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The Impact of Solar Panel Installation on Electricity Consumption and Production

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Since 2010, the Uruguayan government has fostered the installation of solar panels among households and firms to promote small-scale renewable electricity production. Under this policy, agents with solar panels are allowed to feed any electricity surplus into the grid. We study the economic and environmental consequences of this policy. We collect a novel dataset on electricity extraction and injection into the grid at a household-firm level for the whole country. First, we find that installing a solar panel reduces the electricity extracted from the grid. Second, we find that it increases the electricity injected into the grid. Third, we find that it reduces CO_2 emissions between 0.35 and 0.03 kg per month and agent. Fourth, we find evidence of a rebound effect: electricity consumption after the solar panel installation increases between 20% and 26%, on average. Lastly, we propose an alternative policy that allows agents to store their electricity surplus 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, when fossil-fuel facilities satisfy most of the electricity demand. We leverage household and firm-level data to study the effect of a net-metering policy on electricity extraction and injection, showing what countries can expect from implementing such a policy.

KEYWORDS
Microgenerators, Solar Panels, Renewable Electricity, Energy Policy

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El impacto de la instalación de paneles solares en el consumo y producción de electricidad

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Desde 2010, el gobierno uruguayo ha promovido la instalación de paneles solares para fomentar la producción de energía renovable. Bajo esta política, los usuarios con paneles solares pueden verter cualquier excedente de electricidad en la red. En este estudio, analizamos las consecuencias económicas y ambientales de esta política. En primer lugar, encontramos que la instalación de un panel solar reduce la electricidad extraída de la red. En segundo lugar, observamos que aumenta la electricidad inyectada en la red. En tercer lugar, encontramos que reduce las emisiones de CO_2 entre 0.35 y 0.03 kg por mes y agente. En cuarto lugar, encontramos evidencia de un efecto rebote: el consumo de electricidad después de la instalación del panel solar aumenta entre un 20% y un 26%, en promedio. Por último, proponemos una política alternativa que permite a los usuarios almacenar su excedente de electricidad en baterías en lugar de inyectarlo inmediatamente en la red. Según nuestro modelo, el mejor momento para inyectar electricidad en la red es alrededor de las 9 PM, cuando las instalaciones de combustibles fósiles satisfacen la mayor parte de la demanda de electricidad. Utilizamos datos a nivel de hogares y empresas para estudiar el efecto de una política de medición neta en la extracción e inyección de electricidad, mostrando lo que los países pueden esperar al implementar dicha política.

KEYWORDS

Microgeneradores, Paneles solares, Energía renovable, Política energética

1 | INTRODUCTION

Energy production contributes substantially to greenhouse gas (GHG) emissions, which are responsible for anthropogenic climate change. Consequently, numerous countries are transitioning toward cleaner energy production. Governments employ different policies to incentivize and accelerate this transition, including the promotion of microgeneration from renewable resources. Since 2010, the Uruguayan government has incentivized the installation of solar, wind, and small hydro microgenerators among households and firms. Specifically, the government initiated a net-metering policy: it allows agents with clean microgenerators to sell any electricity surplus into the grid at the retail price.

We collect a novel data set in which we observe the electricity extracted and injected into the grid at a household-firm level, before and after the solar panel installation, for all the agents that installed a microgenerator since 2010. We focus exclusively on solar panels, which are the main microgenerators in the country. More specifically, we observe the monthly electricity extracted and injected into the grid at an agent level, 12 months before and 12 months after the solar panel installation. Additionally, we gather data on monthly CO_2 emissions from fossil-fuel facilities, hourly total electricity production by source, and hourly load.

We analyze several aspects of the net-metering policy. First, we study how the installation of solar panels affects "net electricity," which is the difference between electricity extracted and injected into the grid. After the installation of a solar panel, the electricity extracted from the grid is expected to decrease, and the electricity injected into the grid is expected to increase. The magnitude of such effects, however, is an empirical question. We use an event-study approach to quantify these effects. In our context, the study-event approach has a caveat: it misses to consider that the timing of solar panel installation and adaptation is endogenous (Beppler et al., 2023; Boccard and Gautier, 2021). The caveat is twofold. Firstly, when the agent installs a solar panel, she might simultaneously decide to increase her electricity consumption, or, on the contrary, she might start electricity-conservation initiatives. This concern is unlikely to be present in our context: agents must navigate through various bureaucratic processes to get their solar panels installed and thus lack control over the exact moment the solar panel starts working. Secondly, early adopters may differ from future adopters, and hence, future adoption of solar panels might not necessarily yield the same results as the ones we find. We alleviate this concern by estimating the model year by year. We find no statistical difference between the yearly estimators and conclude this form of selection is not prevalent. Since we cannot entirely rule out either of these concerns, we read our estimates as an upper bound of the effect of the policy.

Second, we calculate the effect of the policy on CO_2 emissions and the "rebound effect," which is the potential increase in electricity consumption after the solar panel installation.

Finally, a net-metering policy may have important equity implications. Agents who install solar panels are richer than average. It is usually assumed that electricity prices incorporate the cost of the grid (e.g., Feger et al. (2022); Eid et al. (2014)). Since 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 electricity providers to buy solar-produced electricity at the retail price. In the long run, these factors may raise electricity prices for all consumers. To lessen these concerns and improve the effectiveness of the net-metering policy, we propose an alternative policy: households and firms could be allowed to store any surplus of electricity in batteries and, instead of injecting it immediately into the grid, inject it when optimal. This optimal allocation would reduce CO_2 emissions and spot prices, benefiting other consumers and lessening the equity concerns.

Our findings can be summarized as follows. First, we find that the net effect, the effect of installing a solar panel in the extraction minus injection of electricity into the grid, is a decrease of 2565 kWh. This effect is constant over time. Analyzing extraction and injection separately, we find that the solar panel installation decreases the electricity extracted from the grid and increases the electricity injected into the grid. More specifically, agents decrease their monthly electricity extraction by 1,100 kWh, an 18% reduction from their average extraction, and increase the electricity injected into the grid by 1,570 kWh. Both effects remain constant over time.

Additionally, we consider heterogeneity by agent and analyze households and firms separately. We find that both groups increase the electricity injected into the grid. The reduction in electricity extracted from the grid, however, is large for firms and relatively low for households. This could be explained by firms having a larger capacity and household consumption patterns, as households tend to consume more electricity during the evening when solar production is low.

Second, we use our estimates to determine the policy impact on CO_2 emissions and the rebound effect. To study the reduction in CO_2 emissions, we analyze two scenarios. Firstly, we assume that both the electricity injected into the grid and the reduction in electricity extracted from the grid substitute fossil-fuel production exclusively. In this scenario, we find that each agent reduces 0.35 kg of CO_2 emissions per month, resulting in a total reduction of 442 kg of CO2 per month. Secondly, we assume that micro-generated electricity substitutes fossil fuels proportionally to their share in total electricity production.[1] In such a scenario, each agent reduces CO_2 emissions by 0.03 kg per month, resulting in a total reduction of 38.7 kg of CO_2 per month.

The rebound effect is the increase in electricity consumption after the solar panel installation. We find that, after installing the solar panel, firms increase their electricity consumption between 22% and 30%, and households increase their electricity consumption between 19% and 22%.[2] In theory, this increase in electricity consumption could be explained by agents feeling richer, changing their consumption behavior, or facing a lower average electricity price (Beppler et al., 2023; Boccard and Gautier, 2021). The welfare implications of the rebound effect are ambiguous. On the one hand, the rebound effect reduces the effectiveness of solar panels by decreasing the reduction of CO_2 emissions, especially if the source that it substitutes in the margin is fossil-fuel-based. By a similar token, it could also increase the costs of generation. On the other hand, the increase in electricity consumption could have a positive impact if agents begin an electrification process, such as replacing wood fireplaces with electric ones. This can lead to reduced pollutants at the household and firm level (Beppler et al., 2023). Both implications are likely to be present in our context.

Finally, we find that the optimal time for agents to sell their solar production is between 8 PM and 11 PM when CO_2 emissions from fossil-fuel-based electricity production and spot prices are high. Allowing households and firms to store electricity and sell it at another time generates environmental and economic benefits for the rest of the consumers, alleviating some of the equity concerns of the policy.

We contribute to the literature in several ways. First, we expand the literature on agents' use of solar panels (Borenstein, 2017; Boccard and Gautier, 2021; Sexton et al., 2021; Feger et al., 2022; Pretnar and Abajian, 2023; Beppler et al., 2023). Importantly, and unlike other studies, we observe electricity extracted and injected into the grid directly - we do not infer

[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 electricity extracted from the grid substitute only 8% of the fossil-fuel production.

[2] The range is given by various assumptions on the total peak hours.

it. Furthermore, we use individual-level rather than aggregate data. On that front, our paper is close to Feger et al. (2022). We expand it in numerous ways. First, we directly observe the electricity extracted and injected into the grid, while Feger et al. (2022) have to estimate it. Second, we use more recent data, covering the years 2010-2022 instead of 2008-2014. Given the significant reduction in solar panel prices, this factor is particularly relevant. Lastly, our study focuses exclusively on net metering in contrast to Feger et al. (2022), who study five years of feed-in tariff policy and one year of net-metering policy.

Second, we contribute to the literature on equity problems associated with the net metering policy, the miss-allocation of the electricity injected from microgenerators, and the use of batteries in solar panels (Pretnar and Abajian, 2023; Sexton et al., 2021; Boampong and Brown, 2020; Eid et al., 2014). More specifically, we explore an alternative policy that could improve net metering, lessening some of the equity implications. We propose to allow households and firms to install batteries and store the electricity instead of selling it immediately into the grid.

Third, we contribute to the extensive body of research on calculating the rebound effect (Kattenberg et al., 2023; Beppler et al., 2023; Qiu et al., 2019; Deng and Newton, 2017). Our results are in the upper bound of the findings in this literature, where, for example, Beppler et al. (2023) find a rebound effect of 28.5%, higher than the 18% of Qiu et al. (2019) and the 17%-21% of Deng and Newton (2017). Lastly, we find a negative rebound effect, an increase in electricity consumption, contrary to Kattenberg et al. (2023), who 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 and Verboven (2019); Islam and Meade (2013); Jeong (2013). We use data from a middle-income country, expanding the literature on that front as well.

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. Section 7 concludes.

2 | ELECTRICITY MARKET

The Uruguayan electricity market is highly regulated. It has five primary electricity sources: wind, hydro, biomass, solar, and fossil fuel. The market operator, ADME, buys electricity on a merit-order basis - from the lowest to the highest marginal cost. Afterward, the electricity is distributed to consumers by "Administración Nacional de Usinas y Trasmisiones Eléctricas" (UTE), a state-owned electrical company. The market works 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. Lastly, the electricity price is set by the Executive Power and has periodic adjustments, at least once a year. Different pricing plans are offered to consumers. Figure 1 illustrates the evolution of the prices of one of these plans, "Residential Simple."

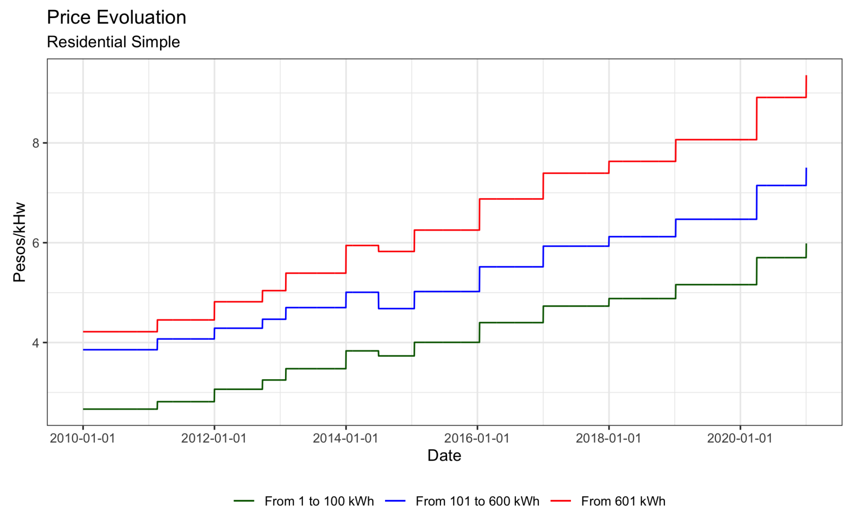


FIGURE 1 Price Example. *Notes:* This figures shows the evolution of the "Residential Simple" electricity rate. *Source: (UTEi, 2022)*

In the last two decades, 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 submit a bid containing the power capacity and the price. Afterward, the government grants permission to install and produce renewable energy to the best offers. This policy resulted in having 94% of the country's electricity grid being powered by renewable sources (MIEM, 2022; CAF, 2022). On a small scale, Uruguay has implemented a "net metering" policy. This policy allows households and firms to produce and sell solar, small-scale wind, and hydroelectricity. In principle, the agent consumes all renewable electricity that he produces. If, at any given moment, the electricity production exceeds consumption, the surplus is injected into the grid. The selling price is the retail price the agent faces, and the electricity injected is discounted in the current month's bill. In May 2017, the policy changed, stipulating that the yearly amount of electricity sold must not exceed the amount of electricity consumed (MIEM, 12/17)[3].

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

[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 12

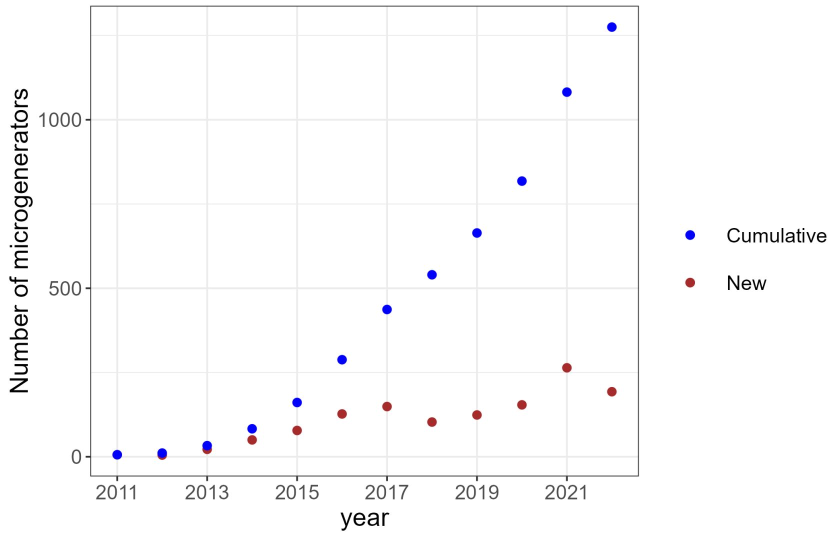
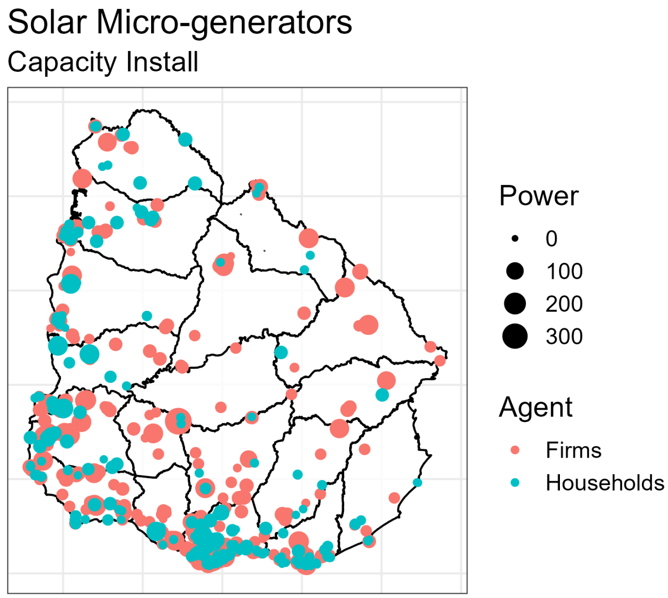


FIGURE 2 Solar Panels. *Notes:* This figure shows the new number of solar microgenerators installed by year in red. And the cumulative number of new solar microgenerators by year in blue. *Source: (UTEi, 2022)*

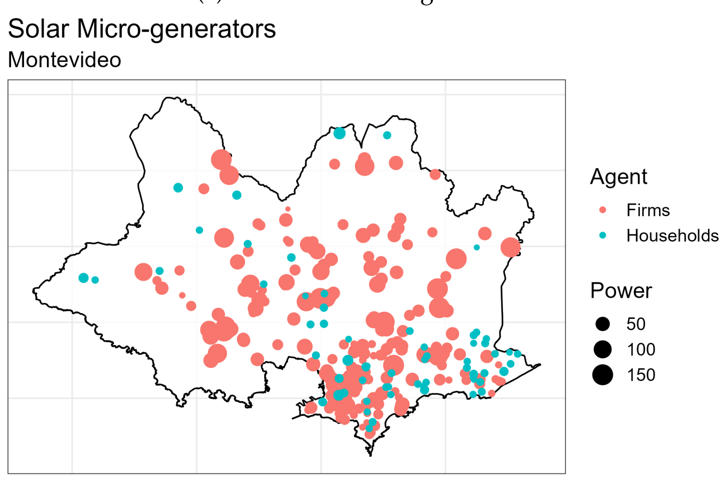
3 | DATA AND DESCRIPTIVE STATISTICS

We use administrative data at the household and firm level to analyze how the electricity extracted and injected into the grid changes after installing a solar panel, under the net-metering policy. The data was provided by UTE, and it includes monthly data on electricity consumption from the grid during the 12 months leading up to the solar panel installation, as well as electricity extracted and injected into the grid 12 months after the solar panel installation.

In total, the dataset contains 1275 agents, 904 firms, and 371 households. Figure 3 shows the location of all solar panels color-coded by type of agent. The size of each dot reflects the capacity installed of the solar panel, for both the whole country and the capital city. Although most microgenerators are concentrated in the capital city, many are scattered throughout the country. Furthermore, the number of firms adopting solar microgenerators is higher than the number of households, with firms exhibiting higher installed capacity on average. While firms have a capacity installed of 37.64 kWh households have a capacity installed of 13.5 kWh. As of 2020, solar capacity accounted for 6% of the total installed electricity capacity, with microgeneration contributing 12% to that solar capacity (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 also construct CO_2 emission from the fossil fuel electricity generation, collecting monthly data on gas oil, fuel oil, and natural gas consumption from UTEi (2022). Specifically, we use the CO_2 emission factor derived from the IPCC (2006) to recover the CO_2 emissions from the thermal sector on a monthly basis. The data is constructed from 1:00 AM to 1:00 AM of the following month.[4]

The descriptive statistics are presented in Table 1. As shown, the average amount of electricity extracted from the grid is 6740 before installing the solar panels and decreases to 5388 kWh afterward. The amount of electricity injected into the grid is on average 1546 kWh. In both cases, firms exhibit higher extraction and injection levels compared to households.

[4]For example, from midnight October 1 until midnight November 1.

In addition, the average amount of emissions over the period is 10.8 million kg of CO_2.

TABLE 1 Descriptive Statistics

	Mean	Standard Deviation	Min.	Max
Before				
Net effect (kWh)	6740.13	14274.64	0.08	256032.2
Firms	9134.80	16354.92	0.08	256032.2
HH	995.48	2042.16	0.43	33108.8
After				
Net effect (kWh)	3617.43	11907.99	-118643.1	235825.8
Firms	5324.41	14454.4	-118643.1	235825.8
HH	460.01	1517.46	-20533.36	20933.04
Extractions (kWh)	5388.75	13795.12	0.08	297253.2
Firms	7144.57	15854.25	0.08	297253.2
HH	810.63	1463.37	2	27704.48
Injections (kWh)	1545.98	3272.36	0	136844.1
Firms	2139.35	3877.2	0	136844.1
HH	448.41	925.15	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 per month	10.81	10.41	3.44e-06	35.02
N	132	132	132	132

Notes: The net effect is defined as "extraction minus injections". Therefore, the net effect is the same as the extractions before installing the solar panel. After installing the solar panel, while extractions show the amount of electricity taken from the grid, injections show the average of electricity sold into the grid. CO_2 emissions are in millions of kilograms (kg) per month. HH is short for households. Data obtained from (UTEi, 2022).

4 | METHODOLOGY

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

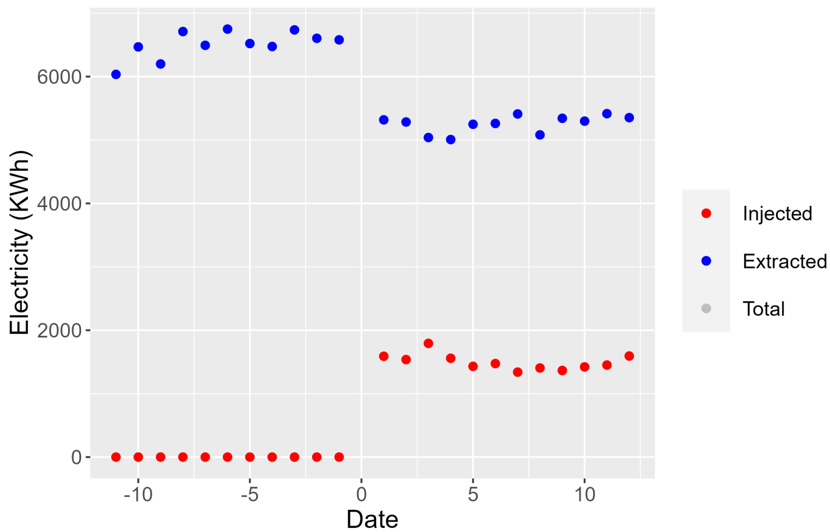


FIGURE 4 Electricity extracted and injected into the grid. *Notes:* This figure shows the total amount of electricity injected and extracted into the grid 12 months before and after the solar panel installation. *Source:* (*UTEi, 2022*)

To quantify the changes in the electricity extracted and injected into the grid after installing a solar panel, we run regression (1).

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

where y_{ist} is the electricity extracted or injected into the grid for agent i in state 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, capturing weather and seasonal changes; 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 equation (2):

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

In this equation, the first summation shows the anticipatory effects, while the second summation quantifies the post-treatment effects after the solar panel installation. The installation occurs at time $\tau = 0$, however, we do not observe that month. As a consequence, all the estimations are compared to $\tau = -1$. The remainder is as specified in regression (1).

A potential limitation in our specification is that solar adaptation and the installation time are endogenous. If the agent installs a solar panel with the intention of increasing their electricity consumption, our results are upwardly biased (Beppler et al., 2023). Conversely, if the agent simultaneously increases electricity conservation initiatives when installing a solar panel, then the estimations are a lower bound. However, given that previous research has found more evidence supporting the former and to be conservative, we will understand these estimations as upward biased. In addition, we are less concerned about the timing of the installation, mainly because the agent has to upload paperwork to the electricity

[5]We also cluster at agent level, and the results are presented in the Appendix A.2 Table 10 and 11.

company to be approved. Afterward, the electricity company has to send a technician to approve the installation. Consequently, the agent has little control over the installation timing, lessening this concern. Another problem that could arise is that early adopters have larger systems and are able to produce more electricity than late adopters. However, we try to lessen this concern by comparing the extraction and the net effect estimations every year. We find there is no statistical difference between the estimations. These results help lessen the concern that the early adopters are different from the late adopters. We present these results in the Appendix Figure 11 and Table 13.

5 | RESULTS

This section shows the effect of installing a solar panel on the net effect, defined as the difference between electricity extracted minus injected into 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), which controls for agent and month $*$ year fixed effects. 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 the agent level.

TABLE 2 Net effect

	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

Notes: his table shows the effect of installing a solar panel on the net electricity (extractions − injections) taken from the grid, using different sets of time 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 clustered at the state level. Significance levels: ***0.01 **0.05 *0.1.

To be conservative, we continue our analysis using just ID + month fixed effects (column 1).[6]. 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).

[6]We perform the same regression, but using the Sun and Abraham (2021) approach. The results are presented in Table 14 in the Appendix A.2.

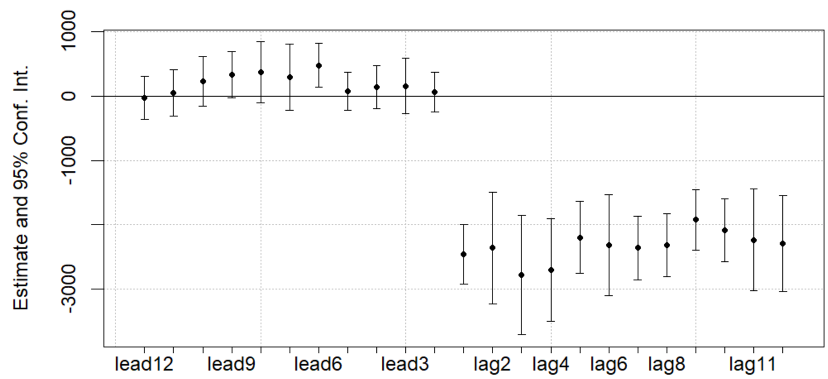


FIGURE 5 Event study plot - Net effect. *Notes:* This figure shows the event study plot of the net effect, defined (extractions − injections) from the grid. Using 12 leads/lags before/after the solar panel installation, controlling for ID + month fixed effects.

Figure 5 shows that the net effect reduction is constant over time.

In section 5.2 we introduce agent heterogeneity to explore potential differences between firms and households.

5.2 | Heterogeneity by Agent

In this section, we present how the net effect changes depending on the type of agent, household or firm. The results are presented in Table 3. Firms that install solar panels decrease the net effect between 3584 and 3769 kWh, while households reduce the net effect between 566 and 753 kWh. As shown in the next sections, in the case of firms this result is driven by a decrease in the electricity extracted and an increase in the electricity injected. In contrast, for households, this result is driven mostly by an increase in the electricity injected. These differences could be explained by different usage patterns. For example, households consume more electricity at night, leading to relatively stable extraction patterns, while firms consume more electricity during daylight hours, resulting in lower extraction levels.

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

5.3 | Electricity extracted 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 kWh on average. These results are somewhat robust to different specifications.

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

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

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

TABLE 3 Net effect by type of agent: household or firm

	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

Notes: This table shows the effect of installing a solar panel on the net effect, i.e., the difference between electricity extracted minus injected, using different sets of time-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 clustered at the state level. Significance levels: ***0.01 **0.05 *0.1.

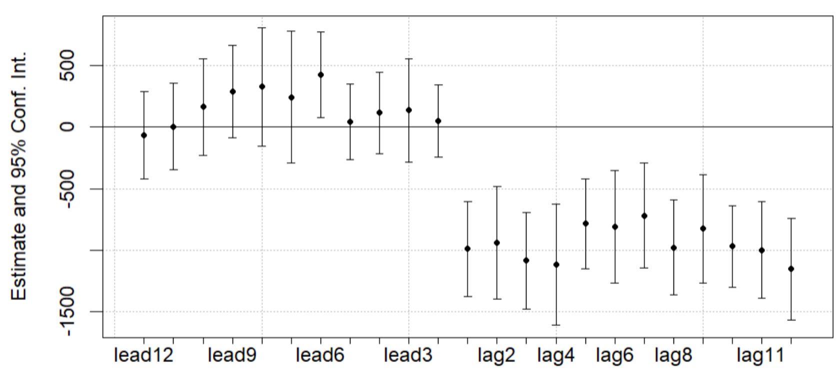


FIGURE 6 Event study plot - Extraction from the grid. *Notes:* This figure shows the event study plot using 12 leads/lags before/after the solar panel installation, controlling for ID + month fixed effects.

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

Notes: This table shows the effect of installing a solar panel on the electricity extracted from the grid, using different time-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 clustered at the state level. Significance levels: ***0.01 **0.05 *0.1.

5.3.1 | Heterogeneity by Agent

In this section, we analyze how the electricity extracted from the grid changes depending on the type of agent: household or firm. The results are presented in Table 5. The findings are mostly driven by firms; the installation of solar panels decreases the electricity taken from the grid between 1,427 and 1,491 kWh. In addition, results are robust to different specifications. However, for households, the effect is smaller and varies greatly depending on the specification.

5.4 | Electricity injected into the grid

Table 6 presents 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.

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 shows the increase in electricity injected in the grid remains constant over time.

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	-108.87***	-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

Notes: This table shows the effect of installing a solar panel on the electricity taken from the grid, using different sets of time-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 clustered at the state level. Significance levels: ***0.01 **0.05 *0.1.

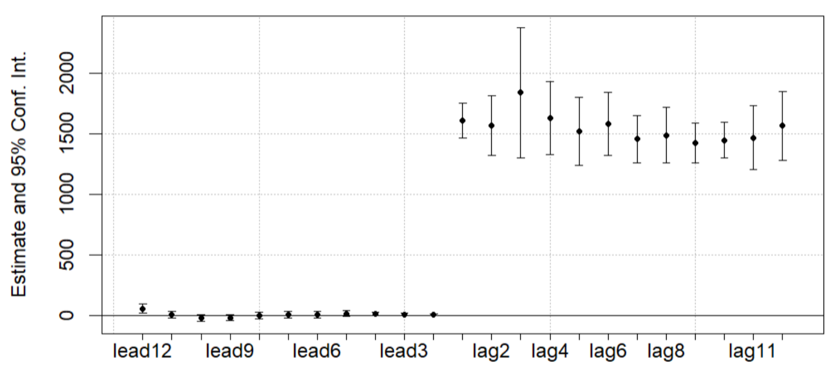


FIGURE 7 Event study plot - Injection into the grid. *Notes:* This figure shows the event study plot using 12 leads/lags before/after the solar panel installation, controlling for ID + month fixed effects.

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

Notes: This table shows the effect of installing a solar panel on the electricity injected into the grid, using different time-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 clustered at the 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.

5.4.1 | Heterogeneity by Agent

In this section, we explore 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, the installation of 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, legislation obliged that the yearly amount of electricity sold must be less than or equal to the amount of electricity consumed (MIEM, 12/17). We explore this policy change in more detail. Specifically, we construct a variable equal to 1 if the installation date is after May 2017 and 0 otherwise. We then interact this variable with the treatment. The results are presented in Table 15 in the Appendix Section A.2. We find 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 cannot perform the same estimation for the electricity injected into the grid due to a lack of observations.

5.4.2 | Value to consumers

To quantify the total effect on cost savings, we do the following analysis. For firms, we use the "middle consumers" rate, which divides the day into three tiers: peak, off-peak, and plain rate. By using a weighted average of these rates and considering 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 three 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 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.

Furthermore, to assess the time required to recoup the initial investment, we considered the installation of solar panels with a capacity of 40 kW for firms and 15 kW for house-

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

Notes: This table shows the effect of installing a solar panel on the electricity injected into the grid, using different sets of time-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 clustered at the state level. Significance levels: ***0.01 **0.05 *0.1.

holds. Our calculations indicate that while firms need a minimum of 6 years to break even households need a minimum of 15 years.

5.5 | CO_2 Emissions

We use our estimates to understand the effect of installing solar panels on CO_2 emissions, under two different scenarios. First, we assume that all the injection and extraction-reduction substitute fossil fuel production entirely. To illustrate, if 1,570 kW is injected into the grid and 1,100 kW is not extracted, this leads to a monthly reduction of 0.35 kg of CO_2 per agent[9]. Given our sample of 1275 households/firms, the total reduction by month is 442 kg of CO_2 emissions. In the second scenario, we assume that solar panels proportionally substitute fossil fuel production. During the study period, fossil fuel production accounted for 8.8% of all electricity generated. Hence, we assume that only 8.8% of the solar panel electricity

[9]We gather the total fossil fuel production and total CO_2 emissions from fossil fuel electricity production. To calculate the emission of 1 kW of fossil fuel electricity, we divide the total CO_2 emissions by fossil fuel electricity production. This calculation indicates that for each kW of fossil fuel 0.00013 kg of CO_2 emissions are emitted.

produced displaces fossil fuel production. In this context, each agent reduces 0.03 kg of CO_2 every month. Consequently, the total monthly reduction in kg of CO2 emissions is 38.7.

5.6 | Rebound effect

Solar panel installation can induce a "rebound effect", this happens when electricity consumption increases after installing a solar panel. 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 and Gautier, 2021). Conversely, solar panels can lead to an energy conservation situation; this happens when electricity consumption decreases after installing the solar panel. Rai and McAndrews (2012) conducted a survey in Central and Northern Texas from August to November 2011 and found that solar panel installations were associated with increased environmental and electricity use awareness. Unfortunately, we do not observe electricity consumption post-solar panel installation for each agent. We can, however, study the average change in consumption by using the solar panel capacity to estimate production. Specifically, we write:

$$\mathit{Consumption}_{\text{before solar panel}} = \mathit{Extraction}_{\text{before solar panel}} \tag{3}$$

$$\begin{aligned} \mathit{Consumption}_{\text{after solar panel}} =& (\mathit{Production} - \mathit{Injection}) + \\ & (\mathit{Extraction}_{\text{bsp}} - \mathit{Extraction}_{\text{asp}}) \end{aligned} \tag{4}$$

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

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

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 $\mathit{extraction}_{\text{asp}}$), as shown in equation 4. We then subtract 4 and 3, as in 5. By doing some calculations, we find that the difference in consumption after and before installing a solar panel is equal to the production of the solar panel minus the injection and the reduction in extraction of electricity from the grid, as stated in equation 6.

Using sample means equation 6 can be expressed as in equation 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.

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

$$\frac{1}{N}\sum_{i=1}^{N}\left[\sum_{t=1}^{12} C_{it} - \sum_{-12}^{-1} C_{it}\right] = \frac{1}{N}\sum_{i=1}^{N}\left[\sum_{t=1}^{12} P_{it} - \sum_{-12}^{-1} P_{it}\right] + \frac{1}{N}\sum_{i=1}^{N}\left[\sum_{t=1}^{12} E_{it} - \sum_{-12}^{-1} E_{it}\right] - \frac{1}{N}\sum_{i=1}^{N}\left[\sum_{t=1}^{12} I_{it} - \sum_{-12}^{-1} I_{it}\right] \quad (7)$$

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 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

Notes: 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 present the average rebound effect in Table 9.

After installing solar panels, we observe an increase in electricity consumption between 22% and 30 % for firms, and between 19% and 22% for households [13]. This increase in consumption depends on the solar panel capacity and the peak hours of sunlight. As a benchmark, Beppler et al. (2023) find a rebound effect of 28.5%. In addition, 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.

After the solar panel installation, we find that agents increase their electricity consumption. This could be explained by several factors, for example, agents feeling richer, electricity

[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.

[13] For a calculation example, please see A.1 in the Appendix.

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%)

Notes: 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.

being cheaper on average; and/or changes in their consumption behavior (Beppler et al., 2023; Boccard and Gautier, 2021). We will explain each one of these below. First, we find that after installing the solar panel, firms and households save between 198-450 USD, and 30-68 USD per month at 2017 prices, respectively. Therefore, this saving could induce the agent to feel richer and consume more electricity. Second, given that the agent buys and sells the electricity at the retail price, the opportunity cost of electricity consumption has not changed, hence, 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 the reduction in the average electricity price. Finally, agents may change their consumption behavior and use more electricity during solar hours, changing their charging patterns and increasing electrification, for example, changing from a gas heater to an electric heater.

This increase in electricity consumption has ambiguous effects. On one hand, the rebound effect reduces the effectiveness of the solar panels. For example, it reduces the environmental effect depending on which source is extracted marginally from the grid. In addition, it could also increase other costs of generation. Finally, it also brings into discussion the potential leakage effect from this policy.

On the other hand, an increase in electricity consumption can be beneficial if the household/firm initiates a process of electrification, for example, by changing the wood fireplace to an electric one. This shift reduces the location and potentially harmful effects of other pollutants (Beppler et al., 2023). This would explain why we found a rebound effect in both, households and firms.

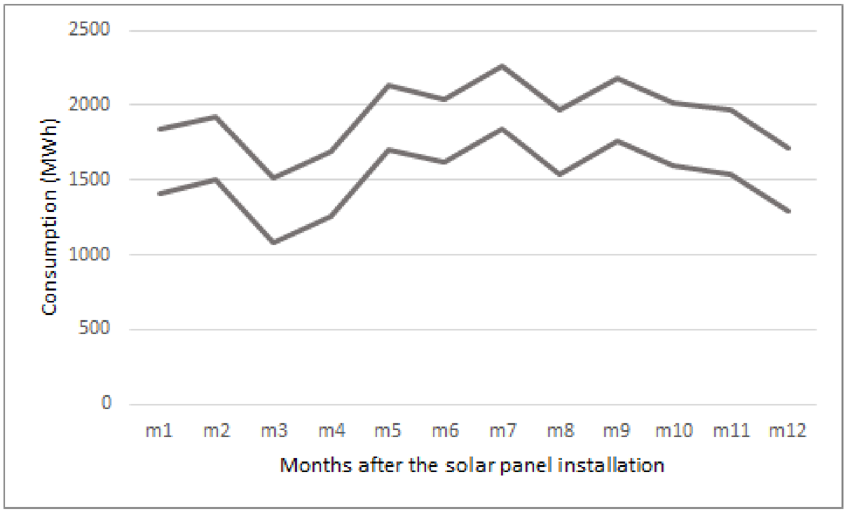


FIGURE 8 Rebound effect. *Notes:* This figure shows the lower and upper bound of the rebound effect, for each month after installing a solar panel.

6 | BATTERIES AND EMISSIONS

The reduction of CO_2 emissions could be further improved if households and firms were allowed and incentivized to decide the timing of injection. This could be achieved by allowing agents to have batteries. In this section, we explore the potential benefits of this policy change.

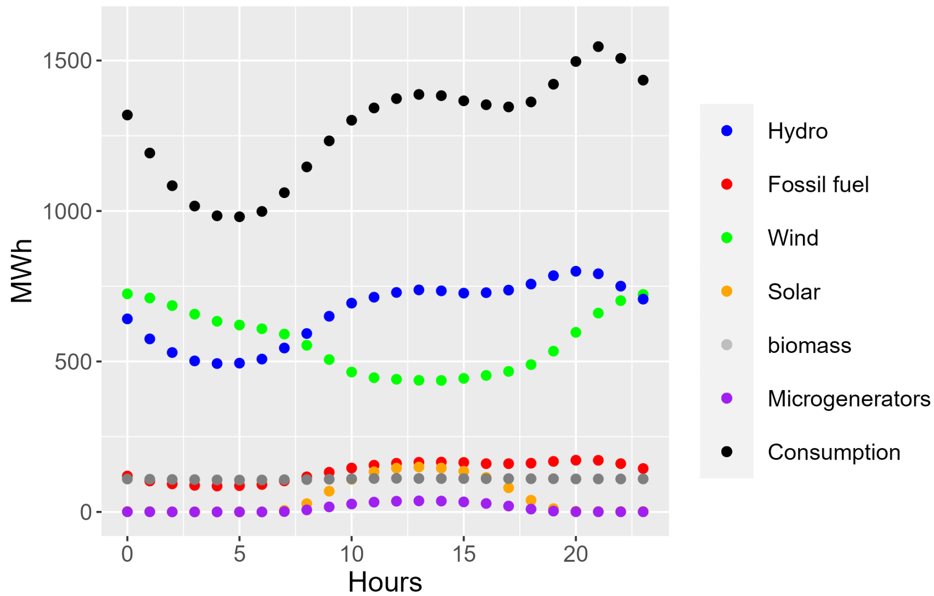
Specifically, we would like to find an optimal way to minimize CO_2 emissions given agents' electricity production. To address this problem, we use another database containing hourly electricity production by source and demand, from November 2018 to August 2022. This problem can be expressed as a linear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

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

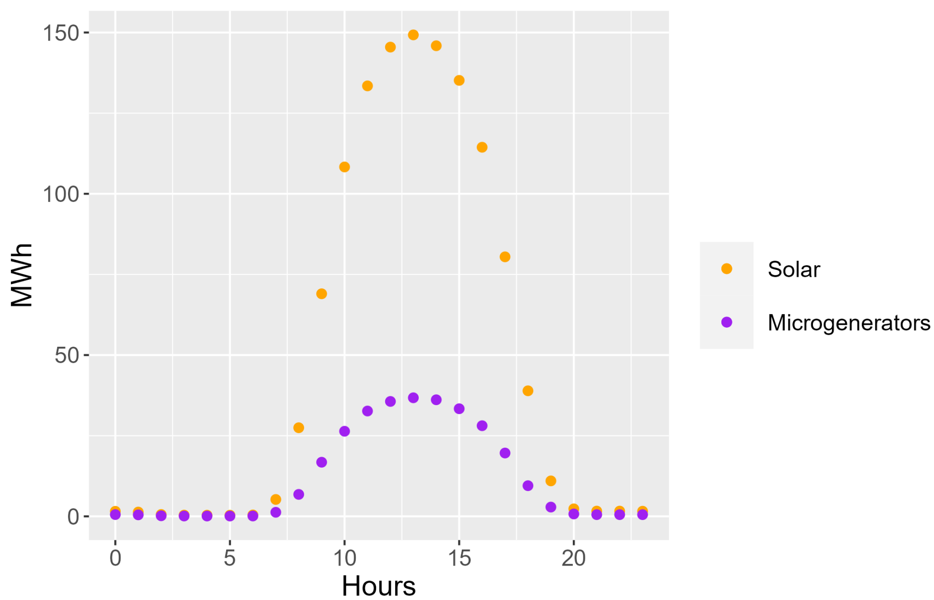
where q^i_{th} is the electricity sold to the grid from solar panels for agent i on day t at hour h; F_{th} is the fossil-fuel-based electricity production at day t and hour h; $\alpha^{CO_2}_{th}$ is the CO_2-emissions-factor of producing a unit of electricity on the day t at hour h from fossil-fuel 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 that the total hourly sales to the grid are equal to the total production by household/firm i. The second restriction ensures that fossil-fueled-based production plus the microgenerator production are at least as much as the (residual) demand. We expand the calculations of the model in the Appendix Section A.

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

Intuitively, we would like agents to sell their solar-produced electricity when CO_2 emissions are at their highest, which occurs when fossil-fuel facilities are producing. Since firms and households only sell solar electricity when they generate it and fossil-fuel production peaks at night, the only possible way to substitute fossil-fuel production with solar production at household/firm level is through the use of 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 shows the optimal allocation of electricity injections into 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 the results. Each dot represents the number of times the model chooses that hour as the optimal time to inject the microgenerator-electricity into the grid for each year. The optimal time for injecting electricity into the grid is around 9 pm (21 hrs.) for both CO_2 emissions and spot prices.

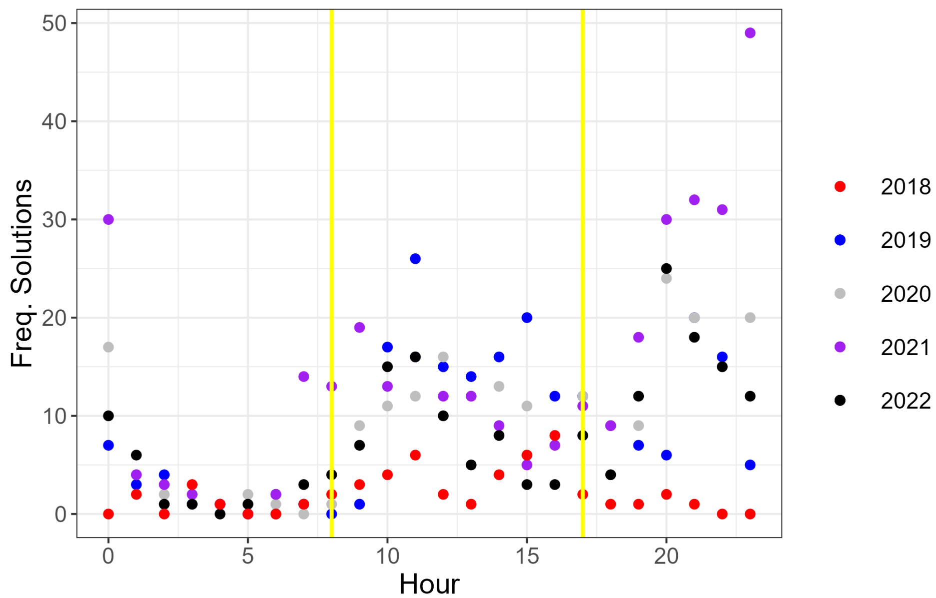
7 | CONCLUSION

We use granular data on electricity injected and extracted into the grid to study the net-metering policy in Uruguay. First, we do an event study to analyze the "net effect," the effect of installing a solar panel in the extraction minus the injection of electricity into the grid. Then, we analyze the change in electricity extracted and injected into the grid, separately. A caveat of the event-study specification in this context is that solar adoption and installation timing are endogenous (Beppler et al., 2023). Furthermore, early adopters may be different from future adopters. Since agents go through many bureaucratic steps to install solar panels, the timing of installation timing is not entirely under their control, lessens the timing issue. In addition, we alleviate the selection issue by showing there is no significant difference between the electricity extracted and the net effect across years. Being conservative, we interpret our estimations as an upper bound 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 (immediately) into the grid.

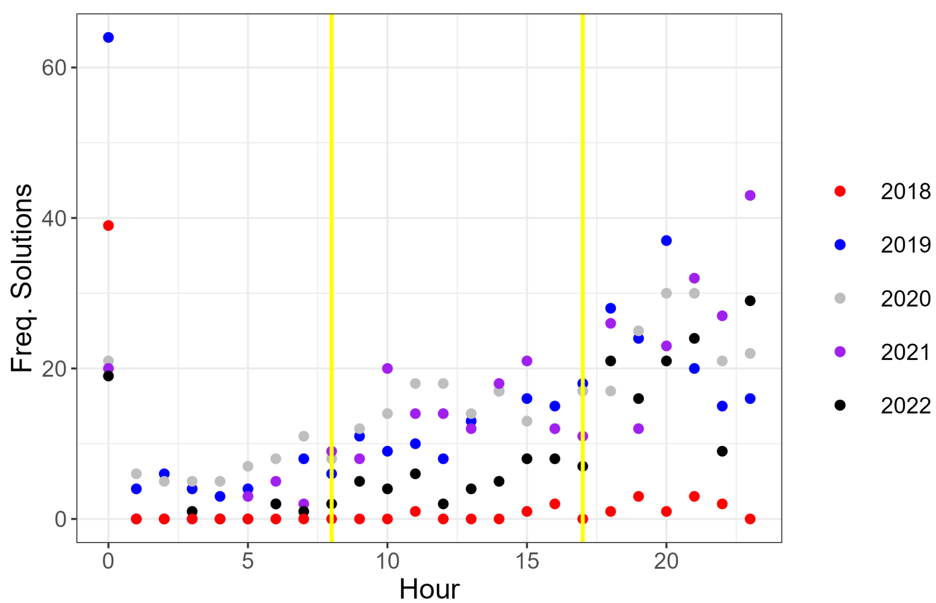
On the one hand, the policy has clear positive effects. First, agents extract less electricity from the grid. After installing the solar panel, the electricity extracted from the grid decreases by 1,100 kWh on average, an 18% reduction in the average electricity taken from the grid. This effect is constant over time. Second, the agent is now injecting clean energy into 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. This effect is constant over time. Finally, the net effect of installing a solar panel (extraction − injection) is a decrease of 2565 kWh. Third, the policy has a positive impact on CO_2 emissions. We study two potential scenarios. The first scenario assumes that all the electricity injected and the reduction of electricity extracted substitute fossil fuels exclusively; in this scenario, monthly CO_2 emissions decrease by 442 kg. The second scenario assumes that the substitution is proportional to the production of fossil-fuel-based electricity; in this scenario, monthly CO_2 decreases by 38.7 kg. Finally, we use the solar panel's capacity to study the rebound effect. We find that, after installing a solar panel, 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 and Gautier, 2021).

On the other hand, the policy has important equity implications. Electricity prices embed the cost of the grid (Feger et al. (2022)). Since agents who install solar panels are richer than average, prices are progressive in electricity consumption, and richer agents tend to

[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 consume more electricity, this implies that richer agents are now contributing less to the grid costs. Moreover, the marginal cost of solar electricity is almost zero, but the net-metering policy implies that it is purchased by the electric company at the retail price. In the long run, these may increase electricity prices for all. To partially alleviate these concerns and to further improve the reduction of CO_2 emissions, we propose an alternative policy: rather than immediately selling surplus electricity into the grid, households and firms could store it in batteries 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, in which the optimal time to inject electricity is between 8 and 11 PM when the electricity production in fossil-fuel-based facilities is high and the spot price is also high.

To translate our results in dollars, we find that, after installing a solar panel, firms save between 120 and 270 USD, and households save between 25 and 55 USD, both in 2017 prices. In 2017, the maximum cost of a solar panel battery in the Uruguayan local market was 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, another interesting topic for future work.

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A | APPENDIX

In this section, we developed the model.

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

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}

$$
\begin{bmatrix} D_0 & D_1 & D_2 & \cdots & D_{23} & 0 & 0 & 0 & \cdots & 0 \end{bmatrix} \times \begin{bmatrix} t_0 \\ t_1 \\ t_2 \\ \vdots \\ t_23 \\ \sum_i q_0^i \\ \sum_i q_1^i \\ \sum_i q_2^i \\ \vdots \\ \sum_i q_2^i3 \end{bmatrix}
$$

The first constraint takes the value equal one on 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 $x_{(24,48)}$)

$$
\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}
\geqslant
\begin{pmatrix} rd_0 \\ rd_1 \\ rd_2 \\ rd_3 \\ rd_4 \\ rd_5 \\ rd_6 \\ rd_7 \\ rd_8 \\ rd_9 \\ rd_10 \\ rd_11 \\ rd_12 \\ rd_13 \\ rd_14 \\ rd_15 \\ rd_16 \\ rd_17 \\ rd_18 \\ rd_19 \\ rd_20 \\ rd_21 \\ rd_22 \\ rd_23 \end{pmatrix}
$$

The second constraint:

$$\left(0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1 \right) \times \begin{pmatrix} t_0 \\ t_1 \\ t_2 \\ \vdots \\ t_23 \\ \sum_i q_0^i \\ \sum_i q_1^i \\ \sum_i q_2^i \\ \vdots \\ \sum_i q_2^i 3 \end{pmatrix} = \left(Q^i \right)$$

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: residual demand = demand - wind - hydro - solar - biomass.

A.1 | Appendix B

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

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

A.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

Notes: 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 clustered at the 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

Notes: 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 clustered at the ID level. Significance levels: ***0.01 **0.05 *0.1. [4] The difference in N comes from having more missing values in the injection's observations than in the extraction's observations.

TABLE 12 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

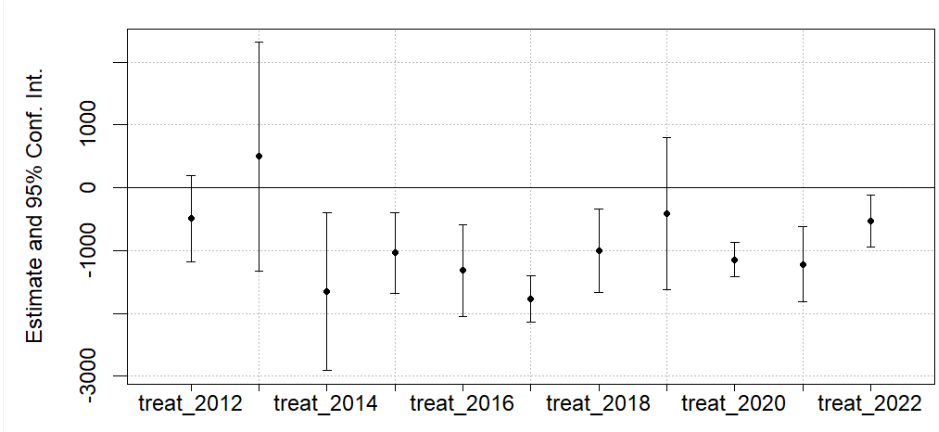
Notes: This table shows the effect of installing a solar panel on the net electricity (extractions $-$ injections) taken from the grid, using different sets of fixed effects. Column (1) uses ID + month fixed effects; column (2) uses ID + month +year fixed effects; finally, column (3) uses ID + month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

This section tries to lessen the selection bias concern by comparing the yearly estimations of the electricity extracted and the net effect (electricity $extracted - injected$). First, we multiply the treatment variable for a year dummy, a variable equal to one for a specific year, and zero otherwise. Then we run regression 1. Results are in Figure 11. For the extraction estimations (panel a), all the estimations are similar. For the net effect, the only different year is 2017. To explore this further, we compare the extraction estimation of 2013 versus 2014 and 2018. Results are in Table 13. We are not able to reject the hypothesis that the extraction estimation of the year 2012 is not equal to the estimation of the years 2014 and 2018 using different specifications. These results help lessen the concern that the early adopters are different from the late adopters.

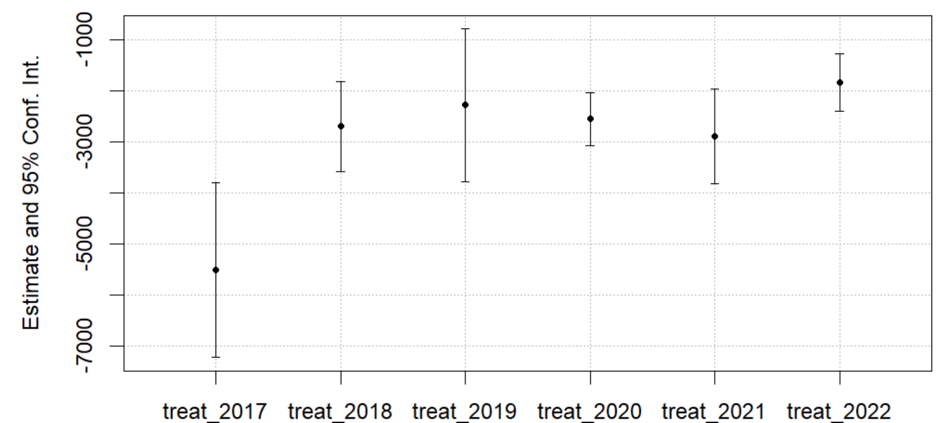
TABLE 13

	P-values		
	Model 1	Model 2	Model 3
$\beta_{2012} - \beta_{2014} = 0$	0.145	0.197	0.201
$\beta_{2012} - \beta_{2018} = 0$	0.218	0.296	0.526
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

Notes: This table shows the difference between the extraction estimation of the year 2012 versus 2014 and 2018, using different specifications. 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 clustered at the state level. Significance levels: ***0.01 **0.05 *0.1.



(a) Extraction estimations



(b) Net effect estimations

FIGURE 11 Yearly estimations. *Notes:* Panel (a) shows the yearly estimations of extractions. Panel (b) shows the yearly estimations using the net effect. Data before 2017 have many missing values. The regression uses ID and month-fixed effects.

In this section, we present the estimation results using the Sun and Abraham (2021) approach. The results are presented in Table 14.

TABLE 14 Sun and Abraham's 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

Notes: 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 clustered at the state level. Significance levels: ***0.01 **0.05 *0.1.

TABLE 15

	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

Notes: 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 a value equal to 1 after installing the solar panel. Solar panel installation $*$ After May 2017, is the interaction. Standard errors are clustered at the state level. Significance levels: ***0.01 **0.05 *0.1.