] For example, on March 13th, the data starts at 2 a.m. and continues until March 14th at 2:00 a.m.

capacity installed. Exports to the region are (on average) higher than imports. Finally, spot prices are 85 $U\$S/MWh$ on average, but fluctuate greatly - reaching a maximum of 275 $U\$S/MWh$.

This figure shows the evolution of the spot prices over time. Each point represents a monthly average in $U\$S$/MW$h$, adjusted for inflation using the real exchange rate index based on 2017. Source: (ADME, 2022).

Figure 5: Spot prices

5 Methodology

Substitution of electricity sources

I use the randomness in wind and solar availability to identify the substitution patterns between electricity sources. However, it is worth noting that wind and solar exhibit some predictable patterns. For example, wind is higher during the early hours, particularly in winter, whereas in summer, its power decreases. Similarly, solar power is higher at noon, especially in summer. Therefore, I use a rich set of time-fixed effects to control for these

Table 1: Descriptive Statistics

	Mean	Standard Deviation	Min.	Max
Hydro electricity production (MWh)	755.32	344.64	0	1808.48
Wind electricity production (MWh)	236.76	314.66	0	1429.57
Fossil fuel electricity production (MWh)	109.91	164.49	0	1040.59
Biomass electricity production (MWh)	73.37	37.65	0	206.12
Solar electricity production (MWh)	15.6	41.29	0	224.11
Electricity consumption (MWh)	1134.01	255.59	20.92	2505.68
Export electricity (MWh)	67.04	193.33	0	1702.07
Exports *Brazil* (MWh)	27.97	101.32	0	573.87
Exports *Argentina* (MWh)	40.18	157.75	0	1638.77
Import electricity (MWh)	12.33	52.16	0	1000.01
Import *Brazil* (MWh)	7.74	25.82	0	586.48
Import *Argentina* (MWh)	4.6	45.2	0	1000.01
Spot prices ($U\$S/MWh$)	85.27	94.06	0	275.85
N	105,166	105,166	105,166	105,166
CO_2 emissions (kg)	3.6M	4.8M	0	33.7M
N	4383	4383	4383	4383

Data obtained from ADME (2022). CO_2 emissions were obtained from UTEi (2022). Spot prices are deflated using the real exchange rate index with base in 2017 (Xavier, 2022).

seasonal patterns. The source of exogeneity comes from changes in weather within an hour.

The main specification regression takes the following form (2):

$$\begin{aligned} Q_{shdmt} = \quad & \alpha_1 + \beta W_{hdmt} + \gamma S_{hdmt} + \rho C_{ihdmt} + \phi D_{hdmt} + \\ & \text{hour} * \text{month} + \text{month} * \text{year} + \epsilon_{shdmt} \end{aligned} \tag{2}$$

Where Q_{shdmt} is the observed amount produced by source s at hour h, on day d, in month m, and year t from fossil fuel, hydro, or biomass source. W_{hdmt} and S_{hdmt} are the total wind and solar electricity produced, respectively. C_{ihdmt} is the congestion dummy at facility level i, which takes a value of 1 if wind, solar, or source s facility experiences congestion at hour h. D_{hdmt} is the electricity consumption. Finally, ϵ_{shdmt} is the error term, which is clustered at month*year to allow for serial correlation within a month (Fell et al., 2021). Consumption also presents some predictable patterns: it is higher during the night in winter and in the afternoon in summer. Therefore, to control for any seasonal variations in wind and solar production and consumption, I introduce two sets of time-fixed effects: hour*month fixed effects to account for differences between hours in different months (e.g. higher wind production during winter mornings), and month*year fixed effects to account for long-term differences, such as the closure of a facility. After controlling for $\text{hour} * \text{month} + \text{month} * \text{year}$ fixed effect, any remaining change in wind and solar production or electricity consumption can be considered random, originating from exogenous weather shocks. Furthermore, consumers have their electricity prices fixed by contracts and are thus unaffected by changes in wholesale spot market prices. The contracts do change once or twice a year, however, and these changes are captured by the month*year fixed effects.[14]

Fossil fuel production

For a more granular analysis of the effect on fossil fuel production, I run regression (3) at the facility level. By using facility-level data, I show how an average fossil fuel facility's

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[14] Changes are between 2 and 10%, possibly reflecting changes in inflation more than in the market.

production changes due to an increase in wind or solar production.

$$\begin{aligned} q_{ihdmt} = \quad & \alpha + \beta W_{hdmt} + \gamma S_{hdmt} + \rho C_{ihdmt} + \phi D_{hdmt} + \\ & \text{hour} * \text{month} + \text{month} * \text{year} + \epsilon_{ihdmt} \end{aligned} \tag{3}$$

Where q_{ihdmt} is the observed quantity produced by facility i from fossil fuels at hour h, on day d, in month m, and year t. ϵ_{ihdmt} is the error term, which is clustered at date and follows a Driscoll-Kraay with 16 lags. These standard errors allow for dependence across facilities and temporal dependence for up to 16 hours (Hoechle, 2007)[15]; the rest is the same as in equation (2).

CO_2 emissions

To analyze the effect of wind and solar production on CO_2 emissions, I run the following regression at daily level (4):

$$\begin{aligned} \text{CO}_2 \text{ emissions}_{dmt} = \quad & \alpha_2 + \beta W_{dmt} + \gamma S_{dmt} + \rho C_{idmt} + \phi D_{dmt} + \\ & \text{day} + \text{month} + \text{year} + \epsilon_{dmt} \end{aligned} \tag{4}$$

Where $\text{CO}_2 \text{ emissions}_{dmt}$ is the daily aggregate of CO_2 pollution from fossil fuel facilities at day d, month m, and year t. W_{dmt} and S_{dmt} are the daily aggregates of wind and solar production, respectively. C_{idmt} is the congestion dummy, which takes a value of 1 if the wind, solar, or facility i is congested at least once in a day d. D_{dmt} is the daily aggregate of electricity consumption. *day* is a day's fixed effects; *month* is a month's fixed effects; and *year* is a year's fixed effects. Finally, ϵ_{idmt} is clustered at month*year to allow for serial correlation within a month (Fell et al., 2021).

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[15] Driscoll-Kraay (D-K) is preferred when the time dimension is large, and the number of cross-sections is small (Hoechle, 2007).

Spot prices

As shown in Figure 5, spot prices tend to decrease as renewable electricity production increases. However, spot prices fluctuate greatly from month to month. To analyze how spot prices change as wind and solar production increases, I run specification (5).

$$\begin{aligned} \text{spot price}_{hdmt} = \quad & \alpha_3 + \beta_w W_{hdmt} + \beta_s S_{hdmt} + \rho C_{ihdmt} + \phi D_{hdmt} + \\ & \text{hour} * \text{month} + \text{month} * \text{year} + \epsilon_{hdmt} \end{aligned} \tag{5}$$

Where, spot price_{hdmt} is the spot price at hour h, on day d, in month m, and in year t. To retain all the zeros, I do an inverse hyperbolic sine function transformation of the spot prices. The rest is the same as in equation (2).

6 Results

Wind and solar substitution for fossil fuel, hydro, and biomass

This section presents the results from equation 2, which estimates wind and solar substitution for fossil fuel, hydro, and biomass at the source level. As presented in Table 2, wind has a negative effect on fossil fuels and hydro, with a greater effect on the latter: a 1 MWh increase in wind reduces fossil fuel and hydroelectricity production by 0.17 and 0.69 MWh, respectively. Solar only displaces hydro: an additional MWh in solar decreases hydro production by 0.84 MWh. These findings contradict the prediction in Cullen (2013) that hydro and nuclear are the least crowded sources. On the contrary, the substitution of hydro aligns with the results of Abrell and Kosch (2022) and Holland et al. (2022). Abrell and Kosch (2022) find that 1 MWh of renewable electricity replaces 0.21 MWh of hydro[16] and that hydropower is the primary source displaced in Austria, France, and Sweden. Holland et al.

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[16] The authors find a similar substitution effect for fossil fuels, where 1 MWh of renewable electricity replaces 0.24 MWh of coal, 0.23 MWh of gas, and 0.22 MWh of lignite.

(2022) calibrate a long-run model that examines the possibility that a decrease in the cost of renewables could increase carbon emissions if they displace other renewable sources. Finally, I find no substitution effect of wind and solar on biomass, which is consistent with biomass being a baseload source. The analysis of the electricity consumption shows that a 1 MWh increase in consumption increases fossil fuel and hydro production by 0.07 and 0.93 MWh, respectively - this is consistent with hydro being used to satisfy consumption after wind and solar have been used. It is important to note that fossil fuel production reacts less than hydro to consumption changes, mainly because fossil fuels are considered a backup source (Verdolini et al., 2018; Popp et al., 2011). However, by analyzing hourly heterogeneity, it shows that consumption has the greatest impact on fossil fuel production from 2 pm to 6 pm. These are the same hours when solar is peaking and wind production is the lowest. Because solar production is insufficient to satisfy consumption, fossil fuels must be used. These results are presented in Appendix Figure A2.

As explained in Section 3, the dispatcher chooses which firm's electricity to buy by solving a minimization problem, however, given the stochastic nature of renewables, the market operator may not anticipate which sources will be displaced. Therefore, I examine seasonal heterogeneity to further understand these effects. Table 3 shows how wind and solar affect fossil fuel and hydro production, controlling for seasonal variation. Wind and solar consistently displace hydro and there is no statistically significant difference between seasons. The effect of wind on fossil fuels is essentially the same across the seasons, and the difference between seasons is very close to zero. Solar shows a more pronounced negative effect on fossil fuels in winter, which is consistent with wind and hydro production being at their lowest during the summer, and since solar production is not sufficient to satisfy consumption, fossil fuels still need to be used.

Wind displaces hydro and fossil fuels, while solar displaces hydro but affects fossil fuels

Table 2: Aggregate level data

	Fossil fuel (1)	Hydro (2)	Biomass (3)
Wind	-0.166***	-0.696***	-0.003
	(0.019)	(0.033)	(0.002)
Solar	0.029	-0.835***	0.006
	(0.033)	(0.074)	(0.006)
Consumption	0.069***	0.929***	0.002
	(0.016)	(0.044)	(0.002)
Congestion	Y	Y	Y
hour ∗ month	Y	Y	Y
month ∗ year	Y	Y	Y
N	105,166	105,166	105,166

Columns 1, 2, and 3 show how an increase in wind and solar production substitutes for fossil fuel, hydro, and biomass electricity production, respectively. Standard errors clustered at month∗year. Significance levels: ***0.01 **0.05 *0.1.

only in winter. A potential explanation for this is that fossil fuels are used as a baseload in summer. Another possibility is that the majority of the renewable energy produced is exported to Argentina and Brazil. To explore this further, I run the same regression as in equation 2, changing the dependent variable to total exports and imports to Argentina and Brazil - Table 4 presents these results. Wind and solar production increases electricity exports to Argentina and Brazil. Solar has a small effect on imports. Figure A4 in the Appendix shows the evolution of exports per hour. It demonstrates how exports to the region peak between 12 a.m. and 6 a.m., coinciding with the hours wind production peaks. Moreover, exports are stable and high between 9 a.m. and 5 p.m., which could be satisfied by any source, including solar.

To further understand how wind and solar interact with fossil fuel, hydro, and biomass production, I add wind and solar square and date fixed effects following Cullen (2013). The

Table 3: Wind and solar substitution for fossil fuel and hydro by season

	Fossil fuel			Hydro		
	(1) A/W	(2) S/S	(3) W.S seasons	(4) A/W	(5) S/S	(6) W.S seasons
Wind	-0.145**	-0.194***	-0.195***	-0.748***	-0.638***	-0.665***
	(0.025)	(0.029)	(0.027)	(0.045)	(0.044)	(0.049)
wind*winter			0.051**			-0.053
			(0.023)			(0.075)
Solar	-0.061*	0.059	0.061	-0.912***	-0.738***	-0.756***
	(0.033)	(0.047)	(0.047)	(0.092)	(0.104)	(0.103)
Solar*winter			-0.115**			-0.161
			(0.054)			(0.129)
Consumption	0.039**	0.097***	0.068***	0.987***	0.872***	0.930***
	(0.016)	(0.027)	(0.016)	(0.065)	(0.053)	(0.044)
Congestion	Y	Y	Y	Y	Y	Y
hour $*$ month	Y	Y	Y	Y	Y	Y
month $*$ year	Y	Y	Y	Y	Y	Y
N	105,166	105,166	105,166	105,166	105,166	105,166

Columns 1 and 2, and 4 and 5 show the effect of wind and solar on fossil fuel and hydro production in autumn/winter (W/A) and spring/summer (S/S), respectively. Wind*winter and solar*winter show the interaction between the sources and a dummy equal to 1 if the season is winter or autumn and 0 otherwise. Winter and autumn are in April, May, June, July, August, and September; summer and spring are in October, November, December, January, February, and March. Standard errors are clustered at month*year. Significance levels: ***0.01 **0.05 *0.1.

results are presented in Table A3 in the Appendix. The quadratic effect of wind and solar on fossil fuels, and of solar on hydro is not significant. However, the quadratic effect of wind on hydro is significant and positive and therefore presents a convex relationship. The first unit of wind crowds out hydro more successfully than the last. Finally, solar and wind do have an effect on biomass, but it is very close to zero.

Table 4: Wind and solar effect on imports and exports

	Total Exports (1)	Total Imports (2)
Wind	0.130***	-0.031
	(0.026)	(0.019)
Solar	0.218***	0.035*
	(0.063)	(0.018)
Consumption	0.014	-0.002
	(0.043)	(0.006)
Congestion	Y	Y
hour $*$ month	Y	Y
month $*$ year	Y	Y
N	105,166	105,166

Columns 1 and 2 show the effect of wind and solar on electricity exports and imports to Argentina and Brazil, respectively. Standard errors are clustered at month*year. Significance levels: ***0.01 **0.05 *0.1.

CO_2 Emissions

In this section, I explore the effects of wind and solar production on CO_2 emissions. The results are presented in Table 5. On average, a 1 MWh increase in wind production decreases CO_2 emissions by 17 kg, and this effect is robust to different time-effect specifications. This result is particularly important because most fossil fuel plants are located near the capital city, where the majority of the population lives.[17] Solar has a positive effect on CO_2 emissions, but it is only significant at 10%. Wind effectively crowds out fossil fuels, reducing pollution. I am also able to reject that wind and solar have the same effect on CO_2 emissions at 1%; these results are presented in columns (2) and (4).

For 2019 and 2020, I also collect hourly data on Nitrogen Dioxide (NO_2), Ozone (O_3), particulate matter 2.5 ($PM_{2.5}$), and particulate matter 10 (PM_{10}) in $ug/m3$. Table A4 in the

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[17] Refer to Figure 2.

Table 5: Effect of wind and solar on CO_2 emissions

	kg CO_2 emissions			
	(1)	(2)	(3)	(4)
Wind	-17.42***		-17.99***	
	(3.012)		(3.357)	
Solar	79.45*		78.54*	
	(40.290)		(44.419)	
Wind – solar		-19.18***		-19.71***
		(3.237)		(3.578)
Consumption	-5.87	-5.23	-7.56	-6.92
	(4.002)	(4.037)	(4.658)	(4.681)
Congestion	Y	Y	Y	Y
Day ∗ month	N	N	Y	Y
Day	Y	Y	N	N
Month	Y	Y	N	N
Year	Y	Y	Y	Y
N	4383	4383	4383	4383

This table shows the effect of wind and solar on kg of CO_2 emissions. Standard errors are clustered at month*year. Columns (1) and (2), (3) and (4) have the same time fixed effects. Significance levels: ***0.01 **0.05 *0.1.

Appendix presents the results. While wind reduces the amount of NO_2, $PM_{2.5}$, and PM_{10}, solar only reduces $PM_{2.5}$ and PM_{10}.

Spot prices

In this section, I explore the effect of wind and solar production on spot prices. The spot price is the marginal cost of increasing the demand for one unit of electricity across the entire country. [18] If wind or solar satisfies the one-unit increase in demand, the spot price remains at zero. In contrast, if fossil fuels are used to meet this additional unit of demand, the spot prices are positive.

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[18] Uruguay does not report spot prices at node level.

The results of equation (5) are presented in Table 6. Increasing wind electricity production by one MWh decreases spot prices by 0.22%. Similarly, increasing solar by one unit decreases spot prices by 0.17%, but only in winter. While the effect of wind is not significantly different between seasons, the effect of solar is; these results are presented in the fourth column and are consistent with solar having a more pronounced effect on fossil fuels in winter. Therefore, given the definition of spot price and the fact that the electricity consumption is satisfied following a merit order (from the lowest to the highest marginal cost), the increase in wind and solar production is shutting off the most marginally costly (and more polluting) plants in a respective hour.

Consumption has a positive and significant effect on spot prices: a one-unit increase in consumption increases spot prices by 0.11%. Figure A3 in the Appendix shows the hourly effect of consumption on spot prices. From 11:00 p.m. to 6:00 a.m., a one-unit increase in consumption is statistically indistinguishable from zero, a pattern that coincides with the peak hours of wind production. In contrast, from 7:00 a.m. to 9:00 p.m., an increase in electricity consumption has a positive and significant impact on spot prices. During these hours, the demand for an additional unit of electricity is met byusing fossil fuels or hydro. Figure A5 in the Appendix further supports the latter, showing a positive correlation between peak wind production and the frequency at which spot prices are zero.

6.1 Fossil fuel

To better understand which fossil fuel facilities are being shut off, I run regression (3). Table 7 presents the results.

An additional unit of electricity produced from wind (MWh) reduces an average fossil fuel facility's production by 0.023 MWh. From Table 3 and Table 6, I conclude that solar affects fossil fuel production and spot prices only in autumn and winter. Furthermore, the

Table 6: Wind and solar on spot prices

	Whole sample (1)	Winter/Autumn (2)	Summer/Spring (3)	whole sample Interaction by seasons (4)
Wind	-0.0022***	-0.0025***	-0.0023***	-0.0023***
	(0.0002)	(0.0003)	(0.0003)	(0.0003)
Wind ∗ winter				0.00002
				(0.0004)
Solar	0.0001	-0.0017***	0.0002	0.0009
	(0.0004)	(0.0006)	(0.0006)	(0.0006)
Solar ∗ winter				-0.0019**
				(0.0007)
Consumption	0.0011***	0.0020***	0.0023***	0.0011***
	(0.0002)	(0.0004)	(0.0004)	(0.0002)
Congestion	Y	Y	Y	Y
hour ∗ month	Y	Y	Y	Y
month ∗ year	Y	Y	Y	Y
N	105,142	52,655	52,487	105,142

This table presents the effect of wind and solar on spot prices for the whole sample in column 1. Columns 2 and 3 show the effect of wind and solar on spot prices for autumn and winter, and spring and summer, respectively. Spot prices are deflated using the real exchange rate index with base 2017. Standard errors are clustered at month*year. Significance levels: ***0.01 **0.05 *0.1. The difference in the number of observations comes from a missing day in the data, July 1st, 2016.

results in Table 7 suggest that some facilities are being substituted. In the case of solar, 43% of the installed fossil fuel capacity comes from the substituted facilities APRA and CTR, which use gas oil as fuel[19]. Aligned with my results, Kaffine et al. (2013); Novan (2015); Bushnell and Novan (2021) find that at certain hours, there is an increase in less efficient fossil fuel production due to how quickly production can start. Contrary to Holladay and LaRiviere (2017), I find that natural gas is not used as a backup generator due to the time required to initiate electricity production.

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[19] See Appendix Table A2 for more details.

Table 7: Fossil fuel facilities

	Fossil fuel (1)	APRA[20] (2)	CCT[21] (3)	CTR (4)	MCB (5)	PDTI (6)	TRB (7)	Z (8)
Wind	-0.023***	-0.004***	-0.027***	-0.055***	-0.021***	-0.053***	-0.0001***	-0.0001***
	(0.001)	(0.001)	(0.004)	(0.002)	(0.001)	(0.003)	(0.00001)	(0.00002)
Solar	0.005	-0.003**	0.048**	-0.028***	0.009**	0.009	-0.00002	-0.0002***
	(0.004)	(0.001)	(0.020)	(0.004)	(0.004)	(0.012)	(0.00002)	(0.0001)
Consumption	0.009***	-0.0003	0.022***	0.014***	0.008***	0.022***	-0.00003**	0.0001***
	(0.001)	(0.001)	(0.004)	(0.002)	(0.001)	(0.004)	(0.00001)	(0.00003)
Congestion	Y	Y	Y	Y	Y	Y	Y	Y
hour ∗ month	Y	Y	Y	Y	Y	Y	Y	Y
month ∗ year	Y	Y	Y	Y	Y	Y	Y	Y
N	736,162	105,166	105,166	105,166	105,166	105,166	105,166	105,166

This table shows, in column 1, the effect of wind and solar on all the fossil fuel facilities. The remaining columns (2 to 8) correspond to individual facilities. Standard errors are Driscoll-Kraay with 16 lags. Significance levels: ***0.01 **0.05 *0.1.

7 Robustness checks

In this section I present several robustness checks to further validate the results.

First, as I am estimating the effect of wind and solar on fossil fuels, hydro, and biomass separately, any potential correlation between equations is not considered. This correlation could arise, for example, from sharing the same shocks. It may also be beneficial to impose certain constraints; for instance, that the substitution effect of wind and solar on fossil fuels, hydro, biomass, and exports is equal to one. Therefore, to impose restrictions in both sets of equations and consider any correlation of the error term, each equation is simultaneously estimated using a Seemingly Unrelated Regression (SUR), with clustered standard errors at year or month level (Moon & Perron, 2006). Results are presented in the Appendix Table A5. These estimates are similar to those of the main specification. However, it is better not to impose these restrictions because renewables are often produced far from consumption centers, leading to potential electricity losses during transportation (Cullen, 2013; Zivin et al., 2014), therefore the substitution effect is not necessarily one-to-one.

Second, considering that hydro production is high, it is possible that wind and solar are displacing hydro within an hour, but hydro is then displacing fossil fuel production in the following hours, days, or weeks. This is particularly relevant for hydro sources with storage capacity, such as reservoirs and pumped-storage (Abrell & Kosch, 2022; Fell et al., 2021). To explore this, I estimate equation (2), aggregating the data at daily and weekly levels. The results are presented in Table A6 in the Appendix. Wind estimates do not change, which is consistent with hydro being a run-of-river facility with very little capacity to act as a reservoir. The effect of solar on hydro, however, is no longer significant. This could be explained by the fact that solar only affects hydro during certain hours of the day. Therefore, this effect dissipates when aggregating the data at the day or week level.

Third, I change the model's specification by excluding the congestion and/or the consumption variables. The results are presented in Table A7 in the Appendix. Although the signs of the coefficients remain unchanged, there are differences in the magnitude of substitution, particularly when the congestion variable is omitted.

Fourth, in constructing the congestion variable, I arbitrarily choose 90% as the cutoff and thus the line is congested if the cumulative production over the line's capacity is greater than 90%. Therefore, another robustness exercise is to use 80% and 95% as alternative congestion thresholds. The results are similar for different cut-off levels and are presented in the Appendix Table A8.

Finally, I consider different time fixed effects. To control for within-week variation, I add day-of-the-week fixed effects (Fell et al., 2021). Furthermore, since weekdays and weekends are different, for example 8 p.m. on Tuesday is different from 8 p.m. on Saturday, I also add hour $*$ day of the week fixed effect. Results are presented in Table A9 in the Appendix and are robust to different specifications.

8 Conclusion

This study analyzes how the expansion of renewable electricity in a regulated market affects several outcomes. First, it examines how an increase in wind and solar production substitutes for hydro, biomass, and fossil fuel electricity production. Second, I evaluate the effect of this expansion on CO_2 emissions in the context of large hydro production. Finally, I examine how this shift in energy production affects spot prices.

The results show that the increase in wind and solar production has several effects. First, there is a substitution for hydropower and fossil fuel production, especially in winter, with no effect on biomass. Second, there is a reduction in CO_2 emissions. Third, there is a positive spillover effect on the region due to an increase in exports to Argentina and Brazil. Finally, a decrease in spot prices is shown due to the shutting off of the most marginally costly plants at a certain hour.

These results help to confirm the hypothesis discussed. During winter, when hydro and wind production peak, fossil fuels are practically unutilized, while in summer (when hydro and wind production are low), fossil fuels are still used to meet electricity consumption. This could be explained either by solar not being enough to substitute fossil fuel due to its use as a baseload (Holland & Mansur, 2008; Holladay & LaRiviere, 2017; Abrell et al., 2019), or because it is more profitable to export it.

To assess the cost-benefit of this policy, I perform some back-of-the-envelope calculations and find that each MW of wind produced saves about 26 USD/MWh. This is calculated by subtracting the average cost of wind (59.30 USD/MWh) from the average spot price for the whole sample (85.27 USD/MWh) - both at a constant dollar price with base 2017.[22] Furthermore, using the CO_2 emission estimates (see Table 5) and the social cost of carbon dioxide, 185 (2020) US dollars per ton of CO_2 (Rennert et al., 2022), I find that it costs 3 US dollars to retrieve one tonne of CO_2 at constant price with base 2017.

During winter, dependence on fossil fuels for electricity production is minimal, whereas in the summer, fossil fuel usage (and consequently pollution) rises (see figure 3). From a policy perspective, when considering what strategies could be implemented to eliminate fossil fuel production altogether, three potential approaches arise. First, hydro could theoretically be used as a natural battery Moita, Monte, and Orestes (2023) but this strategy is not feasible because most hydro production comes from run-of-rivers. Second, to increase the investment in solar energy, especially since most fossil fuel based electricity production occurs during the summer. Finally, the third approach is to increase investment in large-scale battery storage. Based on recent literature (e.g. De Sisternes et al. (2016); Andrés-Cerezo and Fabra (2023)) and given Uruguay's already high penetration of renewables, battery storage appears to be the best solution. Contrary to the suggestion by Moita et al. (2023) that to achieve zero emissions in Uruguay's electricity sector requires a 95% increase in wind and a

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[22] This price is obtained using the bidding price at the moment of signing the contract for 35 wind facilities, which represent 82% of the wind capacity installed.

0.3% increase in hydro production, battery storage could mitigate the hydro substitution by storing wind or solar production. This stored electricity could then be used during periods of peak fossil fuel production. In addition to reducing fossil fuel use, battery storage also facilitates the integration of renewable energy into the grid, lowering generation costs and prices (De Sisternes et al., 2016; Moita et al., 2023; Andrés-Cerezo & Fabra, 2023).

Several regulatory and fiscal policies have already been implemented to encourage the adoption and production of renewable energy. Regulatory measures include feed-in tariffs (FITs), electricity quota obligations, and net metering; while fiscal policies include investment incentives, tax breaks, and public financing. Uruguay has also introduced another policy, agreeing to buy all the electricity produced by wind and solar at a fixed price, which has successfully increased renewable electricity production. This policy offers two major advantages. First, because wind and solar prices are fixed by 20-year contracts, uncertainty surrounding energy prices reduces drastically. Second, firms may be unwilling to install and produce renewable electricity because their production and profits depend on uncontrollable exogenous factors such as the weather. Therefore, the government agreeing to buy all the electricity at a stipulated price may be the incentive firms need to reduce uncertainty and increase investment in renewables. Future studies should further explore this issue, contributing to a growing body of literature on the effect of firms' exposure to climate change, following, for example, Gong, Song, et al. (2023); Gong, Li, et al. (2023); Gong et al. (2022).

9 Competing interest

Declarations of interest: none.

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11 Replication Package

All the data and the files to replicate the manuscript can be accessed in the following folder: Website.

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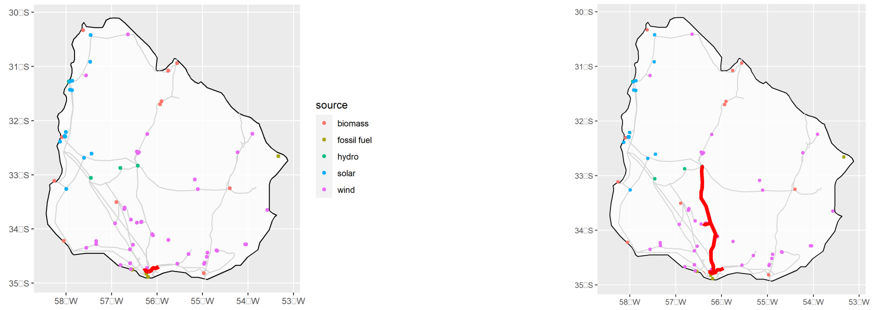
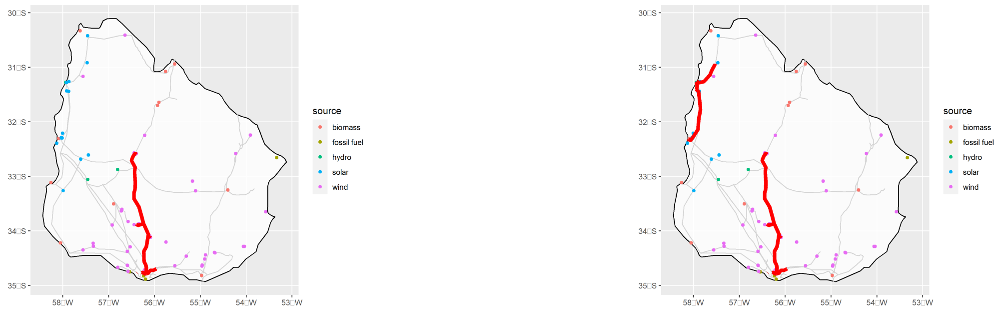
Appendix



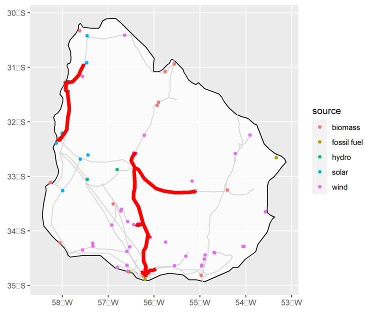
(a) Congestion years 2009 to 2014

(b) Congestion year 2015



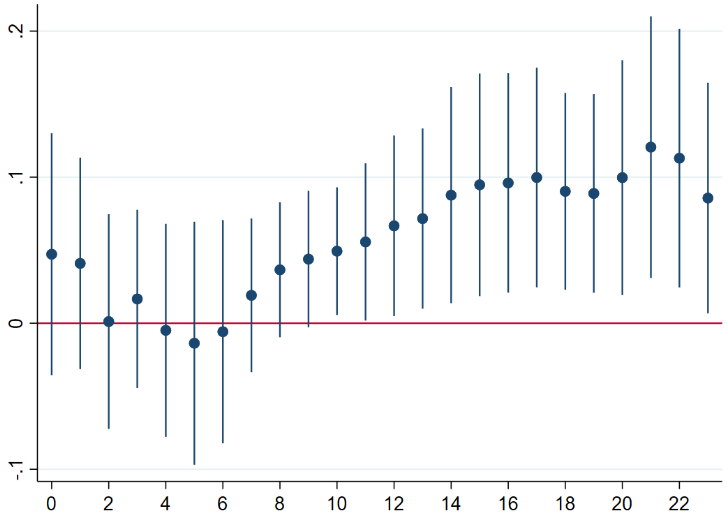
(c) Congestion year 2016

(d) Congestion years 2017 to 2019



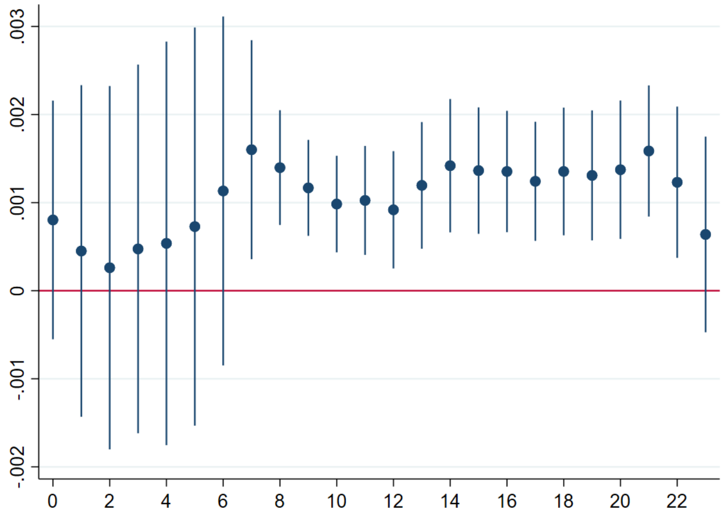
(e) Congestion year 2020

Figure A1: Congestion over time, assuming a 90% cut-off.



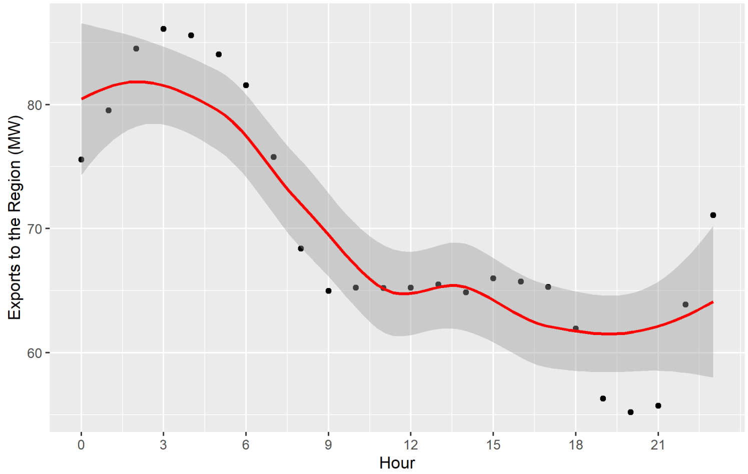
This figure shows the effect of consumption on fossil fuel electricity production by hour. Confidence interval at 95%. The effect is more pronounced in the afternoon when wind production is at its lowest.

Figure A2: Fossil fuel electricity production on consumption - hourly effect



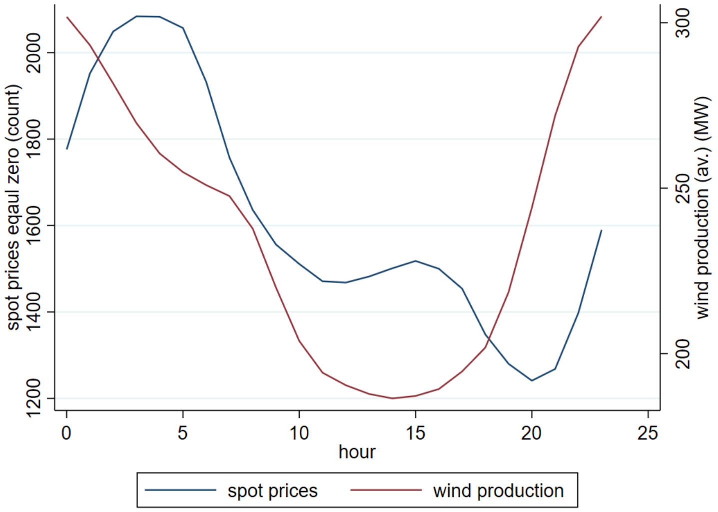
This figure presents the hourly effect of consumption on spot prices. Confidence interval at 95%.

Figure A3: Consumption on spot prices - hourly effect



This figure shows hourly electricity exports to Argentina and Brazil.

Figure A4: Hourly exports to the region



This graph shows the average wind production for different hours of the day and how often the spot prices are zero.

Figure A5: Spot prices and wind production

Summary of the literature related to the substitution of sources.

Table A1: Summary of the literature

Authors	Years	Countries	Outcome
Cullen	2005-2007	Texas, USA	Wind substitutes coal and gas production
Carson and Novan	2007-2009	Texas, USA	electricity arbitrage increases (decreases) renewables and decreases (increases) wholesale prices on on-peak (off-peak) demand times
Novan	2007-2011	Texas, USA	Wind and solar have different external benefits, and these benefits change as production expands
Holladay and LaRiviere	2006-2011	USA	The fracking boom has changed the use of natural gas as a baseload. Consequently, the effect of wind and solar in the substitution for fossil fuels is context-dependant
Callaway, Fowlie and McCormick	2010-2012	USA	Wind and solar substitution for fossil fuels present a large variation depending on the region
Abrell, Kosch and Rausch	2010-2015 2014-2015	Germany Spain	Abatement costs vary depending on the renewable source and the type of subsidy. Ranging between 82-276 and 411-1944 €/CO_2 for wind and solar
Gugler, Haxhimusa, and Liebensteiner	2011-2018 2017-2018	Britain Germany	While in Germany the effect of wind and solar on emissions are larger because the source being substituted is coal, in Britain, the source being displaced is natural gas
Bushnell and Novan	2013-2017	California, USA	The long-run substitution effect of renewables on fossil fuels and consequently on prices, depends on the resource and the time of the day

Table A2: Capacity installed and source used from fossil fuels facilities

Facility	Fuel type	Capacity installed (MW)	Perc. over total	
APRA	Gas oil	550.0	31.2	
CCT	Gas oil or Natural Gas	540.0	30.6	61.8
CTR	Gas oil	212.0	12.0	73.8
MCB	Gas oil or Fuel oil	335	19.0	92.8
PDTI	Gas oil or Natural Gas	100.0	5.7	98.5
TRB	Gas oil or Natural Gas	3.7	0.2	98.7
Z	Natural Gas	3.2	0.2	98.9
Other	Gas oil, Fuel oil, or Natural Gas	20.0	1.1	100.0
Total		1,763.9		

This table shows the installed capacity of fossil fuel facilities, the percentage of the total capacity, and the different fuels used to produce electricity. Source: (MIEM, 2022)

Table A3: Heterogeneity by source with a quadratic effect

	Fossil fuel		Hydro		Biomass	
	Estimations	Mg. effect	Estimations	Mg. effect	Estimations	Mg. effect
Wind	-0.116***	-0.119***	-0.875***	-0.779***	-0.004*	-0.004***
	(0.016)	(0.013)	(0.039)	(0.030)	(0.002)	(0.001)
Wind^2	-7.18e-06		0.0002***		-4.24e-07	
	(0.00002)		(0.00004)		(1.81e-06)	
Solar	-0.074	-0.065*	-0.799***	-0.806***	0.039***	0.035***
	(0.045)	(0.038)	(0.110)	(0.092)	(0.008)	(0.007)
Solar^2	0.0003		-0.0002		-0.0001	
	(0.0003)		(0.001)		(0.00004)	
Consumption	0.079***		0.843***		0.004***	
	(0.007)		(0.021)		(0.001)	
Cong. dummy	Y		Y		Y	
Day dummy	Y		Y		Y	
N	105,166		105,166		105,166	

This table shows the effect of wind and solar on fossil fuel, hydro, and biomass production at the source level. The marginal effect is at the mean. Standard errors are clustered at month $*$ year. Significance levels: ***0.01 **0.05 *0.1.

Table A4: Effect of wind and solar on pollutants

	NO2	PM 2.5	O3	PM 10	All pollutants
Wind	-0.024***	-0.041***	0.022***	-0.017***	-0.045***
	(0.004)	(0.007)	(0.007)	(0.002)	(0.009)
solar	-0.035	-0.076***	0.077***	-0.063***	-0.088*
	(0.033)	(0.015)	(0.018)	(0.008)	(0.049)
Demand	0.022**	0.002	0.004	0.004	0.023
	(0.009)	(0.006)	(0.011)	(0.004)	(0.015)
Cong. dummy	Y	Y	Y	Y	Y
hour $*$ month	Y	Y	Y	Y	Y
month $*$ year	Y	Y	Y	Y	Y
N	11,856	17,534	16,468	14,029	17,542

This table shows the effect of wind and solar on NO2, PM 2.5, O3, and PM 10 in micrograms (one millionth of a gram) per cubic meter of air (ug/m3) for 2019 and 2020. Standard errors are clustered at month*year. Significance levels: ***0.01 **0.05 *0.1.

Table A5: Seemingly unrelated regression

	Fossil fuel	Hydro	Biomass	Exports
Wind	-0.166***	-0.726***	-0.003	0.106**
	(0.026)	(0.055)	(0.002)	(0.052)
Solar	0.033	-0.83***	0.006	0.209***
	(0.031)	(0.071)	(0.009)	(0.040)
Consumption	0.071***	0.93***	0.002	0.011
	(0.024)	(0.071)	(0.002)	(0.071)
Cong. dummy	Y	Y	Y	Y
hour $*$ month	Y	Y	Y	Y
month $*$ year	Y	Y	Y	Y
N	105,166	105,166	105,166	105,166

This table shows the seemingly unrelated regression results. Standard errors clustered at the year level and at the month level give similar results. Significance levels: ***0.01 **0.05 *0.1

Table A6: Wind and solar substitution - Robustness check

	Aggregate at day level		
	Fossil fuel (1)	Hydro (2)	Biomass (3)
Wind	-0.126***	-0.629***	-0.006*
	(0.022)	(0.054)	(0.003)
Solar	-0.161	-0.205	-0.042
	(0.203)	(0.397)	(0.037)
Consumption	0.033	1.01***	-0.004
	(0.022)	(0.046)	(0.003)
Cong. dummy	Y	Y	Y
day ∗ month	Y	Y	Y
month ∗ year	Y	Y	Y
N	4,382	4,382	4,382

	Aggregate at week level		
	Fossil fuel (1)	Hydro (2)	Biomass (3)
Wind	-0.101**	-0.603***	-0.012
	(0.040)	(0.125)	(0.010)
Solar	-0.277	1.479	-0.138
	(0.516)	(2.081)	(0.124)
Consumption	-0.009	1.033***	0.0003
	(0.054)	(0.111)	(0.007)
Cong. dummy	Y	Y	Y
week	Y	Y	Y
month ∗ year	Y	Y	Y
N	751	751	751

This table shows, in columns 1, 2, and 3, the effect of wind and solar on fossil fuel, hydro, and biomass production, respectively. While Panel A aggregates the data at the day level, Panel B aggregates the data at the week level. Standard errors are clustered at month*year. Significance levels: ***0.01 **0.05 *0.1

Table A7: Wind and solar substitution source level - Robustness check

	Fossil fuel			
	(1)	(2)	(3)	(4)
Wind	-0.166***	-0.078***	-0.164***	-0.071***
	(0.019)	(0.012)	(0.019)	(0.012)
Solar	0.029	0.044	0.055	0.067**
	(0.033)	(0.031)	(0.036)	(0.032)
Consumption	0.069***	0.081***		
	(0.016)	(0.018)		
Cong. dummy	Y	N	Y	N
day ∗ month	Y	Y	Y	Y
month ∗ year	Y	Y	Y	Y
N	105,166	106,166	106,166	106,166

	Hydro			
	(1)	(2)	(3)	(4)
Wind	-0.696***	-0.613***	-0.654***	-0.525***
	(0.063)	(0.041)	(0.035)	(0.047)
Solar	-0.835***	-0.762***	-0.478***	-0.490***
	(0.111)	(0.07)	(0.09)	(0.078)
Consumption	0.929***	0.940***		
	(0.069)	(0.045)		
Cong. dummy	Y	N	Y	N
day ∗ month	Y	Y	Y	Y
month ∗ year	Y	Y	Y	Y
N	105,166	105,166	105,166	105,166

This table shows the effect of wind and solar on fossil fuel and hydro production in Panel A and Panel B, respectively. Standard errors are clustered at month*year. Significance levels: ***0.01 **0.05 *0.1

Table A8: Wind and solar substitution source level - Robustness check

	Fossil fuel		
Congestion cut off	90%	80%	95%
Wind	-0.166***	-0.189***	-0.154***
	(0.019)	(0.020)	(0.018)
Solar	0.029	0.027	0.022
	(0.033)	(0.035)	(0.033)
Consumption	0.069***	0.065**	0.070***
	(0.016)	(0.016)	(0.017)
Cong. dummy	Y	Y	Y
day ∗ month	Y	Y	Y
month ∗ year	Y	Y	Y
N	105,166	105,16	105,16

	Hydro		
Congestion cut off	90%	80%	95%
Wind	-0.696***	-0.696***	-0.698***
	(0.033)	(0.034)	(0.032)
Solar	-0.835***	-0.863***	-0.821***
	(0.074)	(0.077)	(0.072)
Consumption	0.929***	0.932***	0.928***
	(0.044)	(0.044)	(0.044)
Cong. dummy	Y	Y	Y
day ∗ 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 on fossil fuel and hydro production for different congestion thresholds in Panel A and Panel B, respectively. Standard errors are clustered at month*year. Significance levels: ***0.01 **0.05 *0.1

Table A9: Wind and solar substitution for fossil fuel, hydro, and biomass

	Fossil fuel (1)	Hydro (2)	Biomass (3)	Fossil fuel (4)	Hydro (5)	Biomass (6)
Wind	-0.166***	-0.697***	-0.003*	-0.166***	-0.696***	-0.003
	(0.019)	(0.033)	(0.002)	(0.019)	(0.033)	(0.002)
Solar	0.031	-0.837***	0.006	0.032	-0.838***	0.006
	(0.033)	(0.074)	(0.006)	(0.033)	(0.074)	(0.006)
Consumption	0.055***	0.943***	0.004	0.052**	0.949***	0.004
	(0.018)	(0.053)	(0.003)	(0.020)	(0.057)	(0.003)
day of the week	Y	Y	Y	N	N	N
hour $*$ day of the week	N	N	N	Y	Y	Y
Cong. dummy	Y	Y	Y	Y	Y	Y
hour $*$ month	Y	Y	Y	Y	Y	Y
month $*$ year	Y	Y	Y	Y	Y	Y
N	105,166	105,166	105,166	105,166	105,166	105,166

This table shows in columns 1, 2, and 3, the effect of wind and solar on fossil fuel, hydro, and biomass production considering day-of-the-week fixed effects. In columns 4, 5, and 6, the effect of wind and solar on fossil fuel, hydro, and biomass production considering hour $*$ day of the week fixed effects is presented. Standard errors are clustered at month*year. Significance levels: ***0.01 **0.05 *0.1