The Impact of Solar Panel Installation on Electricity Consumption and Production

Natalia D'Agosti and Facundo Danza

August 28, 2023

Abstract

Since 2010, the Uruguayan government has fostered the installation of solar panels by households and firms to increase the small-scale production of renewable electricity. The government allows agents with solar panels to inject any excess of electricity into the grid. We study the environmental and economic consequences of this policy. We collect a novel dataset on electricity extraction and injection into the grid at the household/firm level for the whole country. First, we find that solar panels decrease the electricity extracted from the grid. Second, the amount of electricity injected into the grid increases. Third, we calculate the effects on CO_2 emissions and the rebound effect. We find a reduction between 0.35 and 0.003 kg of CO_2 emissions every month for each agent. We find evidence of a rebound effect: consumption increases between 20% and 26% on average. Finally, we propose an alternative policy that allows agents to store the electricity in batteries instead of immediately injecting it into the grid. According to our model, the best time to inject electricity into the grid is around 9 PM. We leverage household-firm level data to study the effect of a net-metering policy on electricity extraction and injection, showing what countries can expect from such a policy.

1 Introduction

Energy production substantially contributes to greenhouse gas (GHG) emissions, which are responsible for anthropogenic climate change. Thus, parts of the world are transitioning to cleaner energy production. Governments apply different policies to incentivize and accelerate this transition, including fostering microgeneration from renewable resources. Since 2010, the Uruguayan government has fostered the installation of solar, wind, and small hydro microgenerators by households and firms. Specifically, the government initiated a net-metering policy: agents with clean microgenerators can sell any excess of electricity to the grid, at the retail price that agents face. This study analyzes several aspects of this policy. We focus exclusively on solar panels, which are the main microgenerators in the country.

First, we study how solar-panel installation affects the net electricity, defined as the extraction minus injection into the grid. After the installation of the solar panel, the electricity taken from the grid is expected to decrease, and the electricity injected is expected to increase. The magnitude of such change, however, is an empirical question. Therefore, we use an event-study approach to quantify it. A problem that arises from this specification is that solar adaptation and installation timing are endogenous (Beppler, Matisoff, & Oliver, 2023). In addition, early adopters may be different from future adopters. Consequently, our estimations should be considered as an upper bound. This is a limitation of the method employed, nevertheless, we still are able to have valid measures of the effect of the policy.

Third, to understand the implications of our estimations, we calculate the effect of the policy on CO_2 emissions and the "rebound effect," that is, the potential increase in electricity consumption after installing a solar panel.

Finally, a net-metering policy may have important equity implications. Agents who install solar panels are richer than the average. It is usually assumed that electricity prices embed the cost of the grid (e.g., Feger et al. (2022); Eid et al. (2014)). Because electricity prices are progressive in electricity consumption and richer agents tend to consume more electricity, this implies that richer agents are now contributing less to the grid's costs. Furthermore, the marginal cost of solar electricity is virtually zero. The net-metering policy, however, forces the electricity provider to buy solar-produced electricity at the retail price. In the long run, both may affect electricity prices for all consumers. To lessen these concerns and improve the effectiveness, we propose an alternative policy: households and firms could, instead of selling the electricity immediately into the grid, store it in batteries and sell it when optimal. This optimal allocation would reduce CO_2 emissions and spot prices, having a positive impact on the rest of the consumers and diminishing the equity problems.

We collect a novel data set in which we observe the electricity extracted and injected into the grid before and after the solar panel installation at the household and firm level, for all the agents that install a solar panel. Specifically, we observe the monthly electricity extracted and injected at the agent level, 12 months before and 12 months after the solar panel installation. We also observe the monthly CO_2 emissions from fossil-fuel thermal plants and hourly total electricity production and consumption.

Our results can be summarized as follows. First, we find that the net effect, i.e., the effect of installing a solar panel in the extraction minus injection into the grid, decreases by 2565 kWh, and this effect is constant over time. Analyzing extractions and injections separately, we find that solar-panel installation decreases the electricity taken from the grid. Agents decrease their monthly electricity extraction by 1,100 kWh, an 18% reduction from its average. In addition, after installing the solar panel, the amount of electricity injected into the grid increases by 1,570 kWh. Both effects remain constant over time. We also consider heterogeneity by agent and analyze households and firms separately. We find that both types increase the amount of electricity injected into the grid. However, the reduction in electricity extracted is large for firms and rather low for households; this could be explained due to firms having larger capacity.

Third, using our estimates, we determine the effect of the policy on CO2 emissions and the rebound effect. To study the reduction in CO_2 emissions, we propose two scenarios. First, we assume that both the electricity injected into the grid and the reduction in the electricity extracted from the grid substitute only fossil-fuel production. In this case, we find that each agent reduces 0.35 kg of CO_2 every month; in total we find a reduction of 442 kg of CO2 every month. Second, we assume that micro-generated electricity substitutes fossil fuels proportionally[1] to their share in the total electricity production. For such a case, we find a reduction of 0.03 kg of CO_2 every month for each agent; and a total reduction of 38.7 kg of CO2 every month. The rebound effect is the increase in electricity consumption after the solar panel installation. We find that after installing the solar panel, firms

[1] Fossil fuel production accounts for 8% of the total electricity production. Therefore, we assume that both the electricity injected into the grid and the reduction in the electricity extracted from the grid substitute only 8% of the fossil-fuel production.

increase their electricity consumption between 22% and 30%, and households increase their electricity consumption between 19% and 22%.[2] This increase in electricity consumption could be explained by agents feeling richer, electricity being cheaper on average, or changes in their consumption behavior (Beppler et al., 2023; Boccard & Gautier, 2021). On one hand, the rebound effect reduces the effectiveness of the solar panels; it reduces the CO_2 emissions effect depending on which source is extracted marginally from the grid, and it also reduces other costs of generation. On the other hand, the increase in electricity consumption could be positive if the agent begins a process of electrification, and this is satisfied by the solar production entirely. This would explain why we found a rebound effect in both, households and firms.

Finally, we find that it would be optimal that agents sell their solar production between 8 PM and 11 PM; at that time, CO_2 from fossil-fuel-based electricity production and the spot prices are high. The environmental benefits of allowing households/firms to store the electricity and sell it at another time generate positive spillovers to the rest of the consumer, lessening the equity implications of the policy.

This study contributes to the literature in several ways. First, we expand the literature on agents' use of solar panels (Borenstein, 2017; Boccard & Gautier, 2021; Sexton et al., 2021; Feger et al., 2022; Pretnar & Abajian, 2023; Beppler et al., 2023). Unlike other studies, we observed electricity extracted and injected into the grid from microgenerators directly instead of inferring it (for example, Boccard and Gautier (2021)). We expand Feger et al. (2022) in several ways. First, we observe the electricity extracted and injected into the grid directly; Feger et al. (2022) have

[2] The range varies with the assumption of total peak hours.

to estimate it. Second, we use more recent data: 2010-2022 instead of 2008-2014. Since the price of solar panels has decreased dramatically in recent years, this factor is relevant. Lastly, Feger et al. (2022) study five years of feed-in tariff policy and one year of net-metering policy; our study focuses exclusively on net metering.

Second, we explore and quantify an alternative approach that could improve the net-metering policy by allowing households/firms to install batteries and store the electricity instead of selling it immediately in the grid. This expands the literature on equity problems from the net metering policy and the misallocation of the electricity injected from microgenerators, as well as the use of batteries in solar panels (Pretnar & Abajian, 2023; Sexton et al., 2021; Boampong & Brown, 2020; Eid et al., 2014).

Thirdly, we expand the vast literature on calculating the rebound effect, such as Kattenberg et al. (2023); Beppler et al. (2023); Qiu et al. (2019); Deng and Newton (2017). While (Qiu et al., 2019) find a rebound effect of 18%, Deng and Newton (2017) find a rebound effect between 17% and 21%. However, Beppler et al. (2023) find a higher rebound effect of 28.5%, which is consistent with our results. In addition, we find a negative rebound effect (increase in electricity consumption), contrary to Kattenberg et al. (2023), which find a decrease in electricity consumption after the solar panel installation.

Finally, the discussion on microgenerators has been focused entirely on the developed world (Feger et al., 2022; De Groote & Verboven, 2019; Islam & Meade, 2013; Jeong, 2013). We use data from a middle-income country expanding the literature in this context.

The remainder of this paper is organized as follows. Section 2 describes the

Uruguayan electric market and the microgenerator policy. Section 3 describes the data. Section 4 presents our identification strategy. Section 5 shows our empirical results. Section 6 describes the minimization problem to optimize the timing of electricity sold to the grid and its results. Finally, Section 7 concludes.

2 Electricity Market

The Uruguayan electricity market is a highly-regulated market. The are five electricity sources: wind, hydro, biomass, solar, and fossil fuel. The market operator, ADME, decides how much electricity to buy from each firm on a merit-order basis - from the lowest to the highest marginal cost. Afterward, "Administración Nacional de Usinas y Trasmisiones Eléctricas" (UTE), a large state-owned electrical company, distributes the electricity to consumers. The structure of the market is as follows. First, the electricity firms sell all the electricity produced to the market operator, ADME, which is thus a monopsony. Consumers, on the other side of the market, can only buy electricity from the state-owned electricity company, UTE, which is thus a monopoly. In addition, the electricity price is set by the Executive Power, and varies (at least) once a year. Different plans are offered to consumers. Figure 1 illustrates the evolution of the prices of one of them: "Residential Simple."

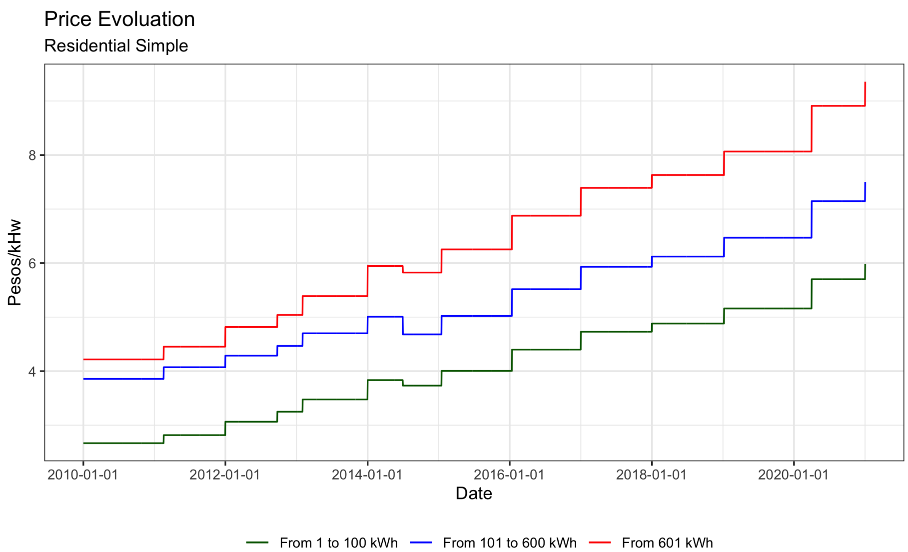


Figure 1: Price Example. *Notes:* This figures shows the evolution of the "Residential Simple" electricity rate. *Source: (UTEi, 2022)*

Uruguay has fostered investments in renewable sources (wind, solar, and biomass) on both large and small scales. On a large scale, it does so through public auctions, where firms give a pair of power capacity and price, and then the government gives permission to install and produce renewable energy to the best offers. This policy resulted in having 94% of its grid from renewable sources (MIEM, 2022; CAF, 2022). On a smaller scale, Uruguay has a "net metering" policy. This policy allows households and firms to produce solar or small-scale wind and hydro electricity. In principle, the agent consumes all renewable electricity produced. If, at a given moment, the production of electricity is higher than its consumption, the difference is injected into the grid. The selling price is the retail price to which the agent agreed, and the electricity injected is discounted in the bill for the current month. Since May 2017, the yearly amount of electricity sold has to be less than or equal to the amount of electricity consumed (MIEM, 12/17)[3].

Figure 2 shows the evolution of solar panel installation by year.

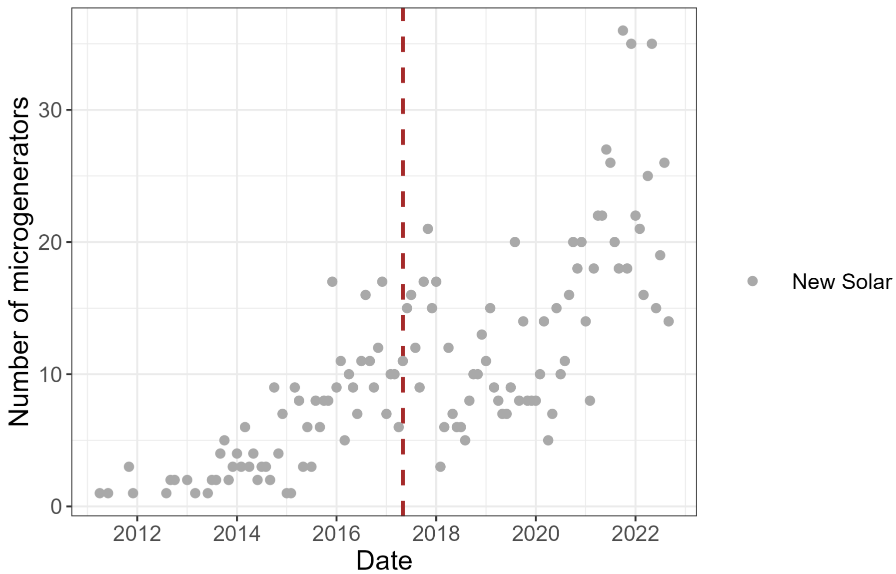


Figure 2: Solar Panels. *Notes:* This figure shows the new number of solar microgenerators installed by year in blue. Since May 2017 the yearly amount of electricity sold has to be smaller or equal to the amount of electricity consumed. *Source: (UTEi, 2022)*

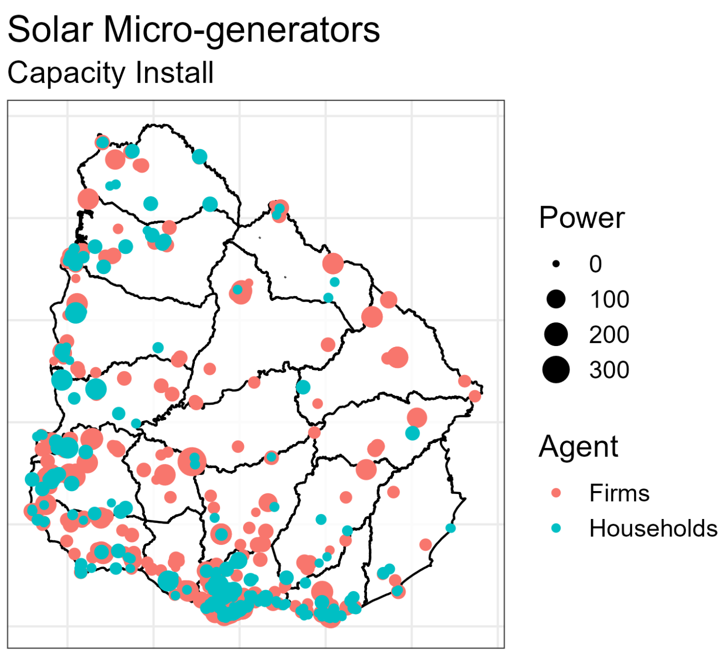
3 Data and Descriptive statistics

We use administrative data at the household and firm level to analyze how the electricity bought and sold from the grid changes after installing a solar panel under the net-metering policy. The data was provided by UTE. We have monthly data, at an agent (household or firm) level, on electricity consumption from the grid 12

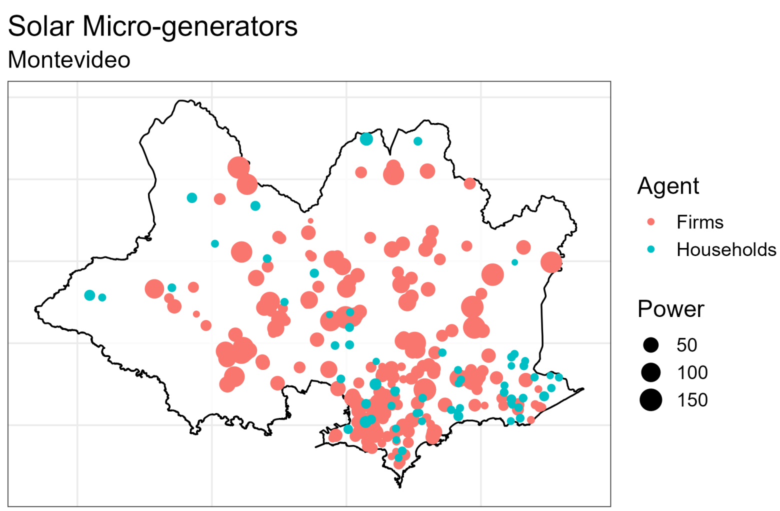
[3]There are 34 agents whose annual electricity injected surpassed the annual electricity extracted. Of those, 25 are firms and 9 are households. We repeat the analyses eliminating these 34 agents, and the results mostly do not change. They can be seen in the Appendix Table 14

months before the solar panel installation, and electricity bought and sold to the grid 12 months after the solar panel installation.

In total, we have 1275 agents (i.e. firms and households). Figure 3 shows the location of all solar panels color-coded by type of agent, and the size reflects the capacity installed of the solar panel, for both the whole country and the capital city. Although most microgenerators are located in the capital city, many are scattered throughout the country. Furthermore, the number of firms that install solar microgenerators is higher than the number of households. In addition, the capacity installed by firms is, on average, higher than households. While households have a capacity installed of 13.5 kWh, firms have a capacity installed of 37.64 kWh. In 2020, the solar capacity was 6% of the total installed electricity capacity, and the solar capacity from microgeneration was 12% of it (MIEM, 2022).



(a) Location of Microgenerators



(b) Capital city - Location of Microgenerators

Figure 3: Microgeneratos location. *Notes:* Panel (a) shows where the different solar microgenerators are distributed across the country. Panel (b) shows where the different solar-microgenerators are distributed in the capital city, Montevideo. Color-coded by residential or commercial customers. *Source: (UTEi, 2022)*

We construct CO_2 emission from the fossil fuel electricity generation, using monthly data on gas oil, fuel oil, and natural gas consumption from UTEi (2022). Specifically, we use the CO_2 emission factor from the IPCC (2006) and recover the CO_2 emissions from the thermal sector by month. The data is constructed from 1:00AM to 1:00AM of the following month.[4]

The descriptive statistics are in Table 1. As Table 1 reports, the average amount of electricity taken from the grid is 6740 and 5388 kWh before and after installing the solar panels, respectively. The amount of electricity injected into the grid is on average 1546 kWh. In both cases, firms extract and inject more than households. In addition, while 70% of the sample are firms, 30% are households. The average amount of emissions over the period is 10.8 million kg of CO_2.

[4]For example, from midnight October first until midnight November first.

Table 1: Descriptive Statistics

	Mean Before/after	S.D Before/after	Min. Before/after	Max Before/after
Extractions (kWh)	6740.13/5388.75	14274.64/13795.12	0.08/0.08	256032.2/297253.2
Firms	8174.38	16145.46	0.08	297253.2
HH	910.12	1800.41	0.43	33108.8
Injections (kWh)	1545.98	3272.36	0	136844.1
Firms	1449.4	3344.24	0	136844.1
HH	287.91	771.80	0	24405.6
Household	0.29		0	1
Firms	0.71		0	1
N	24,386	24,386	24,386	24,386
CO_2 emissions Mill. kg	10.81	10.41	3.44e-06	35.02
N	132	132	132	132

Data obtained from UTEi (2022). The first line of electricity extractions shows the amount of electricity taken from the grid before and after the solar panel installation, considering firms and households together. Injections show the average of electricity sold into the grid after the solar panel installation. CO_2 emissions are in millions of kilograms (kg).

4 Methodology

Figure 4 shows how electricity extracted and injected into the grid changes after installing a solar panel.

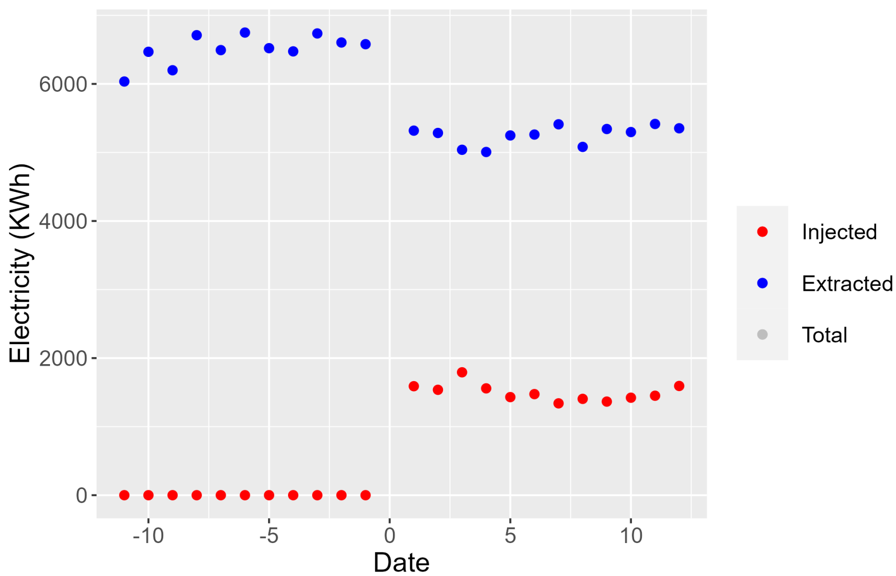


Figure 4: Electricity extracted and injected into the grid. *Notes:* This figure shows the total amount of electricity injected and extracted into the grid 12 months before and after the solar panel installation. *Source: (UTEi, 2022)*

To recover the changes on the electricity extracted and injected into the grid after installing a solar panel, we run regression (1). One of the limitations that arise in our specification is that solar adaptation and the installation time are endogenous; if the agent installs a solar panel because she plans to increase their electricity consumption, then our results are upwardly biased. Similarly, our rebound calculation could also be upward biased (Beppler et al., 2023). In addition, another problem that arises is that early adopters have larger systems and are able to produce more. Consequently, a possible broader adoption of solar panels would not deliver the same results, and these results are an upper bound.

$$y_{ist} = \alpha_i + \beta D_{ist} + \delta_t + \epsilon_{ist} \tag{1}$$

where y_{ist} is the electricity extracted or injected into the grid for agent i in the state level s at month t; D_{ist} is the treatment, a dummy equal one if the agent i installed the solar panel at time t; α_i is the agent fixed effect, where any time-invariant household characteristics are captured; δ_t is the time fixed effect, e.g. month, month $*$ year or month + year, where changes in weather and seasonal variation are captured; and ϵ_{ist} is the error term which is cluster at state level [5].

We also study the dynamic effect of solar panel installation using the following equation:

$$y_{ist} = \alpha_i + \sum_{\tau=-12}^{-2} \rho_\tau D_{is\tau} + \sum_{\tau=1}^{12} \lambda_\tau D_{is\tau} + \delta_t + \epsilon_{ist} \tag{2}$$

where the first summation shows the leads and the second summation shows the lags after installation, and the remainder is as specified in regression (1). The solar panel installation occurs at time $\tau = 0$, however, we do not observe that month. As a consequence, all the estimations are compared to $\tau = 1$.

[5] We also cluster at agent level, and the results are presented in the Appendix 8.2 Table 10 and 11.

5 Results

This section shows the effect of installing a solar panel on the net effect, defined as (extractions $-$ injections) from the grid. In sections 5.3 and 5.4, we show the effect of equation 1 in the extraction and injection of electricity into the grid, separately.

5.1 Net effect

Table 2 shows the effect of installing a solar panel in the net effect (i.e., extractions $-$ injections). After installing a solar panel, the net effect, decreases by 2830.68 kWh. Our preferred specification is column (3), where agent and month $*$ year fixed effects are used. Month $*$ year, captures any changes that happen monthly, for example, if August 2019 was colder than September 2019 and August 2020. The ID fixed effect captures any time-invariant characteristic at agent level.

Table 2: Electricity taken from the grid

	Net effect (extractions $-$ injections (kWh))		
	(1)	(2)	(3)
Solar panel installation	-2564.97***	-2839.05***	-2830.68***
	(249.20)	(363.62)	(354.73)
ID F.E	Y	Y	Y
month	Y	Y	N
year	N	Y	N
month $*$ year	N	N	Y
N	18,964	18,964	18,964

This table shows the effect of installing a solar panel on the net electricity (extractions $-$ injections) taken from the grid, using different sets of fixed effects. Column (1) uses ID + month fixed effects; column (2) uses ID + month +year fixed effects; finally, column (3) uses ID + month $*$ year. Standard errors are cluster at state level. Significance levels: ***0.01 **0.05 *0.1.

To be more conservative, we continue our analysis using just ID + month fixed effects (column (1)).[6] Therefore, Figure 5 plots the event study coefficients using ID + month fixed effects. All the results are compared with the month before installing the solar panel (lead1).

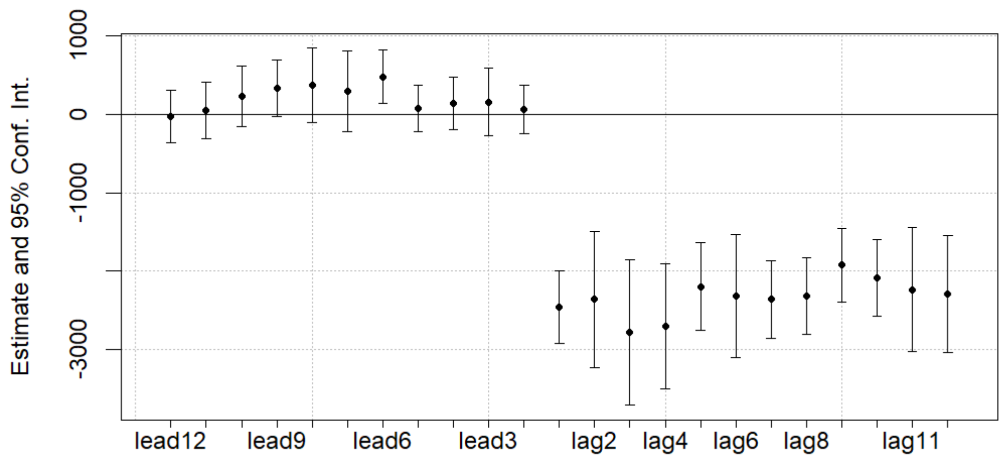


Figure 5: Event study plot - (extractions $-$ injections) from the grid. *Notes:* This figure shows the event study plot using 12 leads/lags before/after the solar panel installation, controlling for ID + month fixed effects.

Figure 5 shows that the net effect (i.e, extractions $-$ injections from the grid) reduction is constant over time.

From the previous analysis, we can conclude that injections are higher than extractions. However, to explore how electricity extracted and injected from the grid behaves[7], we will explore them separately in the following sections.

[6] We perform the same regression, but using the Sun and Abraham (2021) approach. The results are presented in Table 12 in the Appendix 8.2.

[7] By analyzing the net effect (defined as extraction - injections), we can conclude injections are bigger than extractions. But does this means that extractions do not change and injection increases? Looking at both injections and extractions separately, we can reject that

Table 3: Electricity injected into the grid by type of agent: household or firm

5.2 Heterogeneity by Agent

In this section we present how the net effect, defined as the electricity extracted minus injected, changes depending on the type of agent: household or firms. The results are presented in Table 3. While for firms installing solar panels decreases the net effect by 3769 kWh, for households it decreases by 753 kWh.

	Panel (a): Net effect (kWh) - Firms		
	(1)	(2)	(3)
Solar panel installation	-3584.38***	-3822.37***	-3768.55***
	(305.23)	(482.84)	(497.86)
ID Fixed Effects	Y	Y	Y
month	Y	Y	N
year	N	Y	N
month $*$ year	N	N	Y
N	13,033	13,033	13,033

	Panel (b): Net effect (kWh) - Households		
	(1)	(2)	(3)
Solar panel installation	-566.31***	-734.09***	-752.83***
	(56.72)	(155.00)	(172.92)
ID Fixed Effects	Y	Y	Y
month	Y	Y	N
year	N	Y	N
month $*$ year	N	N	Y
N	5,931	5,931	5,931

This table shows the effect of installing a solar panel on the net effect, i.e., electricity extracted minus injected, using different sets of fixed effects. Column (1) uses ID + month fixed effects; column (2) uses ID + month +year fixed effects; finally, column (3) uses ID + month $*$ year. Standard errors are cluster at state level. Significance levels: ***0.01 **0.05 *0.1.

5.3 Electricity taken from the grid

Table 4 presents the event study results, using electricity extracted from the grid as the dependent variable. After installing a solar panel, the agent's electricity taken from the grid decreases by 1,100 kW_h on average. These results are somewhat robust to different specifications. Our preferred specification is column (3), for the reasons explained above.

Table 4: Electricity taken from the grid

	Electricity taken from the grid (kWh)		
	(1)	(2)	(3)
Solar panel installation	-1099.2***	-1085.68***	-1091.55***
	(71.41)	(146.19)	(142.94)
ID F.E	Y	Y	Y
month	Y	Y	N
year	N	Y	N
month $*$ year	N	N	Y
N	24,386	24,386	24,386

This table shows the effect of installing a solar panel on the electricity taken from the grid, using different sets of fixed effects. Column (1) uses ID + month fixed effects; column (2) uses ID + month +year fixed effects; finally, column (3) uses ID + month $*$ year. Standard errors are cluster at state level. Significance levels: ***0.01 **0.05 *0.1.

Figure 6 plots the event study coefficients using ID + month fixed effects (column (1)). All the results are compared with the month before installing the solar panel (lead1).

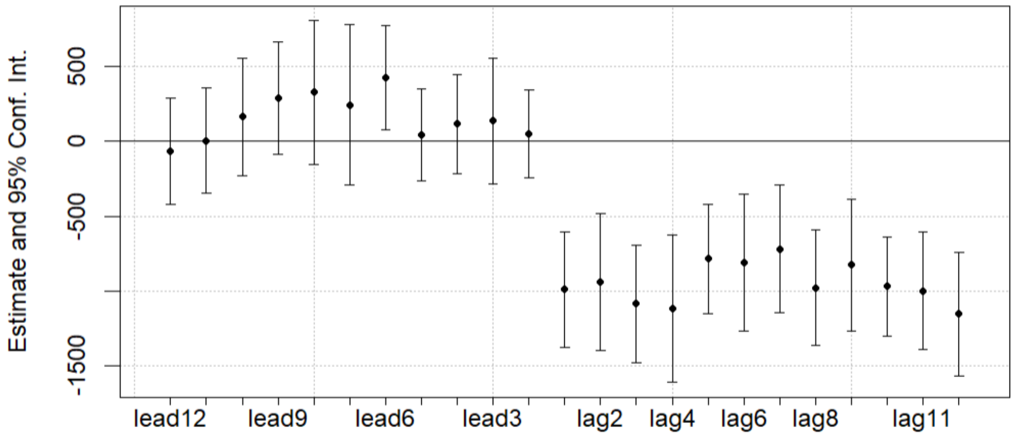


Figure 6: Event study plot - Extraction from the grid. *Notes:* This figure shows the event study plot using 12 leads/lags before/after the solar panel installation, controlling for ID + month fixed effects.

Figure 6 shows that the extraction reduction remains constant over time. This decrease represents an 18% reduction in the average electricity taken from the grid, for the entire period [8].

5.3.1 Heterogeneity by Agent

In this section, we analyze how the electricity taken from the grid changes depending on the type of agent: household or firm. The results are presented in Table 5.

The results are mostly driven by firms; installing solar panels decreases the electricity injected from the grid between 1,427 and 1,491 kWh. In addition, the results are robust to different specifications. However, for households, the effect is smaller and changes greatly depending on the specification.

[8]The average electricity extracted from the grid for the entire period is 6096.025 kWh.

Table 5: Electricity taken from the grid by type of agent: household or firm

	Panel (a): Electricity taken from the grid - Firms		
	(1)	(2)	(3)
Solar panel installation	-1491.19***	-1427.34***	-1439.81***
	(97.51)	(204.10)	(200.91)
ID Fixed Effects	Y	Y	Y
month	Y	Y	N
year	N	Y	N
month $*$ year	N	N	Y
N	17,409	17,409	17,409

	Panel (b): Electricity taken from the grid - Households		
	(1)	(2)	(3)
Solar panel installation	-108.872***	-191.25**	-193.71**
	(25.87)	(89.55)	(89.523)
ID Fixed Effects	Y	Y	Y
month	Y	Y	N
year	N	Y	N
month $*$ year	N	N	Y
N	6,977	6,977	6,977

This table shows the effect of installing a solar panel on the electricity taken from the grid, using different sets of fixed effects and different types of agents. Panel(a) uses only firms, whereas Panel (b) uses only households. Column (1) uses ID + month fixed effects; column (2) uses ID + month +year fixed effects; finally, column (3) uses ID + month $*$ year. Standard errors are cluster at state level. Significance levels: ***0.01 **0.05 *0.1.

5.4 Electricity injected into the grid

Table 6 shows the event study results using electricity injected into the grid as the dependent variable. After installing the solar panel, the agent's electricity injected into the grid increases by 1,570 kWh on average. The result changes slightly depending on the time-fixed effects used.

Table 6: Electricity injected into the grid

	Electricity injected into the grid		
	(1)	(2)	(3)
Solar panel installation	1569.75***	1708.83***	1697.76***
	(110.65)	(128.93)	(122.93)
ID Fixed Effects	Y	Y	Y
month	Y	Y	N
year	N	Y	N
month ∗ year	N	N	Y
N	18,964	18,964	18,964

This table shows the effect of installing a solar panel on the electricity injected into the grid, using different sets of fixed effects. Column (1) uses ID + month fixed effects; column (2) uses ID + month +year fixed effects; finally, column (3) uses ID + month ∗ year. Standard errors are cluster at state level. Significance levels: ***0.01 **0.05 *0.1. [4] The difference in N comes from having more missing values in the injections observations than in the extractions observations.

Figure 7 plots the event study coefficients using ID + month fixed effects. All the results are compared with the month before installing the solar polar (lead1).

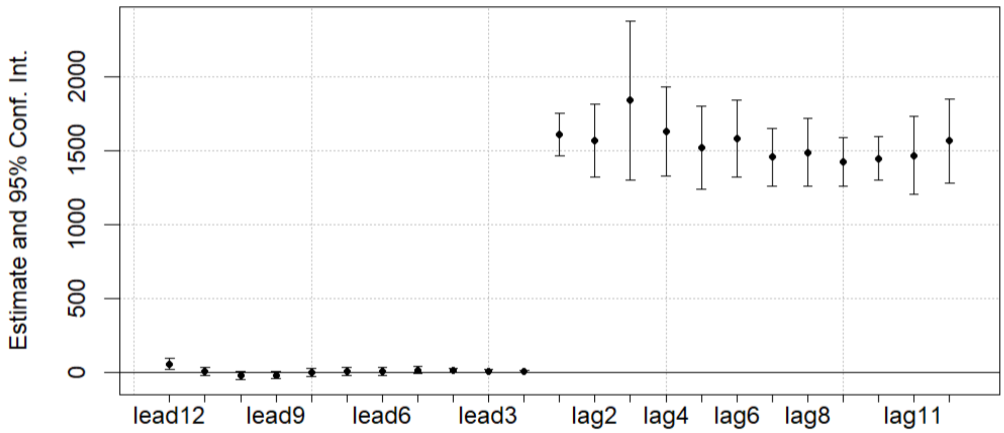


Figure 7: Event study plot - Injection into the grid. *Notes:* This figure shows the event study plot using 12 leads/lags before/after the solar panel installation, controlling for ID + month fixed effects.

Figure 7 shows the effect remains constant over time

5.4.1 Heterogeneity by Agent

In this section, we analyze how the electricity injected into the grid changes depending on the type of agent: household or firm. The results are presented in Table 7.

For firms, installing solar panels increases the electricity injected into the grid between 2,136 and 2,2286 kWh. For households, the electricity injected grid increases between 455 and 496 kWh.

Since May 2017, the yearly amount of electricity sold must be less than or equal to the amount of electricity consumed (MIEM, 12/17). We explore this change in the legislation in more detail. Specifically, we construct a variable equal to 1 if the date of installation is higher than May 2017 and zero otherwise. We then interact this variable with the treatment. The results are presented in Table 13, in

Table 7: Electricity injected into the grid by type of agent: household or firm

	Panel (a): Electricity injected into the grid - Firms		
	(1)	(2)	(3)
Solar panel installation	2135.82***	2286.01***	2257.25***
	(109.20)	(137.41)	(136.88)
ID Fixed Effects	Y	Y	Y
month	Y	Y	N
year	N	Y	N
month $*$ year	N	N	Y
N	13,033	13,033	13,033

	Panel (b): Electricity injected into the grid - Households		
	(1)	(2)	(3)
Solar panel installation	455.28***	495.76***	491.71***
	(33.39)	(42.62)	(43.02)
ID Fixed Effects	Y	Y	Y
month	Y	Y	N
year	N	Y	N
month $*$ year	N	N	Y
N	5,931	5,931	5,931

This table shows the effect of installing a solar panel on the electricity injected into the grid, using different sets of fixed effects. Column (1) uses ID + month fixed effects; column (2) uses ID + month +year fixed effects; finally, column (3) uses ID + month $*$ year. Standard errors are cluster at state level. Significance levels: ***0.01 **0.05 *0.1.

the Appendix Section 8.2. There is no difference in the electricity extracted from the grid between agents that installed a solar panel before and after the change in legislation. Unfortunately, we can not perform the same estimation of the electricity injected into the grid due to a lack of observations.

5.4.2 Value to consumers

To quantify the total effect on savings, we do some calculations. For firms, we use the "middle consumers" rate. This rate divides the day into three tiers: peak, off-peak, and plain rate. Using a weighted average of these three rates and using only the net effect estimates, we find that firms save between 198 and 450 USD (at 2017 prices) each month (Xavier, 2022). For households, we use the "intelligent rate", which also consists of 3 different rates: peak, off-peak, and plain. Given our estimates for the average household net effect, we find that they save between 30 and 68 USD (base 2017) each month (Xavier, 2022). We repeat the same analysis but using only the electricity injected into the grid. We find that while firms save between 120 and 270 USD (at 2017 prices), households save between 25 and 55 USD (base 2017) each month. Introducing solar panels with capacities of 40 kW for firms and 15 kW for households is calculated to necessitate at least 6 years and 15 years to break-even, respectively.

5.5 CO_2 Emissions

We use our estimates to understand the effect of installing solar panels on CO_2 emissions. First, we assume that all the injection and extraction-reduction substitute fossil fuel production entirely. Therefore, if 1,570 kW is being injected into the grid and 1,100 kW is not being extracted, 0.35 kg of CO_2 is reduced every month by each household/firm [9]. We have 1275 households/firms in our sample, consequently, the total reduction by month is 442 kg of CO2. Second, we assume that solar panel proportionally substitutes for fossil fuel production. For the time period studied, fossil fuel production accounted for 8.8% of all electricity produced. Therefore we assume that only 8.8% of the electricity produced substitutes fossil fuel production. In this case, 0.03 kg of CO_2 is reduced every month for each household/firm. Furthermore, the total reduction in kg of CO2 emissions by month is 38.7.

5.6 Rebound effect

Solar panel installation can induce a "rebound effect": electricity consumption increases after installing a solar panel. Unfortunately, we do not observe electricity consumption after the solar panel installation for each agent. We can, however, study the average rebound effect by using solar panel capacity as a proxy for pro-

[9] We gather the total fossil fuel production and total CO_2 emissions from fossil fuel production. To calculate how much 1 kW of fossil-fuel electricity is emitted, we divide the total CO_2 emissions by fossil fuel electricity production. We find that for each kW of fossil fuel 0.00013 kg of CO_2 emissions are emitted.

duction. Specifically, we write:

$$Consumption_{\text{before solar panel}} = Extraction_{\text{before solar panel}} \tag{3}$$

$$\begin{aligned} Consumption_{\text{after solar panel}} =& (Production - Injection) + \\ & (Extraction_{\text{bsp}} - Extraction_{\text{asp}}) \end{aligned} \tag{4}$$

$$\begin{aligned} & C_{\text{asp}} - C_{\text{bsp}} = (Production - Injection) + \\ & (Extraction_{\text{bsp}} - Extraction_{\text{asp}}) - Extraction_{\text{bsp}} \end{aligned} \tag{5}$$

$$C_{\text{asp}} - C_{\text{bsp}} = (Production - Injection) - Extraction_{\text{asp}} \tag{6}$$

Where consumption before installing the solar panel is the same as extraction before installing the solar panel (hereafter bsp), as in equation 3. After installing the solar panel (hereafter asp), the consumption of electricity equals the production of the solar panel minus the electricity injected, plus the extraction before the solar panel minus the reduction in the extraction (hereafter $extraction_{\text{asp}}$), as shown in equation 4. We then subtract 4 and 3, as in 5. By doing some calculations, as stated in equation 6, we find that the difference in consumption after and before installing a solar panel is the production of the solar panel minus the injection and the reduction in extraction of electricity from the grid.

Using sample means, we present equation 6 as in 7 [10]. where C_{it} is the electricity consumed for agent i at time t; P_{it} is the electricity produced from agent i at time t; E_{it} is the electricity extracted from the grid for agent i at time t; and I_{it} is the electricity injected into the grid for agent i at time t.

$$\begin{aligned} \frac{1}{N}\sum_{i=1}^{N}\left[\sum_{t=1}^{12} C_{it} - \sum_{-12}^{-1} C_{it}\right] =& \frac{1}{N}\sum_{i=1}^{N}\left[\sum_{t=1}^{12} P_{it} - \sum_{-12}^{-1} P_{it}\right] \\ &+ \frac{1}{N}\sum_{i=1}^{N}\left[\sum_{t=1}^{12} E_{it} - \sum_{-12}^{-1} E_{it}\right] \\ &- \frac{1}{N}\sum_{i=1}^{N}\left[\sum_{t=1}^{12} I_{it} - \sum_{-12}^{-1} I_{it}\right] \end{aligned} \tag{7}$$

From our estimation, we can deduce $\frac{1}{N}\sum_{i=1}^{N}\left[\sum_{t=1}^{12} E_{it} - \sum_{-12}^{-1} E_{it}\right]$ and $\frac{1}{N}\sum_{i=1}^{N}\left[\sum_{t=1}^{12} I_{it} - \sum_{-12}^{-1} I_{it}\right]$ (Table 4 and Table 6, respectively).[11] We also observed $\sum_{t=-12}^{-1} C_{it}$ in our data: 6740.13 kWh.[12]. Finally, we use the capacity of the solar panels to infer electricity production. The electricity production depends on the solar panel capacity and peak sunlight hours (Solar, AE solar). The total solar panel capacity is 29.56 kW, 37.64 kW for firms, and 13.45 kW for households. Uruguay has between 4.52 and 5.0 hours of sunlight per day(Global Solar Atlas. Therefore, the production of the solar panel

[10]We use the sample means because the capacity installed of the solar panel is in a different dataset. This dataset has 13 additional agents.

[11]The extraction of electricity estimation without time fixed effect is: -1089.72, similar to the estimations with time fixed effects. For the injection into the grid, the estimation without fixed effects is 1546.98, which is also very similar to the estimation with time-fixed effects.

[12]Before the solar panel installation, extraction from the grid and consumption is the same.

ranges between 5100 and 5646 kWh for firms, and between 1824 and 2018 kWh for households, considering 4.52 or 5 peak hours of sun (Table 8).

Table 8: Electricity production from solar panels

	Monthly Production		
	Total	Firms	Households
Cap. installed (kW)	29.56	37.64	13.45
Sunlight = 4.52 hours	4008	5104	1824
Sunlight = 5 hours	4434	5646	2018

This table shows the electricity production from solar panels given their installed capacity and the average peak hours of sunlight. Differentiating between firms and households.

Given the estimation and the production values, we find the following average rebound effect in Table 9. In addition, we calculate the monthly lower and upper bound rebound effect in Figure 8.

Table 9: Rebound effect

	Rebound Effect (kW)		
	Total	Firms	Households
Sunlight = 4.52 hours	1338 (20%)	1477 (22%)	1260 (19%)
Sunlight = 5.0 hours	1764 (26%)	2019 (30%)	1454 (22%)

This table shows the average rebound effect after installing a solar panel, which depends on the solar panel installed capacity and the average peak hours of sunlight. Differentiating between firms and households.

Thus, consumption increases between 22% and 30 % for firms, and between 19% and 22% for households [13]. This increase in consumption depends on solar panel capacity and the peak hours of sunlight. As a benchmark, Beppler et al. (2023)

[13] For a calculation example, please see 8.1 in the Appendix.

find a rebound effect of 28.5%. Figure 8 shows the lower and upper bounds of the rebound effect by month for all agents using the previous estimations. The lower bound considers 4.52 hours of peak sunlight, and the upper bound considers 5 hours of peak sunlight.

On one hand, the rebound effect reduces the effectiveness of the solar panels, it reduces the CO_2 emissions effect and other costs of generation, and the environmental effect could also be diminished depending on which source is extracted marginally from the grid. Given that the agent buys and sells the electricity at the retail price, the opportunity cost of electricity consumption has not changed, therefore, there is no economic incentive to increase consumption or electrification. However, Ito (2014) shows that in electricity markets, agents react to the average price. Thus this increase in electricity consumption could be explained by agents feeling richer, electricity being cheaper on average, or changes in their consumption behavior (Beppler et al., 2023; Boccard & Gautier, 2021).

On the other hand, an increase in electricity consumption is not necessarily bad if the consumption of electricity is satisfied by the solar production entirely. In addition, the household/firm can begin a process of electrification, for example, by changing the gas heater to an electric heater. This would explain why we found a rebound effect in both, households and firms.

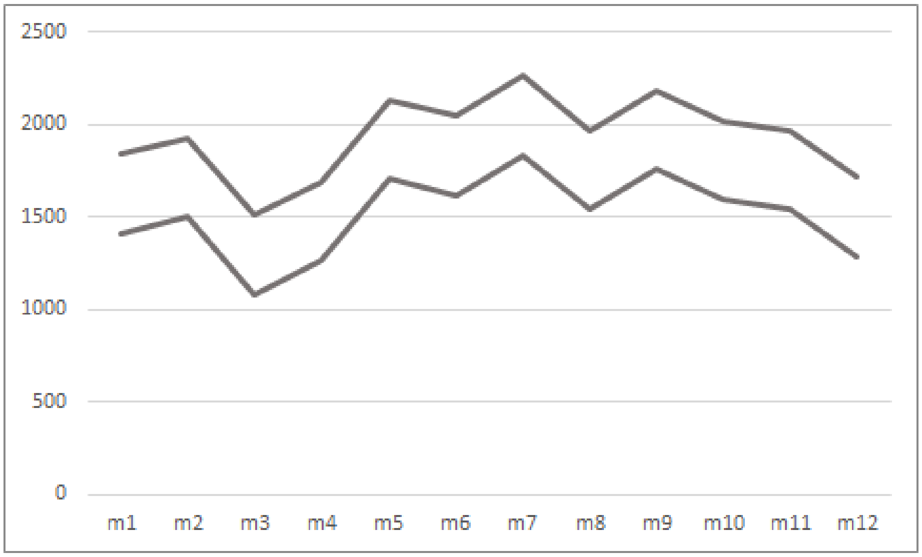


Figure 8: Rebound effect. *Notes:* This figure shows the lower and upper bound of the rebound effect, for each month after installing a solar panel.

.

6 Batteries and Emissions

The reduction of CO_2 emissions could be further improved if households and firms were allowed (and incentivized) to decide when to sell their electricity optimally, namely, if they were to have (small) batteries. In this section, we explore the potential benefits of this policy change.

Specifically, we would like to find an optimal way to minimize CO_2 emissions given agents' production. For this problem we use another database in which we exploit hourly electricity production by source and hourly demand, from November 2018 to August 2022. This problem can be expressed as a linear problem:

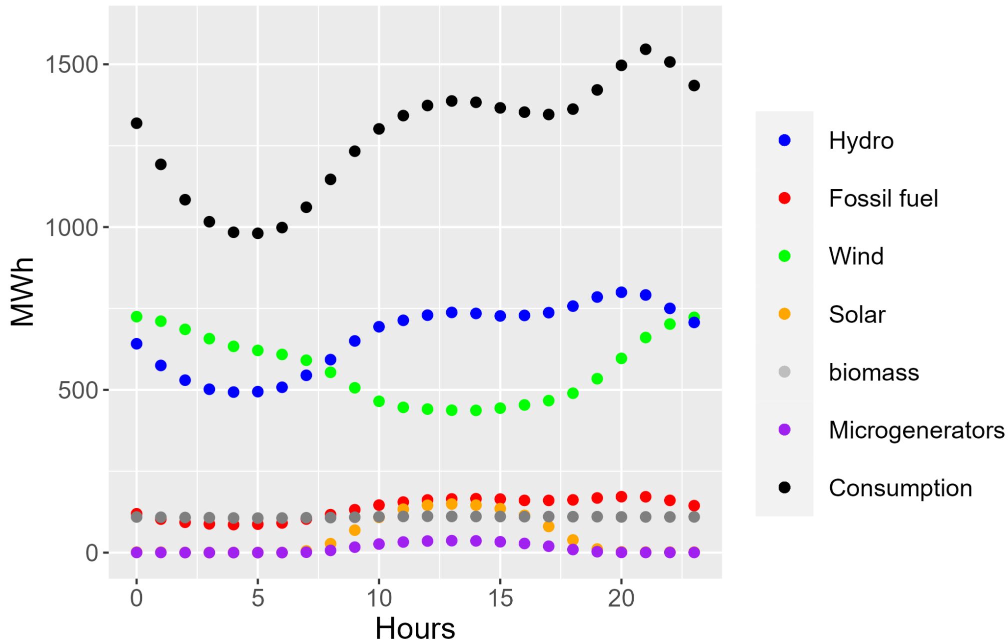
$$\begin{aligned} \min_{q^i_{th}, F_{ht}} & \sum_{h=0}^{23} \alpha_{th}^{CO_2} \times F_{th} \\ s.t & \sum_{h=0}^{23} q^i_{th} \leq Q^i, \forall i \\ & \mathrm{RD}_{th} \leq F_{th} + \sum_i q^i_{th}, \forall h \end{aligned} \tag{8}$$

where q^i_{th} is the electricity sold to the grid from solar panels for agent i on day t at hour h; F_{th} is the fossil-fuel-based electricity production at day t and hour h; $\alpha_{th}^{CO_2}$ is the CO_2-emissions-factor of producing a unit of electricity on day t at hour h from fossil-fuel-based facilities; Q_i is the total electricity production of agent i in the period $t = 1$ to T; and RD_{th} is the residual demand at time t and hour h.[14] The first restriction imposes, for each i, that the total hourly sales to the grid are equal to the

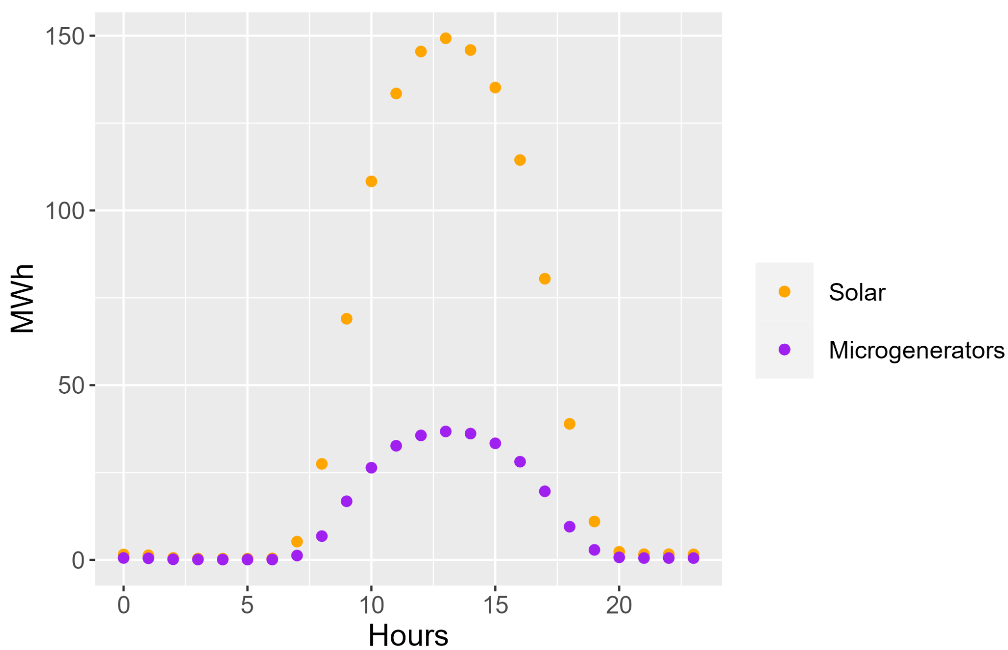
[14]Formally, the residual demand is calculated as the hourly demand minus the wind, solar, hydro and biomass production.

total production by household i. The last restriction imposes that fossil-fueled-based and microgenerators generate at least as much electricity as the (residual) demand. We expand the calculations of the model in the Appendix Section 8.

Intuitively, we would like agents to sell their solar-produced electricity when emissions are highest, that is when fossil-fuel facilities are producing. Given that firms and agents only sell solar when they produce and fossil-fuel production is highest at night, the only possible way to substitute fossil-fuel production with solar production at housheold/firm level is with batteries. Figure 9 shows how different sources behave hourly.



(a) Electricity production by source



(b) Electricity production by large solar and microgenerators

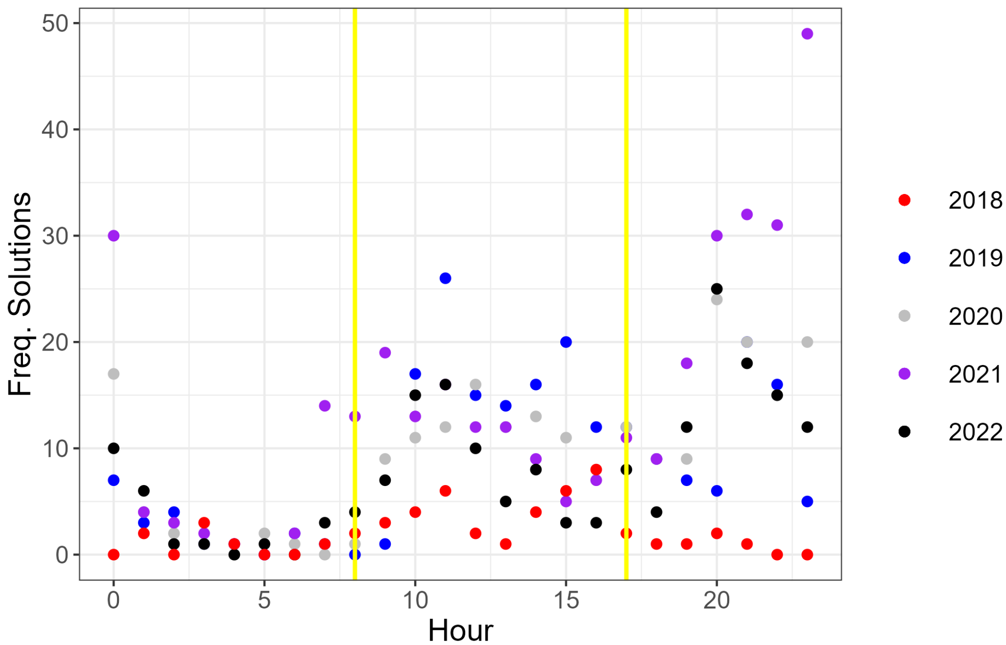
Figure 9: Electricity source. *Notes:* Panel (a) shows how the different electricity sources behave hourly, from November 2018 until August 2022. Panel (b) shows how the large solar and the microgenerator production behaves. *Source: (UTEi, 2022)*

6.1 Results

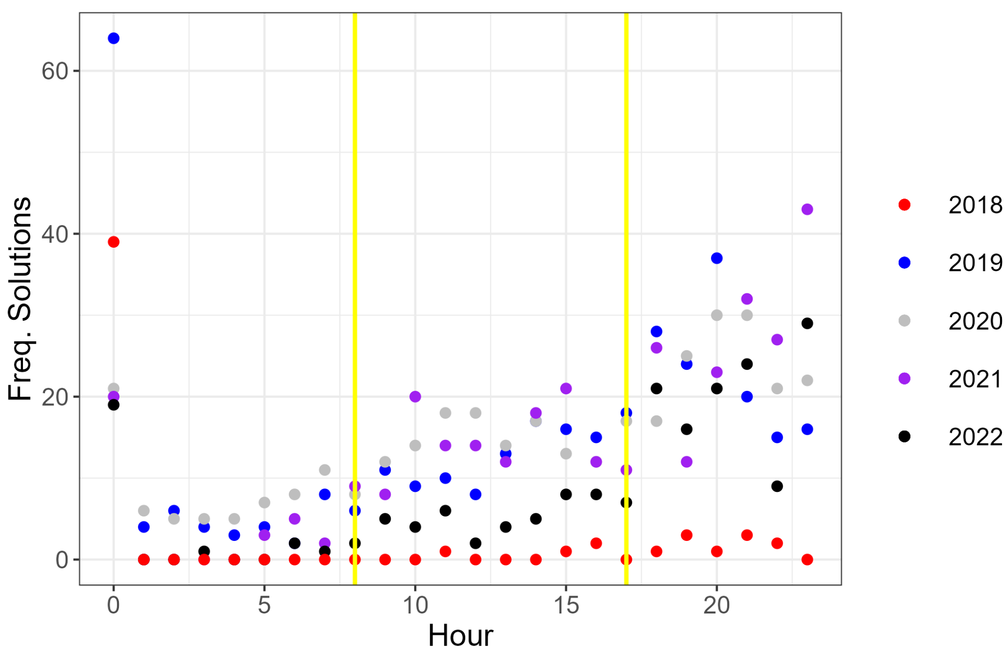
The solution to this problem provides the optimal way to allocate electricity injections to the grid. From this, we can recover the potential benefits of offering batteries to households and firms.

We solve the model using both the CO_2 emission factors and the spot price.[15] Figure 10 presents our results. Each dot represents the number of times the model chooses that hour as optimal to inject the microgenerator-electricity into the grid for each year. The optimal time to inject electricity into the grid is around 9 pm (21 hrs.) for both CO_2 emissions and spot prices.

[15] The spot price is the marginal cost of increasing the demand for one unit.



(a) Model solution using CO_2



(b) Model solution using spot prices

Figure 10: Minimization solution. *Notes:* Panel (a) shows the model solution minimizing the CO_2 emissions. Panel (b) shows how the minimization solution using spot prices

7 Conclusion

We use granular data, in which we observe the amount of electricity injected and extracted into the grid at agent level, to study a net-metering policy in Uruguay. We do an event-study to analyze, first, the net effect, that is the effect of installing a solar panel in the extraction minus the injection into the grid. Then, we analyze the change in electricity extracted and injected into the grid, separately. A problem that arises from this specification is that solar adaptation and installation timing are endogenous (Beppler et al., 2023). In addition, early adopters may be different from future adopters. Consequently, our estimations should be considered as an upper bound. This is a limitation of the method employed, nevertheless, we still are able to have valid measures of the effect of the policy. Third, we use our estimates to determine the effect of the policy on CO_2 emissions and the rebound effect. Finally, we perform a minimization problem that illustrates the benefits of installing batteries to store solar-produced electricity instead of selling it into the grid.

On one hand, the policy has positive impact. First, agents demand less electricity from the grid. After installing the solar panel, the electricity taken from the grid decreases by 1,100 kWh on average, and this effect is constant over time. This represents an 18% reduction in the average electricity taken from the grid. Second, the agent is now selling clean energy to the grid, which is then consumed by other agents. After installing the solar panel, the electricity injected into the grid increases by 1,600 kWh on average, and this effect is constant over time. Finally, the effect of installing a solar panel in the net effect (extraction $-$ injection) decreases by 2830.68 kWh, and this effect is constant over time. Third, to determine the reduction in

CO_2 emissions, we study two potential cases. First, assuming that all the electricity injected and the reduction of electricity extracted substitute fossil fuels entirely, then the CO_2 decreases by 0.35 kg per month per agent, and a total of 442 kg of CO2 every month. Second, assuming that the substitution is proportional to the production of fossil fuels, the CO_2 decreases by 0.03 kg per month per agent, and a monthly total of 38.7 kg of CO2. Finally, we use the capacity of the solar panel and find evidence of a rebound effect. Specifically, we find that firms increase their electricity consumption between 22% and 30%, and households increase their electricity consumption between 19% and 22%. This increase could be explained by agents feeling richer, electricity being cheaper on average, or changes in their consumption behavior (Beppler et al., 2023; Boccard & Gautier, 2021).

On the other hand, the policy may have important equity implications. Agents who install solar panels are richer than average. It is usually assumed that electricity prices embed the cost of the grid (e.g., Feger et al. (2022)). Since prices tend to be progressive in electricity consumption (see Figure 1) and richer agents tend to consume more electricity, this implies that richer agents are now contributing less to the grid costs. Furthermore, the marginal cost of solar electricity is virtually zero. The electricity company, however, is buying solar electricity at the retail price. In the long run, both may affect electricity prices for all consumers. Therefore, to partially alleviate these concerns and to have an ever higher (negative) impact on the CO_2 emissions, we propose an alternative policy: instead of selling the electricity immediately into the grid, households/firms could store it in a battery and sell it at another time. Installing a battery has some positive spillovers to the rest of the consumers by decreasing CO_2 emissions and spot prices. To analyze this, we solve a minimization linear problem. We find that for most days, the model indicates that the best hour to inject electricity is between 8-11 PM.

We do some calculations to quantify how much firms and agents save on their electricity bills by installing solar panels. We find that firms save between 120 and 270 USD in 2017 prices. For households, we find that they save between 25 and 55 USD in 2017 prices. The maximum cost of a solar panel battery in the Uruguayan local market in 2017 prices, is 717 USD for 12V and 100ha and 1132 USD for 12V 200ha (Mercado Libre). Thus, the agent could completely eliminate the injection of electricity into the grid by buying a battery, and the cost of the battery would pay for itself in a few months. Alternatively, the agent could sell the electricity to the grid when optimal, as studied in our linear model solution.

Future studies could explore the rebound effect further. Moreover, our work does not include solar panels with batteries off-grid (i.e., not connected to the grid), which could benefit households without the cost of expanding the grid, an interesting topic for future work.

8 Appendix

In this section, we developed the model.

$$
\begin{aligned}
&\min_{q_{th}^i, t_{th}} \sum_i \sum_{t=1}^{T} \sum_{h=0}^{23} CO_2^{th}(q_{th}^i) + \sum_{t=1}^{T} \sum_{h=0}^{23} CO_2^{th}(t_{th}) \\
&s.t \ \ \sum_{t=1}^{T} \sum_{h=0}^{23} q_{th}^i \geq Q^i, \forall i \\
&\qquad T_{ht} + q_{th} \geq \text{Residual Demand}
\end{aligned} \tag{9}
$$

Where q_{th}^i is the electricity injected into the grid from the microgenerator i, and t_{th} is the thermal production in a certain hour and day.

The objective function is a matrix$_{48x1}$ times a matrix$_{1x48}$

$$
\begin{bmatrix} D_0 & D_1 & D_2 & \cdots & D_{23} & 0 & 0 & 0 & \cdots & 0 \end{bmatrix} \times \begin{bmatrix} t_0 \\ t_1 \\ t_2 \\ \vdots \\ t_23 \\ \sum_i q_0^i \\ \sum_i q_1^i \\ \sum_i q_2^i \\ \vdots \\ \sum_i q_2^i 3 \end{bmatrix}
$$

One of the constraint is the following, where the only ones are in their diagonal (i.e. $a_{(1,1)}$, $a_{(1,24)}$, $b_{(2,2)}$, $b_{(2,25)}$, $c_{(3,3)}$, $c_{(2,26)}$,...,$x_{(24,24)}$, and $x_{(24,48)}$)

$$\setcounter{MaxMatrixCols}{48}\begin{pmatrix}
1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1
\end{pmatrix}
\times
\begin{pmatrix} t_0 \\ t_1 \\ t_2 \\ \vdots \\ t_23 \\ \sum_i q_0^i \\ \sum_i q_1^i \\ \sum_i q_2^i \\ \vdots \\ \sum_i q_2^i3 \end{pmatrix}
\geq
\begin{pmatrix} \mathrm{rd}_0 \\ \mathrm{rd}_1 \\ \mathrm{rd}_2 \\ \mathrm{rd}_3 \\ \mathrm{rd}_4 \\ \mathrm{rd}_5 \\ \mathrm{rd}_6 \\ \mathrm{rd}_7 \\ \mathrm{rd}_8 \\ \mathrm{rd}_9 \\ \mathrm{rd}_10 \\ \mathrm{rd}_11 \\ \mathrm{rd}_12 \\ \mathrm{rd}_13 \\ \mathrm{rd}_14 \\ \mathrm{rd}_15 \\ \mathrm{rd}_16 \\ \mathrm{rd}_17 \\ \mathrm{rd}_18 \\ \mathrm{rd}_19 \\ \mathrm{rd}_20 \\ \mathrm{rd}_21 \\ \mathrm{rd}_22 \\ \mathrm{rd}_23 \end{pmatrix}$$

The second constraint:

$$\begin{pmatrix} 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1 \end{pmatrix} \times \begin{pmatrix} t_0 \\ t_1 \\ t_2 \\ \vdots \\ t_23 \\ \sum_i q_0^i \\ \sum_i q_1^i \\ \sum_i q_2^i \\ \vdots \\ \sum_i q_2^i3 \end{pmatrix} = (Q^i)$$

Where D_k is either the CO_2 emission coefficient or the spot price for hour $k = (0,\ 1,\ 2, \cdots,\ 23)$. rd_k is the residual demand for hour k. The residual demand is found as:

8.1 Appendix B

$$\sum_{1}^{12} \frac{Consumption_i}{N} - 6740.13 = 4008 - 1,110 - 1,570 \text{ if hours of sunlight } = 4.52$$
$$\sum_{1}^{12} \frac{Consumption_i}{N} - 6740.13 = 1338 \tag{10}$$

$$\sum_{1}^{12} \frac{Consumption_i}{N} - 6740.13 = 4434 - 1,110 - 1,570 \text{ if hours of sunlight } = 5$$
$$\sum_{1}^{12} \frac{Consumption_i}{N} - 6740.13 = 1764 \tag{11}$$

8.2 Appendix C

Table 10: Electricity taken from the grid

	Electricity taken from the grid (kWh)		
	(1)	(2)	(3)
Solar panel installation	-1099.2***	-1085.68***	-1091.55***
	(128.51)	(185.11)	(187.97)
ID F.E	Y	Y	Y
month	Y	Y	N
year	N	Y	N
month $*$ year	N	N	Y
N	24,386	24,386	24,386

This table shows the effect of installing a solar panel on the electricity taken from the grid, using different sets of fixed effects. Column (1) uses ID + month fixed effects; column (2) uses ID + month +year fixed effects; finally, column (3) uses ID + month $*$ year. Standard errors are cluster at ID level. Significance levels: ***0.01 **0.05 *0.1.

Table 11: Electricity injected into the grid

	Electricity injected into the grid		
	(1)	(2)	(3)
Solar panel installation	1569.75***	1708.83***	1697.76***
	(98.36)	(113.62)	(114.53)
ID Fixed Effects	Y	Y	Y
month	Y	Y	N
year	N	Y	N
month $*$ year	N	N	Y
N	18,964	18,964	18,964

This table shows the effect of installing a solar panel on the electricity injected into the grid, using different sets of fixed effects. Column (1) uses ID + month fixed effects; column (2) uses ID + month +year fixed effects; finally, column (3) uses ID + month $*$ year. Standard errors are cluster at ID level. Significance levels: ***0.01 **0.05 *0.1. [4] The difference in N come from having more missing values on the injection's observations than in the extraction's observations.

In this section, we present the estimation results using the Sun and Abraham (2021) approach. The results are presented in Table 12.

Table 12: Sun and Abraham (2021) estimation approach

	Net effect (kWh)	Extraction (kWh)	Injections (kWh)
Solar panel installation	-2488.46***	-891.69***	1532.81***
	(298.47)	(169.31)	(90.39)
ID F.E	Y	Y	Y
Month F.E	Y	Y	Y
N	18,963	24,386	18,963

This table shows the effect of installing a solar panel on the electricity taken from the grid using ID + month fixed effect. Column (1) shows the net effect, i.e, the electricity extracted − injected into the grid; column (2) shows the electricity taken from the grid; finally, column (3) shows the electricity injected into the grid. Standard errors are cluster at state level. Significance levels: ***0.01 **0.05 *0.1.

Table 13

	Extraction (kWh)		
Solar panel installation	-1201.92***	-1261.41***	-748.1**
	(202.51)	(274.84)	(396.62)
Solar panel installation $*$ After May 2017	142.12	231.54	-454.83
	(312.46)	(354.74)	(534.99)
ID Fixed Effects	Y	Y	Y
month	Y	Y	N
year	N	Y	N
month $*$ year	N	N	Y
N	24,386	24,386	24,386

This table shows the effect of installing a solar panel on the electricity taken from the grid, using different sets of fixed effects. Column (1) uses ID + month fixed effects; column (2) uses ID + month +year fixed effects; finally, column (3) uses ID + month $*$ year. After May 2017 takes the value equal to 1 if the Agent installs a solar panel after May 2017. Solar panel installation takes the value equal to 1 after installing the solar panel. Solar panel installation $*$ After May 2017, is the interaction. Standard errors are cluster at state level. Significance levels: ***0.01 **0.05 *0.1.

Table 14: Electricity taken from the grid

	Net effect (extractions − injections (kWh))		
	(1)	(2)	(3)
Solar panel installation	-2564.97***	-2839.05***	-2830.68***
	(249.20)	(363.62)	(354.73)
N	18,964	18,964	18,964
Solar panel installation	-2538.08***	-2834.24***	-2834.01***
	(254.70)	(369.81)	(360.50)
N	18,476	18,476	18,476
	extractions (kWh))		
	(1)	(2)	(3)
Solar panel installation	-1099.2***	-1085.68***	-1091.55***
	(71.41)	(146.19)	(142.94)
N	24,386	24,386	24,386
Solar panel installation	-1118.87***	-1106.04***	-1114.73***
	(72.17)	(146.90)	(142.16)
N	23,898	23,898	23,898
	Injections (kWh))		
	(1)	(2)	(3)
Solar panel installation	1569.75***	1708.83***	1697.76***
	(110.65)	(128.93)	(122.93)
N	18,964	18,964	18,964
Solar panel installation	1512.66***	1672.01***	1666.8***
	(112.72)	(128.77)	(123.52)
N	18,476	18,476	18,476
ID F.E	Y	Y	Y
month	Y	Y	N
year	N	Y	N
month $*$ year	N	N	Y

This table shows the effect of installing a solar panel on the net electricity (extractions − injections) taken from the grid, using different sets of fixed effects. Column (1) uses ID + month fixed effects; column (2) uses ID + month +year fixed effects; finally, column (3) uses ID + month $*$ year. Standard errors are cluster at state level. Significance levels: ***0.01 **0.05 *0.1.

References

Beppler, R. C., Matisoff, D. C., & Oliver, M. E. (2023). Electricity consumption changes following solar adoption: Testing for a solar rebound. *Economic Inquiry*, *61*(1), 58–81.

Boampong, R., & Brown, D. P. (2020). On the benefits of behind-the-meter rooftop solar and energy storage: The importance of retail rate design. *Energy economics*, *86*, 104682.

Boccard, N., & Gautier, A. (2021). Solar rebound: The unintended consequences of subsidies. *Energy Economics*, *100*, 105334.

Borenstein, S. (2017). Private net benefits of residential solar pv: The role of electricity tariffs, tax incentives, and rebates. *Journal of the Association of Environmental and Resource Economists*, *4*(S1), S85–S122.

CAF. (2022). The corporacion andina de fomento – banco de desarrollo de américa latina. Retrieved from `https://www.caf.com/es/actualidad/noticias/2021/07/uruguay-lider-en-el-uso-de-fuentes-renovables-en-america-latina/`

De Groote, O., & Verboven, F. (2019). Subsidies and time discounting in new technology adoption: Evidence from solar photovoltaic systems. *American Economic Review*, *109*(6), 2137–72.

Deng, G., & Newton, P. (2017). Assessing the impact of solar pv on domestic electricity consumption: Exploring the prospect of rebound effects. *Energy Policy*, *110*, 313–324.

Eid, C., Guillén, J. R., Marín, P. F., & Hakvoort, R. (2014). The economic effect of electricity net-metering with solar pv: Consequences for network cost recovery, cross subsidies and policy objectives. *Energy Policy*, *75*, 244–254.

Feger, F., Pavanini, N., & Radulescu, D. (2022). Welfare and redistribution in residential electricity markets with solar power. *The Review of Economic Studies*, *89*(6), 3267–3302.

IPCC. (2006). Guidelines for national greenhouse gas inventories, prepared by the national greenhouse gas inventories programme, eggleston h.s., buendia l., miwa k., ngara t. and tanabe k. (eds). *IGES, Japan*. Retrieved from https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/

Islam, T., & Meade, N. (2013). The impact of attribute preferences on adoption timing: The case of photo-voltaic (pv) solar cells for household electricity generation. *Energy Policy*, *55*, 521–530.

Ito, K. (2014). Do consumers respond to marginal or average price? evidence from nonlinear electricity pricing. *American Economic Review*, *104*(2), 537–563.

Jeong, G. (2013). Assessment of government support for the household adoption of micro-generation systems in korea. *Energy policy*, *62*, 573–581.

Kattenberg, L., Aydin, E., Brounen, D., & Kok, N. (2023). Converting the converted: Subsidies and solar adoption. *MIT Center for Real Estate Research Paper*(23/12).

MIEM. (12/17). Resolución ministerial. ministerio de industria, energía, y minería. Retrieved from https://portal.ute.com.uy/sites/default/files/files-cuerpo-paginas/Resoluci%C3%B3n%20Ministerial%20-%

20Modificaciones%20al%20r%C3%A9gimen%20jur%C3%ADdico%20de%20la%20Microgeneraci%C3%B3n.pdf

MIEM. (2022). Balance energético nacional. Retrieved from https://ben.miem.gub.uy/

Pretnar, N., & Abajian, A. (2023). Subsidies for close substitutes: Evidence from residential solar systems. *Available at SSRN 3771496*.

Qiu, Y., Kahn, M. E., & Xing, B. (2019). Quantifying the rebound effects of residential solar panel adoption. *Journal of environmental economics and management*, *96*, 310–341.

Sexton, S., Kirkpatrick, A. J., Harris, R. I., & Muller, N. Z. (2021). Heterogeneous solar capacity benefits, appropriability, and the costs of suboptimal siting. *Journal of the Association of Environmental and Resource Economists*, *8*(6), 1209–1244.

Sun, L., & Abraham, S. (2021). Estimating dynamic treatment effects in event studies with heterogeneous treatment effects. *Journal of Econometrics*, *225*(2), 175–199.

UTEi. (2022). La administración nacional de usinas y trasmisiones eléctricas. Retrieved from https://www.ute.com.uy/clientes/redes-inteligentes/microgeneracion

Xavier, R. (2022). Econ uy. Retrieved from https://econ.uy/