Ca' Foscari University of Venice

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Toward Net Zero in the midst of the energy and climate crises: the response of residential photovoltaic systems

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Abstract
This paper aims to provide insights on potential strategies for a sustainable energy transition amidst market fluctuations. We analyze the impact of PV adoption on electricity consumption during a volatile price time span, leveraging high-frequency consumption data of over 10,000 households in Northern Italy during the period of the 2022 energy crisis. Our findings reveal that PV adoption reduces electricity consumption responsiveness during extreme price and temperature events, enhancing energy security and affordability. Based on estimated demand, we measure changes in consumer surplus, highlighting substantial benefits from PV adoption: the change in the annual consumer surplus due to the 2022 price increase is around 300 euros for the median consumer with no PV and 133 euros when PV is adopted by a comparable median household.

Keywords
electricity demand; solar photovoltaics; energy prices; climate change

JEL Codes
Q20, Q21, Q41, Q42, Q54, Q55

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1. Introduction

In March 2023 the Intergovernmental Panel on Climate Change (IPCC) released the Synthesis Report, finalizing its Sixth Assessment cycle. Global Greenhouse Gasses (GHG) emissions have been rising during the last two decades, and while seeking the Net Zero that would stabilize temperatures, adaptation is not an option (IPCC, 2023). Energy technologies aimed at mitigating the impact of climate change are already available. Photovoltaic (PV) systems are considered relevant means to shift from fossil fuel consumption towards renewable energy sourcing and self-sufficiency. Indeed, many administrations have been providing financial support in order to promote the adoption of those technologies. An additional alternative for reducing emissions, consists of lessening the global energy demand, according to the Low-Demand Illustrative Mitigation Pathway (IMP – LD) (Grubler et al. 2018). The latter could be in contrast with some of the fastest growing adaptation measures, such as air-cooling (AC), which drives electricity demand (Randazzo et al. 2020).

The future development of mitigation and adaptation strategies and their impact on energy demand can not be evaluated in isolation from the recent changes involving the global energy market. The war in Ukraine has led to a sharp increase in energy prices and significant volatility in energy markets. Soaring energy prices have led to a severe impact on consumers worldwide, while energy security remains a key geopolitical concern (IEA, 2023). Euro area energy markets, heavily reliant on Russian supplies before the invasion, have been especially impacted. Energy commodity price volatility started rising in December 2021, when reports of a potential Russian invasion of Ukraine surfaced. During the two weeks after the invasion; oil, coal, and gas prices rose by approximately 40%, 130%, and 180%, respectively, and have remained volatile thereafter. Gas prices, also, affected wholesale electricity prices in the euro area, which rose on average between 100% and 300% in 2022 with respect to the historical level (Adolfsen et al., 2022). After 2022, energy commodity prices have somehow moderated, with oil and coal prices standing 27% and 50% higher than pre-invasion levels, respectively, while gas prices being 11% lower. Currently, wholesale electricity prices are 8% higher than before the invasion, still highly volatile and impacted by policy measures implemented in response to price increases (Adolfsen et al., 2022).

This analysis seeks to understand the marginal effect of PV adoption on grid electricity extraction under periods of high volatility in electricity prices. The analysis is performed at daily and hourly level, as the latter could be informative with respect to consumption shifting behaviors. The main objective is to provide insights on a potential shift in electricity consumption patterns and on a differentiated response to price and temperature shocks, after introducing a technology which exploits a renewable energy source: solar PV. To this aim, we exploit the exceptionally high electricity price shock of the energy crisis of 2022 in order to infer short-run price elasticities from high-frequency consumption data. With respect to adaptation to global warming, the percentage increase in temperature between 2022 and 2021 was greater than the one in solar irradiance, being not in opposition with the tentative proof of our thesis. Indeed, we seek to provide novel evidence on the potential resilience of households who have both the economic means and motivation to undertake an investment in line with the energy transition. To our knowledge, so far, there are no studies that estimate the marginal effect of introducing solar PV on the timing and quantity of electricity demand in Italy. Yet, we can observe only the amount extracted from the grid, and not the overall electricity consumption of PV holders, which comprises the electricity produced. Furthermore, given the large amount of data at our disposal regarding the class without PV, we perform an analysis on the sensitivity with respect to both temperatures and prices, across consumption classes. Briefly anticipating our results, in the middle of a typical summer day, the adoption of a PV system in the municipality of Brescia, reduces electricity consumption from the grid by 90 to 100%. With regards to extreme temperature events, the introduction of a PV system leads to a 68% reduction in electricity extraction from the grid for the same POD compared to the extraction before the PV technology was installed. Moreover, households holding a PV can better face rising electricity prices, since their price elasticity is lower than counterparts. Finally, in line with recent literature (Campagnolo and De Cian, 2022), users without PV belonging to the lowest consumption class can worser cope with climate change impacts than more affluent counterparts, as they are more sensitive to price shocks. We would like to highlight that electricity has become an essential good in this era, and the latter result should be properly taken into account by policy makers, as a relevant source of inequality. Section 2 introduces the literature around the topic. Section 3 provides summary statistics of our sample. Section 4 describes the empirical methods employed. Section 5 shows the results of our investigation. Section 6 provides discussion and conclusions.

2. Literature Review

The focus of this study is on solar PV adoption and usage. In particular we aim at detecting different price and temperature responses for adopters and early adopters of the technology, outlining hourly households load profiles. Related studies span topics from adaptation response to climate change, price elasticity of residential electricity demand, load profiling and demand-side management (DSM) to PV adoption.

A body of literature uses panel data to estimate climate change impacts on residential electricity demand. Aufhammer (2022) exploits inter-ZIP codes daily variations in weather within the U.S. state of California to estimate short and long-run electricity responses to temperatures. With regard to the intensive margin, it finds a U-shaped response curve at around 17.2° C as well as significant heterogeneity across zip-codes in the steepness of the curve. Alberini et al. (2019) look at hourly electricity demand in Italy, and find a J-shaped response to temperatures, where consumption rises steeply above 24.4° C. Interestingly, the slope of the curve is similar across income groups. Both studies operationalize temperatures as time dummies belonging to temperature bins. The results of Alberini et al. (2019) are in line with predictions of electricity loads for the European Union (Damn et al. 2017; Wenz et al. 2017). Damn et al. (2017) observe that in Italy the decrease in energy consumption due to climate change-driven higher temperatures in winters will not offset the augmented increase for cooling in summers. Specifically, under a +2°C global warming scenario electricity demand is projected to increase in the 0.2% to 0.6% range. Wenz et al. (2017) estimate a 0.18% increase in daily electricity consumption by 2055-2059 for daily maximum temperatures under RCP-4.5. A recent assessment focusing on Italian electricity peak demand shows that, when endogenously accounting for adaptation, through the adoption of new air-conditioning equipment, the projected impacts of climate change could become more severe than what previously estimated. Adding an additional 10-15 GW to summer peak demand, corresponds to a 16% increase in electricity consumption from the baseline in 2050 under RCP 8.5 (Colelli et al., 2023).

A broad strand of research deals with price elasticity of electricity demand. Ito (2014), exploiting spatial discontinuities in electricity services across Southern California sub-territories, finds that consumers respond to average price rather than marginal prices, in the presence of a non-linear pricing regime. This choice represents a suboptimal behavior with respect to the policy goal of efficiency maximization and energy conservation. In any case, electricity is an essential good in the digital era, therefore price elasticities of demand for electricity are generally low. Alberini et al. (2011) combining nationwide panel and multi-year cross-sections data at household-level covering 1997-2007 estimates a price elasticity between -0.86 to -0.67 for U.S. large metropolitan areas. Also, they do not find significantly different elasticities between households with electric heat and households with gas heat. In fact, estimates of price elasticities vary quite broadly in the literature. Labandeira et al. (2017) survey 428 papers published between 1990 and 2016 and find the average short-run and long-run price elasticities of electricity demand at −0.13 and at −0.37, respectively. Miller and Alberini (2016) suggest that the sources of this sensitivity could lie in the sign of the price trend (to a small extend); in the level of data aggregation; in how the unobserved heterogeneity is accounted for and in the type of instrumental variables employed to address endogeneity and/or measurement error issues. Modifications of the aforementioned factors can change the estimates by 50-100%.

Recent research analyzing demand data at the consumer level yields remarkable findings, underscoring the significance of such studies. Auffhammer and Rubin (2018) focus on 300 million energy bills in California, revealing that consumers tend to reduce their consumption when faced with higher prices by a higher margin than what has been previously estimated by studies aggregating consumption over geographical jurisdictions and time. Moreover, the analysis uncovers an intriguing seasonal variation: during summer months, price changes have little impact on consumption, while in winter, households significantly cut their energy usage by 4% in response to price increases. One crucial aspect of our paper is the opportunity it provides to understand how households react to significant price shocks, especially in the context of a large price change faced by Europe. Until recently, there has been a scarcity of real-world data on such responses, impeding comprehensive studies on this area, with the exception of a work assessing price increases in Ukraine after subsidies were reduced in 2015 (Alberini et al., 2015). Their findings demonstrate that, for households that did not invest in better heating or insulation, a doubling of prices resulted in a substantial 16% decline in consumption (Alberini et al., 2015).

With regard to load profiling, selected studies suggest that residential loads can be influenced by socio-economic, climate and technological factors. Among the former are the type and size of the housing facility (Fisher 2015); age, income and working status of responsible occupants (Godoy-Shimizu 2014). From the climatic influence follows that electricity consumption patterns are simultaneously region and season-specific (N. Saldanha 2012; Lee 2014). DSM studies further explore how active occupancy and domestic activities involving the use of appliances (heating and cooling excluded), shape the timing and peaks of energy demand. Torriti (2017) analyzes social practices performed by UK households in 2005, assessing stronger time dependence during weekdays than weekends; seasonality of social practices which translates to higher energy demand in winter than in summer; and relatively more erratic patterns in the month of June.

New work has started to evaluate how solar PV technology affects energy consumption levels and residential load profiles. At the root of some studies - and of our analysis - lies an interest in understanding to what extent the electricity generated by solar panels decreases the extraction from the grid. PV self-consumption reduces the overall marginal price for electricity, which might shift total electricity consumption upwards, causing the so-called *rebound effect.* Taking into account the presence of this effect is relevant to ex-ante evaluation of policies aimed at reducing energy consumption and carbon emissions. Dang and Newton (2017) analyzing billing data of a representative sample of Australian households assess a rebound effect between 17% to 21% related to domestic solar PV installations, that include a feed-in tariff. Qui et al. (2019) using high frequency data of a sample of homes in Arizona, between 2013 and 2017, document a rebound effect of 18%. Also, more recent studies provide additional evidence that supports this thesis (Beppler et al. 2021; Boccard and Gautier, 2021). Adjacent literature focuses on the techno-economics of PV and their role in self-consumption when combined with batteries. Cases for Sweden (Nyholm et al., 2016), Australia (Khalipour et al., 2016), and Germany (Linssen et al. 2017) point out self-consumption rates[1] less than 50%. This share almost doubles in countries where energy consumption is 3 to 5 times higher and solar irradiance is abundant, such as Katar. Alrawi et al. (2019) observing electricity load profiles of households with rooftop PV systems assess self-consumption rates amounting to more than 90%. Behind this figure lies a better alignment between PV sizing and domestic consumption. Incidentally, during the warmest months, air-conditioning constitutes between 70% to 95% of total load in Qatar.

A nascent body of literature examines the economic, energy, and environmental consequences of the Ukraine War, in particular on energy prices and its effects on households worldwide. Guan et al. (2023), using a global multi-regional input-output database and household expenditure data, model the direct and indirect consequences of increased energy prices on 201 expenditure groups across 116 countries. The findings highlight a significant surge in household energy costs, ranging from 62.6% to 112.9%. Consequently, this increase contributed to a rise in overall household expenditures by 2.7% to 4.8%. A concerning implication of these rising energy prices is the potential to drive an additional 78 to 141 million people into extreme poverty. The impacts of energy price spikes caused by the Ukraine War, and in particular of higher household energy costs during such period remain largely unexplored. The economic upheaval resulting from the conflict in Ukraine has strengthened the demand for a faster energy transition: countries are now urged to shift away from heavily polluting fuels, often sourced from a few major producers, and move towards low-carbon energy alternatives (IEA, 2023). This transition aims to address environmental concerns and reduce dependency on unstable fossil fuel markets. Understanding how these multiple factors shape energy behaviors is of pivotal importance.

3. Data

This study uses high-frequency data at Point of Delivery (POD) level to investigate residential electricity consumption in the Italian municipality of Brescia. Smart-meter data were provided by an Italian utility and cover information for a sample of 10959 households along the period between January 2021 and December 2022. At the beginning of 2021, 147 households were already equipped with a PV system at home; throughout 2021, 15 households installed a PV technology; while 2 households did the same during 2022. At the end of 2022, 162 households have a PV system installed as opposed to 10797 PODs without PV, in our sample of analysis.

Consumption data were collected every 15 minutes, we aggregated them at hourly level due to computational feasibility and combined with meteorological and price information. Hourly mean temperatures were gathered from the ERA5 database, and aggregated at the Italian municipality level (NUTS 3) from meteorological data at a 0.25x0.25 spatial grid. Solar irradiance, instead, was delivered by Copernicus European database. The dataset also includes national wholesale electricity prices at the monthly level (Prezzo Unico Nazionale, PUN). We aggregated monthly prices into a 3-month moving average; since PODs are typically billed every three months, and wholesale price variations are transferred through the billing cycle with some lag.

[1] Self consumption is measured by electricity consumption from solar production, over total solar electricity production (Alrawi et al, 2019).

Table 1
Descriptive statistics

Daily Electricity Consumption [kWh]	(1) PV	(2) no PV	(3) all	(4) t-test
Mean	5.74	5.17	5.18	0.57*** (35.32)
Std. dev.	4.29	4.4	4.4	
Min.	0.002	0.001	0.001	
Max.	48.34	49.9	49.9	
Obs.	72,067	6,201,734	6,273,801	
N. of PODs	162	10797	10959	

Notes: column (1) reports statistics for pv holders; column (2) for households without a pv system installed; column (3) for the whole sample; column (4) presents t-statistics comparing households with pv and without pv (t-statistic of the t-test is given in parenthesis).

Table 1 displays average electricity extraction from the grid on a daily basis. The statistics show that, during 2021-2022, households with PV on a daily basis extracted on average 0.57 kWh more electricity than households without PV. That is, there is a statistically significant difference in daily average electricity extraction from the grid between the two subsamples: higher extraction for the sample with PV and lower extraction for the sample without PV, throughout our reference period. We underline a relevant difference in sample size and the fact that, beneath electricity extraction of PV holders, lie housing and household-specific characteristics which might have prompted the adoption of the technology and are related to consumption levels. Figure 1 depicts electricity uptake, electricity price, temperature and solar irradiance monthly averages. The period under assessment is of particular interest, as it witnessed a surge in energy prices, reflected across consumers as almost a 230% increase between 2021 and 2022. Moreover, with few exceptions, 2022 was warmer than 2021, exhibiting a severe peak in July 2022, which likely drove a large share of electricity demand through the usage of ACs. We do not aim to compare PV holders with no-PV holders based on their electricity extraction from the grid, but a quick glance at the seasonal patterns is suggestive for the analysis on pre-trends. During winter months we observe a sharp gap between the two subsamples, while this gap shrinks to the point of changing sign, during summer months; as shown in figure 1. Table 2 depicts the percentage change in electricity extraction from the grid between 2021 and 2022 for the two subsamples. We seek to understand the main drivers of this variation, what distinguishes the differential response between the two classes, which might be of interest for understanding to whom and to what extent subsidizing this technology.

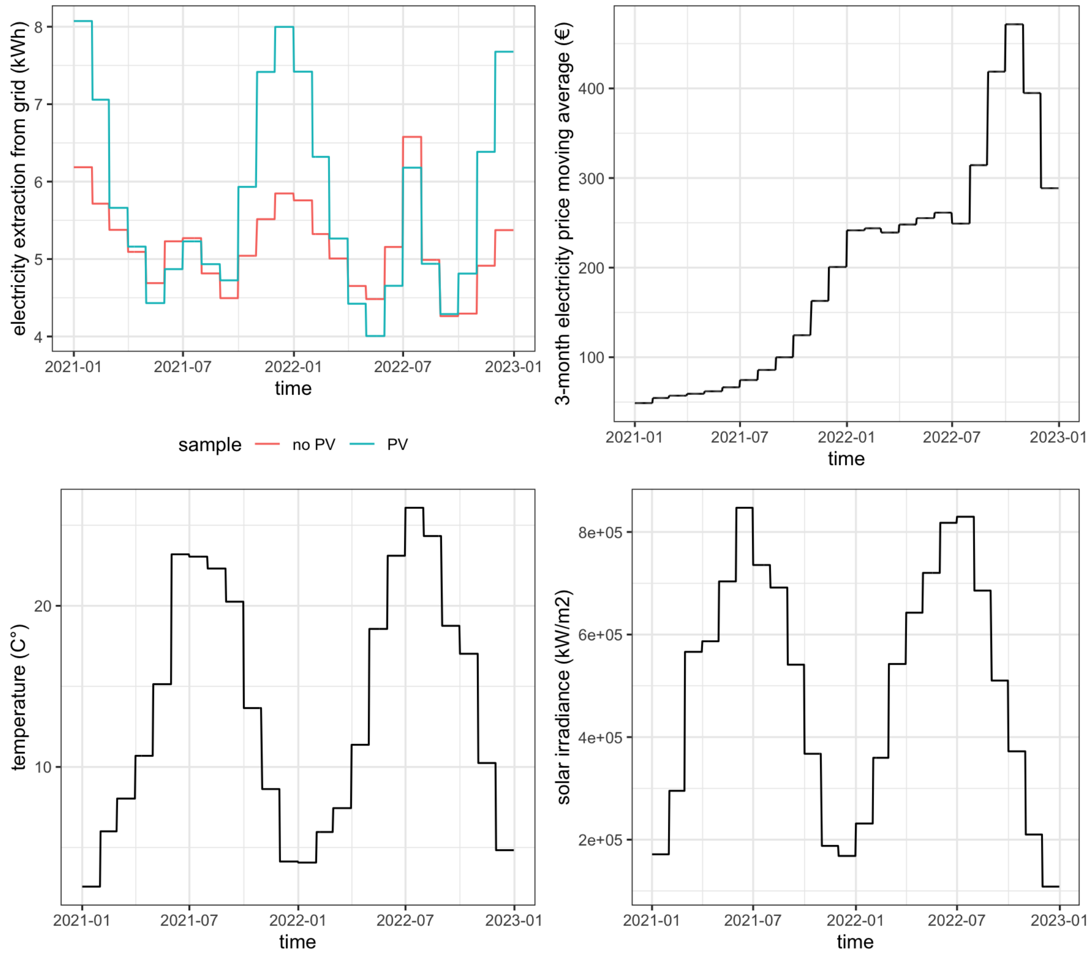

Fig. 1. Time series of electricity consumption, prices, temperature, and solar irradiance.

Table 2
Mean values and time variation by PV ownership.

Percentage change in selected key variables between 2021 and 2022

	2021	2022	% variation
Avg. daily electricity extraction from the grid (kWh) - for PV holders	5.95	5.53	-7%
Avg. daily electricity consumption (kWh) - for PV holders	5.27	5.07	-3%
Avg. differential extraction between PV and no-PV holders	0.68	0.46	-4%
Avg. daily electricity extraction from the grid for both PV and no-PV holders	5.28	5.08	-3.8%
Avg. monthly price (€)	91.61	301.6	229.3%
Avg. daily temp (C°)	13.18	14.33	8.8%
Avg. daily solar irradiance (kw/m^2)	489	503	2.8%

4. Methods

We conduct a regression analysis based on a set of fixed effect panel models. We aggregate 15-minutes grid consumption data into daily and hourly observations, adopting as a dependent variable the natural logarithm of daily and hourly grid consumption *log(q)*. In order to investigate electricity consumption patterns in response to price and temperature, as well as the role of PV technology, we first perform the analysis at daily level, with the following specification:

$$log(q_{i,t}) = \alpha PV_{i,t} + \sum_{z=1}^{20} \beta^z T_t^z \, (1 + \beta^{z,PV} PV_{i,t}) + ssr_{i,t} \, \gamma (1 + \gamma^{PV} PV_{i,t}) + ssr_{i,t}^2 \lambda (1 + \lambda PV_{i,t})$$
$$+ \sigma \, log(p_{i,t}) \, (1 + \sigma^{PV} PV_{i,t}) + \varphi_i + \pi_{i,t}^v + \varepsilon_{i,t} \quad (1)$$

where, $log(q_{i,t})$ the natural logarithm of daily grid consumption of POD *i* at date *t*; is regressed on $PV_{i,t}$, a dummy indicating the adoption of PV by household *i* at date *t*, our key variable of interest. We also include T_t^z, daily mean temperature, binned into k*th* 1.5°C intervals; $ssr_{i,t}$, mean solar irradiance; and $log(p_{i,t})$, the log of three-month electricity price moving-average; with these three independent variables being also interacted with the dummy indicating the adoption of PV in order to capture a differentiated response for households with PV. As controls there are POD fixed effects, denoted by φ_i; and a vector of POD-specific time fixed effects, denoted by $\pi^v_{i,t}$ (with *v* capturing month, day of the week, working day).

In a second specification of our daily model we seek to increase the flexibility of the controls, by adding interaction terms for time fixed effects, in order to capture PV-specific recurrent behaviors, as follows:

$$log(q_{i,t}) = \alpha PV_{i,t} + \sum_{z=1}^{20} \beta^z T_t^z \, (1 + \beta^{z,PV} PV_{i,t}^m) + ssr_{i,t} \, \gamma (1 + \gamma^{PV} PV_{i,t}) + ssr_{i,t}^2 \lambda (1 + \lambda PV_{i,t})$$
$$+ \sigma \, log(p_{i,t}) \, (1 + \sigma^{PV} PV_{i,t}) + \varphi_i + \pi_{i,t}^v (1 + \pi^{v,PV} PV_{i,t}) + \varepsilon_{i,t} \quad (2)$$

Then, we exploit the high-frequency nature of the data at our disposal to perform both models at hourly-level, as follows:

$$log(q_{i,h,t}) = \alpha^h (1 + \alpha^{h,PV} PV_{i,t}) + \sum_{z=1}^{20} \beta^z T_{h,t}^z \, (1 + \beta^{z,PV} PV_{i,t}^m) + ssr_{i,h,t} \, \gamma (1 + \gamma^{PV} PV_{i,t})$$
$$+ ssr_{i,h,t}^2 \lambda \, (1 + \lambda^{PV} PV_{i,t}) + \varphi_i + \pi_{i,t}^v + \varepsilon_{i,h,t} \quad (3)$$

$$log(q_{i,h,t}) = \alpha^h (1 + \alpha^{h,PV} PV_{i,t}) + \sum_{z=1}^{20} \beta^z T_{h,t}^z \, (1 + \beta^{z,PV} PV_{i,t}^m) + ssr_{i,h,t} \, \gamma (1 + \gamma^{PV} PV_{i,t})$$
$$+ ssr_{i,h,t}^2 \lambda \, (1 + \lambda^{PV} PV_{i,t}) + \varphi_i + \pi_{i,t}^v (1 + \pi^{v,PV} PV_{i,t}) + \varepsilon_{i,h,t} \quad (4)$$

where the PV dummy is interacted with the hour *h* fixed effects, in order to assess the differential impact of PV on grid consumption in each hour over the course of the day. In model (3) and (4) we don't include the electricity price moving average, as not relevant to hourly consumption load profiles.

Equations 1-4 are further tested separately for each season of the year, as consumption patterns differ significantly across seasons between the classes of consumers with and without PV. Finally, we restrict the sample only to POD with no PV and re-estimate the model of Eq. 1-2 by dividing the sample into three consumption classes: small, medium and large consumers. Respectively, those consumers are characterized by daily mean consumption in 2021 below the 25th percentile (2.5 kWh/day), between the the 25th and 75th percentile (2.5 kWh/day - 6.7 kWh/day) or above the 75th percentile.

5. Results

5.1 Marginal effects of PV adoption on grid consumption

We find a relevant marginal effect of PV adoption on grid consumption. Regression results based on the daily model show that annual average consumption from the grid is reduced by 75%[2], with a maximum reduction happening in summer - by 88% - and a minimum reduction in autumn - by 34% (estimates of the coefficients are reported in Table 3).

The regression models estimated through Eq. 1- 4 allow to identify the heterogeneous influence of daily and hourly temperatures on grid consumption of households after the adoption of PV. When focusing on the daily model we filter out confounding effects of hourly temperatures and hourly PV production co-occurrence[3]. We find that the response of daily grid consumption to temperatures exhibits a non-linear form, increasing by as much as 60% (40%) with (without) PV, under a day with temperatures above 30°C with respect to the reference temperature (15°C - 21°C). Nevertheless, the relatively low grid extraction during hot summer days of PV users, gives an additional grid consumption of 0.55 kWh/day, corresponding to 68% less than the electricity demand of consumers without PV, the latter being equal to 1.7 kWh (see Fig. 2). The response to cold temperatures is asymmetric (leading to an overall J-shaped non linear curve), as consumption increases by 20%-30% in the coldest temperature bins.

Switching to elasticity of demand to electricity prices at daily-level, despite slight changes across seasons, it seems to be similar between consumers with and without PV, being around -0.067 for the former and -0.06 for the latter. PV users show a relatively higher sensitivity during summer and autumn than consumers without PV: -0.07 and -0.13 compared to -0.03 and -0.075, respectively. Likely, this difference arises because during summer and shoulder seasons abundant PV generation makes it possible to reduce the amount of grid consumption through solar power generation, and to shift part of the demand load during PV production hours. Furthermore, we find that adoption of PV decreases the sensitivity of consumers during winter (-0.03, versus -0.07 of no-PV users).

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[2] Since the model is estimated in log-linear form, the reduction is computed by taking the exponent of the coefficient estimated from Equation 2.

[3] Results of the hourly model are presented in the Supplementary Information, as they do not change the main results found with our preferred, daily specification.

Table 3
OLS estimations at daily-level.

Dependent Variable:			log(q))		
Model:	All year	Winter	Spring	Summer	Autumn
Variables					
PV	-1.368***	-0.4800***	-2.150***	-2.132***	-0.4155***
	(0.0444)	(0.0854)	(0.0833)	(0.1308)	(0.0893)
log(p)	-0.0592***	-0.0703***	-0.0561***	-0.0290***	-0.0754***
	(0.0004)	(0.0009)	(0.0008)	(0.0011)	(0.0010)
ssr	0.0048	0.2339***	-0.1063***	0.3584***	-0.0338*
	(0.0067)	(0.0193)	(0.0176)	(0.0319)	(0.0177)
ssr^2	-0.1066***	-0.5213***	0.0190	-0.4125***	-0.1730***
	(0.0066)	(0.0366)	(0.0161)	(0.0237)	(0.0235)
PV × log(p)	-0.0085**	0.0428***	-0.0132**	-0.0406***	-0.0572***
	(0.0034)	(0.0058)	(0.0064)	(0.0086)	(0.0081)
PV × ssr_mean_mln	-1.779***	-1.653***	-1.361***	-1.164***	-1.457***
	(0.0580)	(0.1516)	(0.1589)	(0.2751)	(0.1384)
PV × ssr^2	0.8235***	0.1562	0.6491***	0.3879*	0.5489***
	(0.0570)	(0.3065)	(0.1434)	(0.2056)	(0.1887)
Temperature bins not shown					
Fixed-effects					
POD	Yes	Yes	Yes	Yes	Yes
weekday-POD	Yes	Yes	Yes	Yes	Yes
month-POD	Yes	Yes	Yes	Yes	Yes
cal_day-POD	Yes	Yes	Yes	Yes	Yes
Fit statistics					
Observations	7,495,392	1,955,099	1,859,468	1,859,534	1,821,291
R^2	0.78188	0.77791	0.80687	0.76571	0.79185
Within R^2	0.00982	0.00645	0.01059	0.01490	0.01080

Heteroskedasticity-robust standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

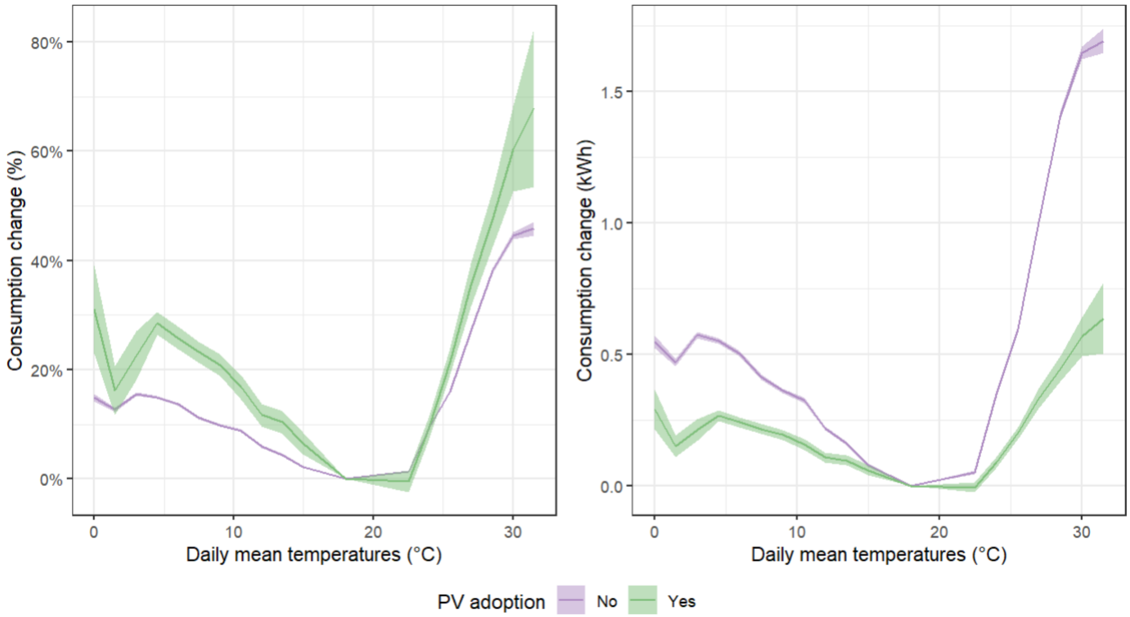

Fig. 2. Estimated change in daily grid consumption due to daily temperature deviations from the reference level at temperatures between 15°C - 21°C, being 3.7 kWh and 0.95 kWh for the consumers, without (purple) and with (green) PV adoption, respectively. Shades represent the 95th confidence intervals.

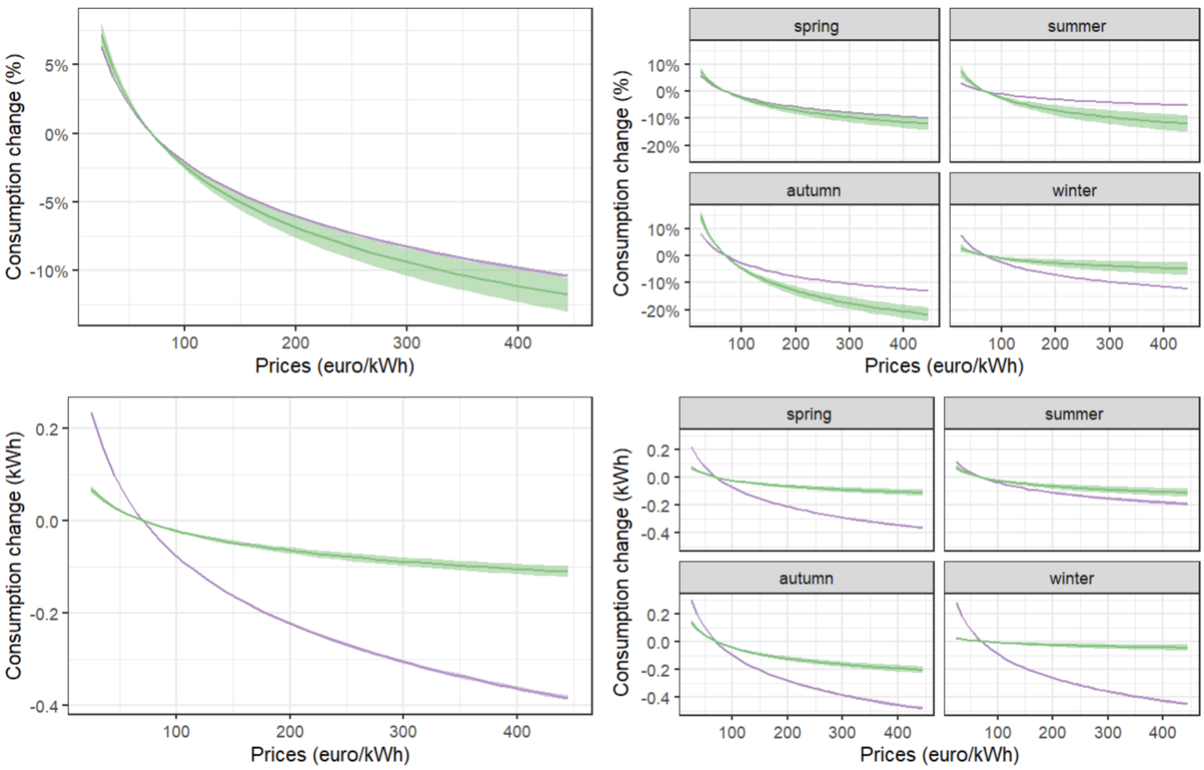

Fig. 3. Estimated change in daily grid consumption due to electricity price deviations from the reference level (70 euro/kWh), without (purple) and with (green) PV adoption. Shades represent the 95th confidence intervals.

In conclusion, no-PV holders seem to be more exposed to price shocks since they reduced their grid consumption levels more considerably than PV-holders throughout the year (see Fig. 3).

Through the hourly regressions we identify the heterogeneity of the impacts by hour of the day across seasons: during the central hours of the day, grid-consumption falls by 75% to 80% in winter and autumn and by almost 100% in spring and summer. Even during morning and evening peak times, despite lower solar production, grid-consumption is reduced by 50% to 60% in spring and summer, while it gets closer to the pre-adoption levels in winter and autumn (see Fig. 4). Noticeably, we find that consumption from the grid for all seasons decreases also when PV is not producing. This result highlights that households may be using PV in combination with storage batteries, allowing self-consumption even during night hours. Furthermore, the change in night-time grid consumption may be related to unobserved interventions correlated with the presence of PV, such as energy retrofit of the building.

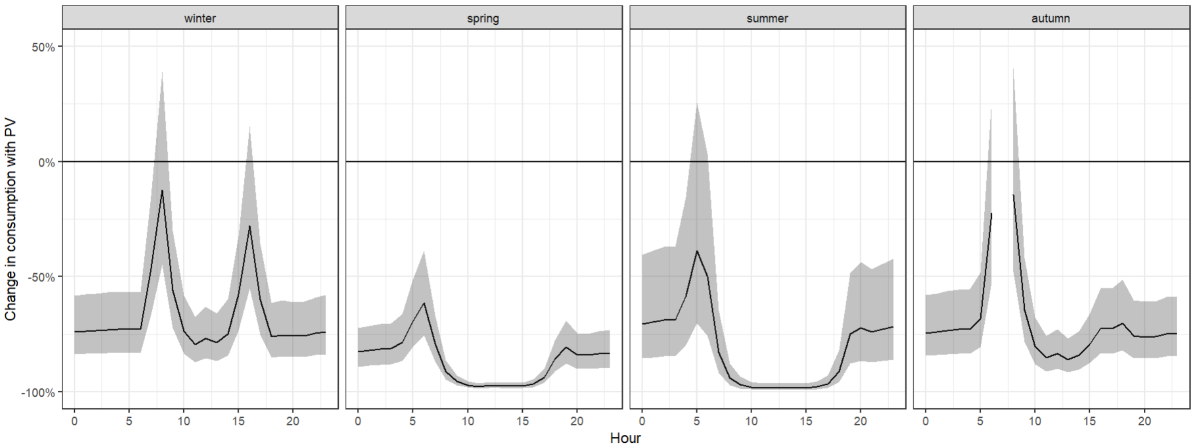

Fig. 4. Estimated change in hourly grid consumption due to PV adoption by season. Shades represent the 95th confidence intervals. Only coefficients statistically significant at the 0.1 level or below are shown.

5.2 Heterogeneous effects by consumption class

We identify heterogeneous effects of weather and prices across consumption classes of PODs without PV. First, we find that "small" consumers (characterized by average daily demand below 2.5 kWh) are less sensitive to cold and hot temperatures than other groups (regression results are presented in Supplementary Table 1). The difference is particularly large as the sensitivity to daily temperatures above 30°C corresponds to relative increase of 45% with respect to the consumption level at the reference temperatures (15°C - 21°C) for the "medium" and "large" groups, and only to a rise of 20% for the "small" group. This effect suggests a lower penetration of mechanical cooling in least affluent households. The scale of total consumption changes due to cold and hot temperature anomalies is amplified by the differences in average electricity consumption across groups, with "small" consumers increasing the demand by less than 0.5 kWh, "medium" consumers by around 2 kWh and "large" by 4.5 kWh, for an additional day with temperatures above 30°C (see Fig. 5).

As for price elasticity, we find that "small" consumers are more price sensitive than other classes, with an average annual elasticity of -0.08, with respect to the elasticities of -0.045 and -0.055 for "large" and "medium" classes, respectively (see Fig. 6). Similarly, the results from the regression model not accounting for heterogeneity across groups show that consumption is more responsive to price shocks in winter than in summer or shoulder seasons, possibly due to differences in the type of appliances used across seasons and, therefore, in the flexibility to adjust consumption following an increase in prices.

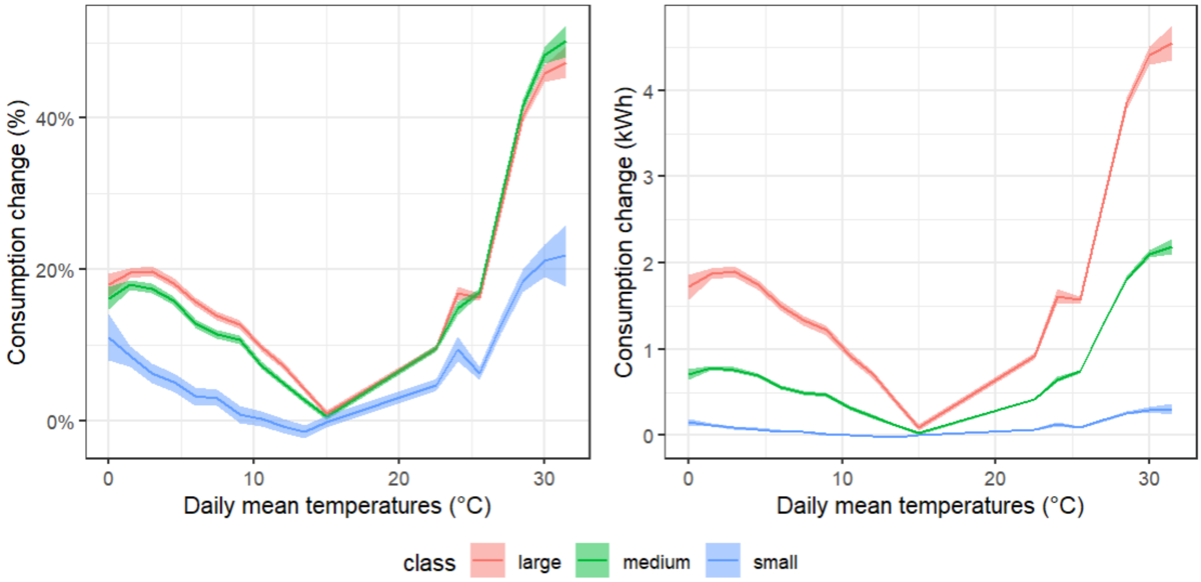

Fig. 5. Estimated change in daily grid consumption due to temperature deviations from the reference level (15°C - 21°C), by consumption class. Shades represent the 95th confidence intervals.

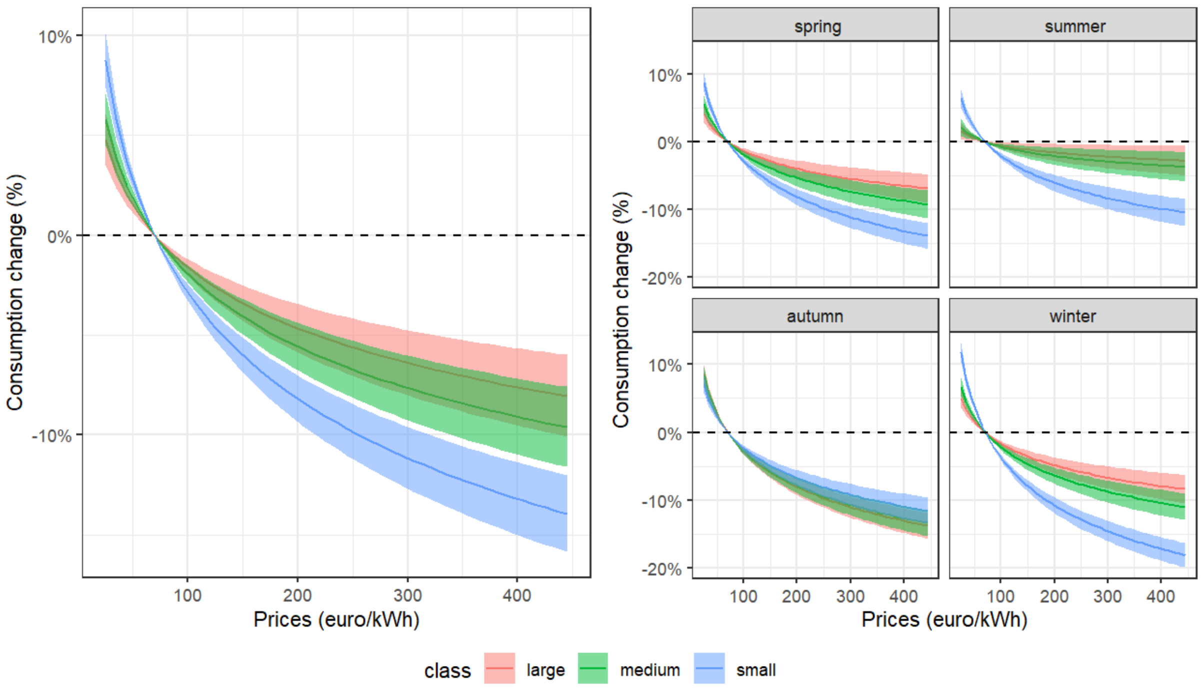

Fig. 6. Estimated change in daily grid consumption due to electricity price deviations from the reference level (70 euro/kWh) - by consumption class. Shades represent 95th confidence intervals.

5.3 Simulation of price shock impacts

The energy crisis in 2022 resulted in exceptionally high electricity prices, which according to the regression model developed in this study resulted in changes in electricity consumption between 5% to 20%, depending on season and group of consumers. Here, we turn to estimate the net consumer welfare change, which results from the price increase and demand adjustments. In standard economic theory, consumer welfare is measured as the area below the demand curve, up to the intersection of prices and quantities in equilibrium at point A (light blue area in Fig. 7, panel a). Note that in the case of household electricity consumption and power market prices, the supply curve is generally perfectly elastic, as it may accommodate any demand level at a given price.

An increase in prices, like the one experienced by households in 2022, can be represented as an upward shift in the supply curve, resulting in a new equilibrium level A*. Assuming a linear demand curve, the consumer surplus is necessarily smaller and is measured by the trapezoid ABCE. We emphasize that these changes in demand and consumer surplus are driven not by changes in primitive properties of consumer tastes, but rather by a change in the equilibrium following the price shock, as shown in a stylized fashion in Figure 7 (for an application of this method to the demand-side shock see Barreca et al., 2016).

By identifying the demand curve through the estimated price elasticities, and adopting a month-specific price-demand shock due to the large differences in prices experienced over the course of 2022, we can measure the net change in monthly (and annual) consumer surplus by each consumer group (without or with PV and by consumption class). Table 4 presents the estimated change in consumer surplus based on the empirical model: we find a substantial annual change of around 300 euro for the median consumer with no PV and of 133 euro after the introduction of PV for the same median household. Note that, the estimation in the case of PV ownership constitutes the upper bound of the change, given that we observe only grid extraction net of electricity consumption from self-production. Large differences in baseline consumption levels across classes result in an heterogeneous surplus loss of 83 to 602 euro per year for the small and large classes, respectively. Ending on this, these values result from the combination of lower (higher) demand as well as higher (lower) elasticity to prices of the two classes, respectively.

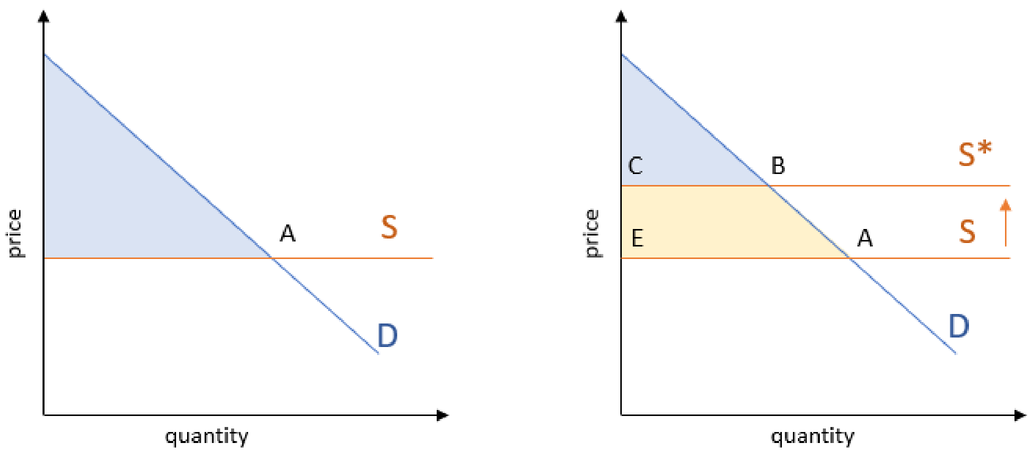

Fig. 7. Stylized representation of the demand-supply curves and the Consumer Surplus Loss resulting from an increase in prices shifting up the supply curve.

Table 4
Estimated Net Consumer Surplus Loss due to the price increase in 2022

Class	Estimate [95th confidence interval]
POD without PV - average	301 € [296 - 305]
POD with PV - average	133 € [131 - 136]
POD without PV - small	83 € [80 - 87]
POD without PV - medium	269 € [264 - 274]
POD without PV - large	602 € [591 - 612]

6. Conclusions and policy implications

This study exploits high-frequency data of households residing in the municipality of Brescia between 2021-2022 to infer the impact of PV adoption and the influence of temperatures on grid electricity consumption, as well as to detect potential differences in price elasticity among different consumption groups and seasons. We find that adopting PV systems significantly reduces grid consumption: by 75% on average and by as much as 100% during sunny hours and warmer seasons. PV adoption leads to significant reductions in electricity consumption responsiveness during extreme temperature and price events, contributing to enhanced energy security and affordability for households. Furthermore, we find that "small" consumers can cope worse with high temperatures and are more sensitive to electricity-prices compared to "medium" and "large" consumers.

Our findings reinforce the literature estimating the benefits of decentralized photovoltaics, including cost savings, environmental advantages, and increased energy independence; making them a compelling option for sustainable energy solutions at the household level. By identifying the demand curve through the estimated price elasticities, we measure the net change in the monthly (and annual) consumer surplus without or with PV and by consumption class. Our analysis indicates a substantial annual change of around 300 euros for the median consumer with no PV and of 133 euros as a result of the marginal introduction of PV in the same median household. This result is an indirect quantification of the benefits of energy independence deriving from solar PV: generating electricity on-site gives residential users greater energy independence, making them less vulnerable to power outages or fluctuations in energy prices.

Moreover, our results show that the adoption of micro-level demand data can provide relevant insights, as they shed light on consumer behavior in response to price fluctuations. In line with Auffhammer and Rubin (2018), the high-frequency nature of our data leads to different price-elasticities estimates with respect to analyses at a more aggregate level: the short-run elasticity of demand in the meta-analysis of Labandiera et al. (2017) is on average two times higher than what we estimated (0.13% and 0.06%, respectively), confirming the relevance of the method adopted in the estimation result and the exceptionality of the Russia-Ukraine price shock. These insights are crucial for policymakers and industries alike, especially when dealing with significant economic shifts and the need for efficient resource management.

There are several aspects that, due to data limitations, could not be measured in this study: lack of data on self-consumption prevents the evaluation of rebound effects in total consumption after the adoption of PV. For this reason, our results on the relative change in consumption following price and temperature shocks for households with PV can only be informative of demand shifts affecting the centralized power system, rather than on actual consumption behavior. Furthermore, we do not have information on the tariff scheme of electricity bills, or if residential users with PV systems were allowed to feed back into the grid the extra electricity produced, earning credits or payments. Therefore, we were unable to quantify the overall benefits of owning a decentralized PV system in terms of reduced electricity bills during the 2022 price shocks. The aforementioned caveats and shortcomings could be considered for further research.

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Supplementary Material

Supplementary Table 1

Results of the regression model with daily data, on the full sample and by consumption class

Dependent Variable:	log(q)			
Model:	(all)	(large)	(medium)	(small)
Variables				
t_l0	0.1533***	0.1795***	0.1619***	0.1104***
	(0.0054)	(0.0063)	(0.0070)	(0.0153)
t_0_1p5	0.1402***	0.1685***	0.1489***	0.0946***
	(0.0031)	(0.0040)	(0.0040)	(0.0086)
t_1p5_3	0.1599***	0.1954***	0.1796***	0.0854***
	(0.0025)	(0.0031)	(0.0032)	(0.0068)
t_3_4p5	0.1525***	0.1980***	0.1750***	0.0628***
	(0.0022)	(0.0028)	(0.0029)	(0.0061)
t_4p5_6	0.1373***	0.1820***	0.1587***	0.0507***
	(0.0022)	(0.0027)	(0.0028)	(0.0061)
t_6_7p5	0.1113***	0.1567***	0.1287***	0.0321***
	(0.0020)	(0.0026)	(0.0026)	(0.0057)
t_7p5_9	0.0990***	0.1386***	0.1138***	0.0305***
	(0.0020)	(0.0025)	(0.0026)	(0.0055)
t_9_10p5	0.0867***	0.1268***	0.1066***	0.0078
	(0.0020)	(0.0026)	(0.0026)	(0.0056)
t_10p5_12	0.0613***	0.0965***	0.0734***	0.0027
	(0.0018)	(0.0023)	(0.0024)	(0.0050)
t_12_13p5	0.0414***	0.0734***	0.0499***	-0.0071
	(0.0016)	(0.0021)	(0.0021)	(0.0045)
t_13p5_15	0.0199***	0.0412***	0.0269***	-0.0148***
	(0.0014)	(0.0018)	(0.0019)	(0.0040)
t_21_22p5	0.0048***	0.0098***	0.0054***	-0.0011
	(0.0014)	(0.0020)	(0.0019)	(0.0036)
t_22p5_24	0.0838***	0.0964***	0.0957***	0.0477***
	(0.0015)	(0.0022)	(0.0021)	(0.0039)
t_24_25p5	0.1415***	0.1635***	0.1701***	0.0631***
	(0.0018)	(0.0027)	(0.0024)	(0.0045)
t_25p5_27	0.2490***	0.2810***	0.2946***	0.1269***
	(0.0024)	(0.0037)	(0.0033)	(0.0060)
t_27_28p5	0.3549***	0.4019***	0.4168***	0.1851***
	(0.0032)	(0.0049)	(0.0044)	(0.0078)
t_28p5_30	0.4090***	0.4594***	0.4830***	0.2118***
	(0.0048)	(0.0071)	(0.0067)	(0.0117)
t_30_31p5	0.4236***	0.4742***	0.5015***	0.2184***
	(0.0088)	(0.0124)	(0.0124)	(0.0216)
log(p)	-0.0591***	-0.0454***	-0.0546***	-0.0813***
	(0.0004)	(0.0006)	(0.0006)	(0.0012)
ssr	-6.59×10^{-13}	3.06×10^{-8}***	1.68×10^{-8}*	-6.33×10^{-8}***
	(6.68×10^{-9})	(8.64×10^{-9})	(8.74×10^{-9})	(1.82×10^{-8})
ssr^2	-1.04×10^{-13}***	-1.27×10^{-13}***	-1.2×10^{-13}***	-4.95×10^{-14}***
	(6.6×10^{-15})	(8.89×10^{-15})	(8.72×10^{-15})	(1.76×10^{-14})
Fixed-effects				
POD	Yes	Yes	Yes	Yes
weekday-POD	Yes	Yes	Yes	Yes
month-POD	Yes	Yes	Yes	Yes
cal_day-POD	Yes	Yes	Yes	Yes
Fit statistics				
Observations	7,396,589	1,830,931	3,705,675	1,859,983
R^2	0.78265	0.51820	0.48072	0.76072
Within R^2	0.00761	0.01825	0.01051	0.00383

Heteroskedasticity-robust standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

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