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Understanding Residential Electricity Consumption Behavior under Dynamic Pricing: Evidence from Spanish Cities

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Abstract: This paper examines the short-run price responsiveness of residential electricity demand under the Spanish Voluntary Price for Small Consumers (PVPC) tariff during the 2023–2024 period, following the profound disruptions of the European energy crisis. Using hourly consumption data from 2,975 households in Madrid, Bilbao, and Valencia, we implement a Two-Stage Least Squares (2SLS) framework with nationwide wind generation as an instrumental variable to address price endogeneity. To move beyond mean-based estimates, we complement this with household-level quantile regressions, which allow us to test whether price sensitivity varies across a household's own consumption distribution distinguishing responses at low-consumption hours from responses at peak-consumption hours. Despite a 26% increase in mean prices and a threefold rise in price volatility relative to the 2016–2017 baseline, our results indicate that price elasticity of demand remains centered at zero both on average and across all quantiles of each household's consumption distribution. This finding rules out the hypothesis that households engage in price-driven peak shifting even under the significantly more volatile post-crisis price environment, and challenges the hypothesis that steeper price gradients alone are sufficient to overcome rational inattention and structural adjustment costs. Temperature is identified as the dominant driver of hourly consumption variation. Our results suggest that enabling technologies and complementary policy instruments are necessary conditions for dynamic pricing to deliver meaningful demand flexibility.

Keywords: Residential electricity consumption; Demand Response; elasticity; price responsiveness.

1. Introduction

The increasing penetration of renewable generation has intensified the need for demand-side flexibility in electricity systems. As the use of variable renewable energy sources, such as wind and solar power, increases, it becomes a key policy objective to ensure that electricity consumption aligns with real-time system conditions [1], [2]. Dynamic pricing schemes, which aim to transmit hourly signals to final consumers, have long been encouraged as an efficient mechanism to promote demand response and reduce reliance on costly backup generation [3], [4].

Spain provides a particularly suitable setting to study residential demand response under dynamic pricing. Since 2015, the Voluntary Price for Small Consumers (PVPC) has exposed a large share of residential users to hourly electricity prices linked directly to the day-ahead wholesale market [5]. Under the PVPC scheme, households face substantial intraday price variation, at least in nominal terms, making Spain one of the few countries where real-time pricing has been implemented at scale for residential consumers.

Despite its theoretical appeal, empirical evidence on the effectiveness of real-time pricing in inducing residential load adjustments remains mixed. A growing literature documents limited price responsiveness of household electricity demand, particularly in the short run and in the absence of enabling technologies or behavioral interventions [6], [7], [8], [9], [10], [11], [12], among others. For the Spanish case, [7] examined the impact of the first large-scale implementation of real-time pricing (RTP) or PVPC. Utilizing a granular dataset of over 20,000 households and an instrumental variable (IV) approach (employing nationwide wind generation forecasts to address price endogeneity) the authors estimated the short-run price elasticity of demand. Their findings reveal that households exposed to RTP exhibited an average price elasticity of zero.

While [7] examined the immediate aftermath of the real-time pricing (RTP) implementation in Spain, covering the period from January 2016 to June 2017, this paper analyzes the 2023-2024 period. This shift in timeframe is non-trivial; the previous study analyzed a market characterized by relative stability following the 2015 regulatory change. In contrast, our period of analysis follows the profound disruptions of the European energy crisis, which introduced structural changes in price levels and consumer awareness that were not present during the initial rollout of the PVPC tariff.

In this sense, [7] reported a mean price of 108.2 €/MWh with a standard deviation (SD) of 17.3 €/MWh. According to our data, the 2023-2024 period exhibits a substantially higher mean price of 137.18 €/MWh, representing a 26% increase in average costs. More importantly, price volatility has escalated dramatically: the SD in our sample (56.75 €/MWh) is more than triple that observed in the 2016-2017 period. This suggests that consumers face a much more uncertain and aggressive pricing environment than those in the previous study.

These statistical differences are theoretically critical for identifying price elasticity. [7] hypothesized that the observed zero elasticity in their sample could be explained by low price variation, which resulted in negligible financial incentives for households to shift load. They specifically noted that "steeper price gradients" might be a necessary condition for RTP to be successful. While the interquartile range (P75-P25) in Fabra's sample was only 18.9 €/MWh, it has expanded to 76.95 €/MWh in our 2023-2024 dataset. This increased dispersion provides

a unique opportunity to test whether higher and more pronounced price signals can overcome the rational inattention and high adjustment costs that previously hindered consumer response.

This paper contributes to an emerging cross-country literature on residential price elasticity under real-time pricing. Recent peer-reviewed evidence documents strikingly similar patterns across European countries: [11], using Danish smart-meter data, find that the average household exhibits no significant price response, although approximately one third of households reduce consumption when prices rise. [12], in a randomized reward-scheme field experiment with 3746 Norwegian households, find an average peak-hour reduction of only 2.92 % despite explicit information and incentives.

The present paper provides the estimate of the short-run price elasticity of PVPC households in the post-crisis price regime (2023–2024). Our empirical strategy follows a dual approach to identify the causal effect of price fluctuations on demand. First, we implement a Two-Stage Least Squares (2SLS) framework, consistent with the identification strategies established by [7], [9], [10], [11]. This allows us to estimate the mean short-run price elasticity by utilizing nationwide wind generation as an exogenous supply-side instrument to resolve the structural endogeneity between price and demand. Second, we extend this analysis by applying household-level quantile regression with control function. While 2SLS provides a robust estimate of the average treatment effect, the QR approach allows us to move beyond mean-based results and identify price sensitivity across the entire conditional distribution of consumption. This is particularly relevant given the potential for heterogeneous responsiveness among households, as suggested by [6], where different usage patterns may dictate varying levels of flexibility. Our models integrate hourly consumption data from Madrid, Bilbao, and Valencia with high-resolution meteorological variables from AEMET and fixed effects for regional holidays and temporal cycles to ensure the validity of the exclusion restriction

Our empirical results show that price coefficients are consistently close to zero across all estimated quantiles, indicating limited price responsiveness not only on average but throughout the entire consumption distribution. This finding holds across cities and remains robust to alternative model specifications and control structures. While temperature plays a significant role in shaping electricity demand, hourly prices under the PVPC scheme appear to have a limited and statistically insignificant impact on residential consumption patterns.

These results reinforce the view that real-time pricing alone may be insufficient to induce meaningful demand response among residential consumers. From a policy perspective, our findings suggest that additional mechanisms (such as enhanced price salience, automation technologies, or complementary tariff designs) may be necessary for dynamic pricing to deliver its intended efficiency gains. More broadly, this paper highlights the importance of moving beyond average effects and adopting distributional approaches when evaluating demand response policies in electricity markets.

The remainder of the paper is organized as follows. Section 2 describes the institutional context of the Spanish PVPC tariff. Section 3 present the data and descriptive evidence. Section 4 develops the analytical approach, including the 2SLS framework and the household-

level distributional approach. Section 5 reports the results, Section 6 presents the discussion and finally, conclusions are offered in Section 7.

2. Institutional context: the Spanish PVPC tariff

Spanish residential electricity consumers have been provided with the Voluntary Price for Small Consumers (PVPC) tariff since October 2015. This regulated pricing scheme applies to households with a contracted power supply of less than 10 kW and supplied by designated retailers [5].

Under the PVPC, the cost of the energy component of the retail electricity price varies hour by hour and is indexed to the outcome of the Iberian day-ahead and ancillary services market. Consumers are informed of the prices for the following day in advance, as hourly prices are published after the day-ahead market clears. As a result, PVPC constitutes a form of real-time pricing that, at least in principle, exposes residential consumers to intraday price variation and scarcity signals in the electricity system.

In addition to the energy component, the total retail electricity bill includes system charges (network and policy costs), which are largely time-invariant and do not vary across hours. These charges apply to any residential end-user, regardless of whether they are under this PVPC option or have contracted with a retailer in the market.

Residential electricity consumers in Spain can choose among several retail supply options. Households may remain under the default regulated tariff (PVPC) or switch to alternative pricing schemes, such as time-of-use (TOU) tariffs, or contract electricity supply directly from a competitive retailer under fixed-price or hybrid contracts. Offers in the competitive retail market typically feature time-invariant prices and, on average, are more expensive than the regulated PVPC tariff.

According to the [13] as of December 31, 2024, approximately 8.4 million residential consumers remained under the PVPC tariff, accounting for around 29% of domestic electricity customers in Spain. In terms of electricity demand, however, PVPC users represented a smaller share —around 22% of total residential consumption— reflecting the lower average consumption levels of households that remain under the regulated tariff.

The number of consumers supplied under PVPC has evolved over time alongside the gradual liberalization of the Spanish electricity retail market. While the migration from PVPC to the competitive market slowed during 2023, partly due to a marked decline in wholesale electricity prices that increased the relative attractiveness of PVPC, this trend reversed in 2024, with an intensification of customer switching toward free-market retail offers. Despite this ongoing migration, the PVPC tariff continues to play a relevant role as a price reference and remains a preferred option for specific segments of residential consumers.

3. Data

This study combines hourly electricity consumption data for 3000 residential users with hourly electricity prices, detailed weather information and detailed calendar effects capturing local and regional public holidays. This dataset constitutes the main empirical basis for the behavioral analysis conducted in this paper. Further details are provided in the following subsections.

3.1 Residential Electricity Consumption

The average annual electricity consumption values reported in Table 1 are consistent with official energy statistics published by the CNMC [13], which indicate an average residential household consumption of 2.004 MWh in 2023 and 2.032 MWh in 2024. This average consumption is significantly lower than the average consumption observed in the competitive retail market. This difference highlights the concentration of the PVPC tariff among households with low to moderate electricity consumption profiles.

Table 1. Average annual consumption by city

Average annual consumption MWh		
City	**2023**	**2024**
Bilbao	2.09	2.09
Madrid	2.26	2.30
Valencia	2.54	2.45

The descriptive statistics for residential consumption and ambient temperature shown in Table 2, reveal significant regional heterogeneity across the three Spanish cities analyzed. Valencia presents the warmest climate with a mean temperature of 20.08°C and the lowest thermal volatility (SD = 6.28°C), while Madrid exhibits the highest temperature dispersion (SD = 8.36°C), reflecting a more volatile continental climate. These meteorological profiles directly influence consumption patterns, as the literature identifies ambient temperature as a primary exogenous determinant of electricity demand due to heating and cooling requirements. Consequently, average hourly consumption is higher in Valencia (0.33 kWh) and Madrid (0.32 kWh) than in Bilbao (0.28 kWh). Across all locations, the standard deviation of consumption (ranging from 0.45 to 0.49 kWh) is notably high relative to the mean, indicating a distribution characterized by pronounced demand peaks.

Table 2. Summary statistics

	Daily Temperature °C					Daily average consumption kWh				
City	**Mean**	**SD**	**P25**	**P50**	**P75**	**Mean**	**SD**	**P25**	**P50**	**P75**
Bilbao	16.91	6.36	12.31	17.03	21.49	0.28	0.45	0.07	0.14	0.29
Madrid	16.89	8.36	10.33	16.12	22.8	0.32	0.49	0.08	0.16	0.34
Valencia	20.08	6.28	15.47	20.2	25.09	0.33	0.46	0.09	0.17	0.35

The dataset described in this paper consists of anonymized hourly electricity consumption data correspond to residential consumers under the PVPC tariff from 3000 electricity supply points. These points are located in three major Spanish cities: Bilbao in northern Spain, Madrid in the central region, and Valencia in the south. These cities represent geographically and climatically distinct areas, allowing us to capture heterogeneous consumption patterns across different climate zones. The dataset covers the period from January 1, 2023, to December 31, 2024, comprising two full calendar years.

To provide an overview of consumption patterns and their relationship with climatic conditions and prices, we conduct a preliminary descriptive analysis based on aggregated consumption at the city level.

Figure 1 presents the monthly evolution of aggregate electricity consumption, obtained by summing hourly consumption across all residential contracts within each city. In Madrid, electricity consumption exhibits a seasonal pattern, with the highest levels observed during the winter months. While consumption increases during the summer, likely reflecting cooling demand, summer usage does not reach the levels observed in winter.

In Bilbao, aggregate consumption also peaks during the winter months, while the lowest consumption levels are observed in summer. This seasonal pattern reflects the milder summer temperatures characteristic of the region and a more limited role for cooling demand relative to heating needs.

In Valencia, electricity consumption displays a bimodal seasonal pattern, with high consumption levels observed both in winter and summer. Notably, aggregate consumption in these two seasons is of comparable magnitude.

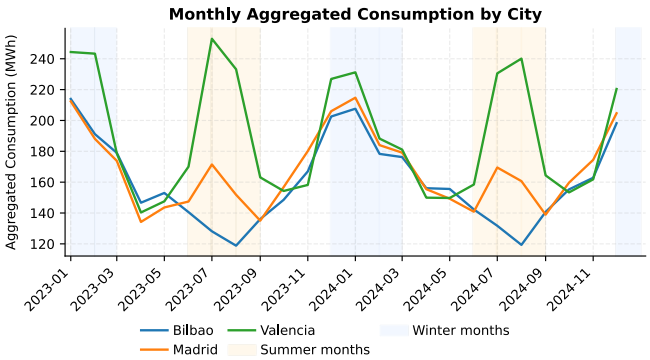


Figure 1 Monthly aggregate consumption by city

3.2 Electricity Prices

The hourly electricity prices used in this study were obtained from ESIOS, the official information platform of the Spanish electricity system operator. Specifically, we use the hourly PVPC (Precio Voluntario para el Pequeño Consumidor) tariff, which is the regulated

retail electricity tariff for small consumers in Spain. Although the PVPC is closely linked to the Spanish day-ahead wholesale electricity market, its final hourly value also incorporates regulated adjustments, network charges, balancing costs, and, since 2024, a component indexed to forward electricity markets. The hourly prices are published one day ahead through the ESIOS platform, expressed in €/MWh. Figure 2 illustrates the relationship between daily aggregated residential electricity consumption and electricity prices for each city. The scatter plots show no clear association between consumption and prices in any of the three cities. This descriptive evidence suggests that, under the PVPC tariff, residential electricity consumption does not visibly respond to hourly price fluctuations at the aggregated level.

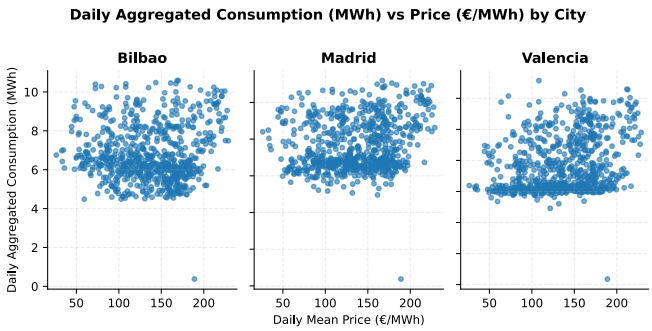


Figure 2 Daily aggregated consumption (MWh) vs price by city

The descriptive statistics for the hourly electricity prices in our sample (2023–2024) shown in Table 3, reflect a market environment characterized by significantly higher price levels and a dramatic escalation in volatility compared to earlier periods. The mean price of 137.18 €/MWh represents a substantial increase over the 108.2 €/MWh reported by [7] for the 2016–2017 period. More critically, price volatility has intensified, with a standard deviation of 56.75 €/MWh, which is more than three times the 17.3 €/MWh observed in the baseline study. The interquartile range has also expanded from a narrow 18.9 €/MWh in the 2016–2017 data to 76.95 €/MWh in our sample, indicating a much broader distribution of price signals.

Table 3 Daily price statistics

Price (€/MWh)						
Mean	**SD**	**Min**	**P25**	**P50**	**P75**	**Max**
137.18	56.75	16.84	98.09	137.42	175.04	357.20

Figure 3. Daily average electricity price PVPC (€/MWh) displays the evolution of daily average electricity prices. On average, electricity prices in Spain were higher in 2023 than in 2024. According to [13], the annual average wholesale electricity price was 63 €/MWh in 2024, which is a 28% decrease compared to 2023. This decline reflects lower gas prices and a higher share of renewables in the generation mix, among other factors.

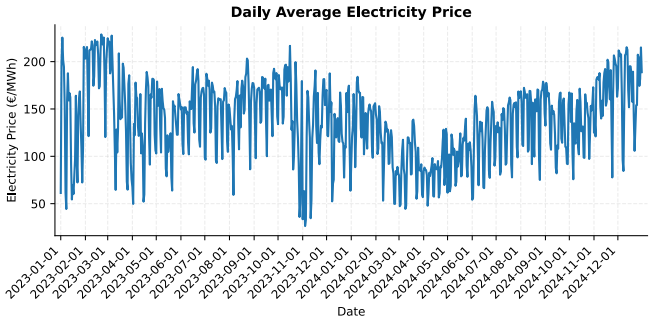


Figure 3. Daily average electricity price PVPC (€/MWh)

One of the institutional factors characterizing 2023 was the Iberian exception [14], a temporary regulatory mechanism implemented in Spain and Portugal to cap the price of natural gas used for electricity generation in the wholesale market. This mechanism was introduced on June 2022 and extended through 31 December 2023 with the approval of the European Commission, aiming to mitigate the volatile impact of international gas prices on electricity prices. Under this scheme, the reference price for gas-fired generation started at 40 €/MWh, increasing gradually (initially 5 €/MWh per month and later at a slower rate), ultimately reaching around 65 €/MWh by the end of 2023.

Within this context, an examination of the reference natural gas prices used under the Iberian exception mechanism in 2023 indicates that the gas price exceeded the regulatory cap (€60/MWh) on only a limited number of days. In January 2023, exceedances occurred on just 10 days, with an average deviation of approximately €3/MWh above the cap. Given both the low frequency and the limited magnitude of these deviations, their effect on the empirical analysis is expected to be negligible.

3.3 Weather Data

Weather information is obtained from the Spanish Meteorological Agency (AEMET) via its official API. For each city, we collect daily maximum and minimum temperatures from the corresponding central meteorological stations, ensuring spatial consistency between consumption and weather conditions.

Since electricity demand is measured hourly, daily temperature observations are transformed into hourly temperature series using linear interpolation between daily minimum and maximum. This approach allows for a smooth intraday temperature profile that approximates observed thermal cycles and is commonly used when high-frequency meteorological observations are unavailable. It should be noted that the linear interpolation between daily minimum and maximum temperatures is a standard simplification when sub-daily meteorological observations are unavailable. As a robustness check, we replicated our main specifications using Heating Degree Hours (HDH) and Cooling Degree Hours (CDH) constructed from the interpolated series, finding qualitatively identical results. Future work

with access to hourly station data from AEMET could refine this temperature characterization.

The resulting hourly temperature series is matched to each residential consumer based on city of location. Temperature enters the empirical models either linearly or through nonlinear transformations to capture the well-documented nonlinear relationship between electricity demand and weather conditions.

To further explore the role of weather conditions, Figure 4 depict the relationship between electricity consumption and temperature. For Madrid and Valencia, the scatter plots reveal a clear nonlinear, approximately quadratic relationship between temperature and electricity consumption, with higher demand observed at both low and high temperature levels. In contrast, for Bilbao, consumption exhibits a predominantly inverse relationship with temperature, reflecting increased electricity use during colder periods and relatively stable demand during warmer months.

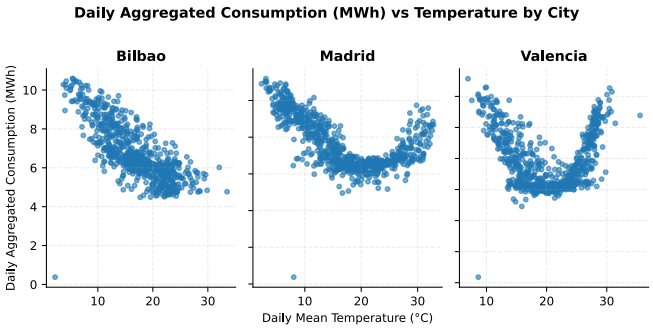


Figure 4. Daily aggregated consumption (MWh) vs Temperature (ºC) by city

3.4 Calendar Effects and Public Holidays

To account for systematic variations in electricity consumption related to activity patterns, the dataset incorporates a detailed set of calendar controls. These include:

- National public holidays in Spain
- Local and regional public holidays specific to each city
- Weekday and weekend indicators

Public holidays are assigned at the city level, reflecting legally recognized local and regional holidays in Madrid, Bilbao, and Valencia. These controls are particularly important to separate behavioral effects from price-induced consumption adjustments, as electricity demand often differs substantially on holidays relative to regular working days.

Overall, these descriptive patterns motivate the empirical strategy adopted in this paper. In particular, they support the inclusion of nonlinear temperature controls in the demand model and anticipate the limited role of prices in explaining short-run consumption dynamics, a

hypothesis that is formally tested using quantile regression techniques in the subsequent sections.

3.5 Wind generation, solar generation, gas and carbon prices.

To account for the endogenous nature of electricity prices, our identification strategy incorporates several key supply-side variables as both instruments and controls. The descriptive statistics for these variables are presented in Table 4. Wind generation, which serves as our primary exogenous instrument, exhibits a mean of 6,850.8 MW with a significant standard deviation of 4,058.3 MW as shown in Table 4, a level of variability that ensures its relevance as a supply-side shifter capable of depressing wholesale prices [9]. Furthermore, we include solar generation (Mean = 4,509.1 MW) and thermal cost indicators to capture broader shifts in the merit order curve. Specifically, carbon prices (Mean = 74.4 €/t) and gas prices (Mean = 36.5 €/MWh) reflect the substantially higher marginal production costs of the 2023-2024 period compared to the more stable price environments documented in previous studies [7], [9]. The inclusion of these covariates is essential to satisfy the exclusion restriction, ensuring that our estimated price elasticity isolates the behavioral response to exogenous price fluctuations from shocks in generation costs.

The hourly wind and solar generation expressed in MW used in this study were obtained from ESIOS, the official information platform of the Spanish electricity system operator. While, the natural gas hourly price data were obtained from the MIBGAS market platform [15], and the hourly carbon price were sourced from [16] These datasets provide daily price information across the study period.

Table 4 Summary statistics

	Mean	SD	Min	P25	P50	P75	Max
Wind generation (MW)	6850.8	4058.3	197.3	3580.9	6102.3	9485.1	20699.2
Solar generation (MW)	4509.1	5675.6	0.0	28.0	316.3	9566.3	19854.3
Carbon prices (€/t)	74.4	10.8	50.9	66.2	72.3	84.2	97.0
Gas prices (€/MWh)	36.5	8.3	22.7	30.6	35.1	40.6	69.8

4. Empirical approach

Starting from an initial sample of approximately 3,000 residential contracts in the dataset, a data cleaning procedure was applied to ensure consistency and reliability. Observations with hourly consumption values exceeding 10 kWh were removed, as well as contracts exhibiting more than 80% of zero-consumption records. Overall, this filtering process led to the exclusion of about 0.8% of the original sample, resulting in a final dataset of 2,975 contracts distributed as follows: 993 in Bilbao, 989 in Madrid, and 993 in Valencia.

To capture key behavioral and structural features of residential electricity demand, additional variables were constructed from the original dataset. These include squared temperature terms to model the nonlinear relationship between temperature and electricity consumption, a set of categorical variables identifying seasons, weekends, and national, regional, and local public holidays was incorporated to control for systematic calendar effects in electricity consumption.

The empirical analysis in this paper is based on a dataset covering residential consumers exposed to hourly price signals under the PVPC tariff. This dataset allows us to estimate price sensitivity across different points of the conditional distribution of electricity consumption. A key challenge in estimating the effect of electricity prices on residential consumption is the potential endogeneity of prices, as hourly electricity prices in Spain are determined in the wholesale market through supply and demand interactions. As a result, observed prices are correlated with electricity consumption.

To address this issue, we adopt a two-stage least squares (2SLS) approach that uses hourly wind power generation as an instrumental variable (IV) for electricity prices, an identification strategy that has been widely applied in the related literature [10], [8], [7], [9]. Hourly wind generation affects wholesale electricity prices through its impact on the supply side of the market, while remaining plausibly unrelated to short-run residential electricity consumption decisions. As a result, increases in wind power generation are associated with lower electricity prices, whereas decreases in wind generation are associated with higher prices.

The exclusion restriction requires that wind generation affects household electricity consumption only through its effect on wholesale electricity prices. The most plausible threat to this assumption is a correlation between wind speed and ambient temperature, which could affect consumption directly through heating and cooling demand. We address this by including temperature and its square as direct controls in all estimation stages, absorbing the weather-driven component of consumption that could otherwise be correlated with wind. The national aggregation of the wind instrument (summed across all Spanish generation zones) further dilutes any local wind-temperature correlation that might affect individual city consumption. Additionally, wind generation has no direct effect on the physical delivery of electricity to residential consumers, ruling out a direct supply-availability channel.

4.1 Model specifications

This section introduces the parametric model specifications. The continuous variables: price, wind generation, solar generation and consumption are transformed using the logarithm to facilitate the interpretation of the estimated coefficients. Under this log-log specification, the coefficients obtained from the second stage can be interpreted as elasticities, measuring the percentage change in electricity consumption associated with a one percent change in electricity prices. In addition, this transformation helps mitigate the influence of extreme

values and preventing negative values and ensuring consistency across the first and second stages of the estimation.

Since electricity prices are uniform across all households in Spain, the first-stage regression is identical for all households. In this stage, hourly electricity prices are predicted based on wind generation and the control variables:

$$\boldsymbol{Ln\,(P_t) = \alpha_0 + \alpha_1\, ln(Wind_t) + \alpha_n X'_t + \varepsilon_t} \quad \textbf{(1)}$$

In the second stage, the predicted electricity prices obtained from the first stage $\widehat{P_t}$ are used to estimate the relationship between prices and electricity consumption:

$$\boldsymbol{ln\left(C_{i,t}\right) = \beta_{0i} + \beta_i\, ln\,(\widehat{P_t}) + \theta_i X'_t + \omega_t} \quad \textbf{(2)}$$

Where.

P_t	Electricity price (PVPC) at hour t
$Wind_t$	Wind power generation at hour t
$C_{i,t}$	Electricity consumption of household i at hour t
X'_t	Control variables (temperature, solar generation, gas prices, CO2 prices, seasonal indicators, weekend and time effects).
β_i	Price elasticity of household i
$\alpha,\ \theta_i$	Modeled linear coefficients
$\varepsilon_t,\ \omega_t$	Error terms

In this study, we estimate household-specific electricity demand elasticities using a 2SLS framework, with the estimation carried out separately for each household using only its own time-series variation.

4.2 Household-Level Distributional Analysis

To examine whether price responsiveness varies across different states of household electricity consumption, we complement the mean-effect 2SLS estimates with a household-level distributional analysis. To address price endogeneity in a nonlinear setting, we adopt a control function approach [17]. This method allows us to correct for endogeneity within the quantile regression framework by explicitly modeling the endogenous component of electricity prices through the first-stage residual. The first-stage regression, expressed in equation (1), is estimated using ordinary least squares (OLS), and the estimated residuals $\boldsymbol{\widehat{\varepsilon_t}}$ are retained. These residuals represent the endogenous component of electricity prices that is orthogonal to the instrument and observed controls.

$$\boldsymbol{Q^{\tau}\left(ln\, C_{i,t}\right) = \beta_{0i}^{\tau} + \beta_i^{\tau}\, ln\, P_t + \delta_i^{\tau}\, \widehat{\varepsilon_t} + \theta_i^{\tau}\, X'_t + \vartheta_t} \quad \textbf{(3)}$$

Where $\tau \in (0, 1)$ indexes quantiles of the household's own consumption distribution over time, $C_{i,t}$ denotes hourly electricity consumption of household i at time t, $\boldsymbol{\beta_i^\tau}$ measures the price elasticity of household i at quantile τ. In this framework, lower quantiles (e.g., $\tau = 0.10$) corresponds to hours of very low consumption such as night-time or periods of absence, while higher quantiles (e.g., $\tau = 0.90$) capture peak-consumption hours where load-shifting incentives are expected to be strongest. This approach follows [17], [18] for the quantile regression estimator, applied individually to each household time series. The parameter $\boldsymbol{\delta_i^\tau}$ captures potential endogeneity in electricity prices through the control function term, while $\boldsymbol{\theta_i^\tau}$ is the vector of coefficients associated with the vector of control variables $\boldsymbol{X_t'}$, including lagged consumption variables to account for temporal dependence (e.g., lags = 1, 24 and 168 hours) and habitual demand patterns, as well as temperature persistence indicators to reflect sustained weather conditions. Finally, $\boldsymbol{\vartheta_t}$ represents unobserved shocks.

The key contribution of this distributional approach is to test the intraday peak-shifting hypothesis: even if mean elasticity is zero, households could exhibit negative price sensitivity specifically at high-consumption hours ($\tau \to 1$), where the financial gain from curtailment is largest. Finding $\beta_i^\tau \approx 0$ uniformly across all quantiles constitutes stronger evidence of structural inelasticity than the 2SLS mean estimate alone, ruling out that aggregate unresponsiveness conceals pockets of flexibility at particular consumption states.

5. Results

5.1 Mean elasticity estimates (2SLS)

In this section, we present the main results. As expected, we find that wind generation show a negative relationship with the electricity prices (**-0.23**) and is significant at the 0.1% level, with partial F-Statistics (3110) far above conventional thresholds suggested by [19], [20], indicating no concerns regarding weak instruments.

The results of the second stage are presented in Figure 5 and Table 5. To further investigate the nature of individual responsiveness, we analyzed the statistical significance of the price coefficients estimated for each household. Our results indicate that in approximately 50 % of household contracts, the estimated price coefficient is statistically distinguishable from zero at the 5% level. However, the distribution of significant coefficients is centered around zero and exhibits only mild asymmetry, indicating that when deviations from zero occur, they tend to be slightly more pronounced in the direction of downward-sloping demand.

Table 5 Results 2SLS by city

	Mean	Median	SD	Min	Max	Skewness
Bilbao	0.04	0.04	0.12	-0.87	0.82	-0.38
Madrid	0.03	0.04	0.13	-0.87	0.75	-0.61
Valencia	0.06	0.06	0.11	-0.51	0.68	-0.09

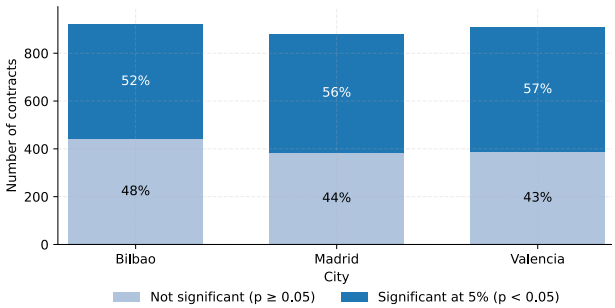


Figure 5. Price significance by city

The distribution of household-level price elasticity coefficients for Bilbao, Madrid, and Valencia is illustrated in **Figure 6** using violin plots. It is important to emphasize that these plots are constructed exclusively from the subset of contracts where the price coefficient was found to be statistically significant. These plots provide a comprehensive visualization of the data by combining aspects of a box plot with a kernel density estimation; the width of each "violin" represents the frequency of households at a specific coefficient value, while the internal horizontal blue lines denote the median elasticity for each city, providing a robust measure of central tendency that is less sensitive to extreme values in the distribution tails. As shown in the figure, the median response for all three cities is situated in proximity to zero values. While the central tendencies are consistent across regions, the results reveal significant heterogeneity in the dispersion of the estimates. Specifically, Bilbao exhibits a substantially broader distribution with pronounced tails (extending from approximately -1.2 to 1.7) whereas the coefficient densities for Madrid and Valencia are more tightly concentrated around their respective medians. Interestingly, Madrid displays a slightly more negative lean in its median response compared to Valencia, which shows a marginal positive shift, though neither deviates significantly from a zero-effect null hypothesis. Despite these regional variations in variance, the vast majority of the probability mass in each city remains localized within the near-zero range.

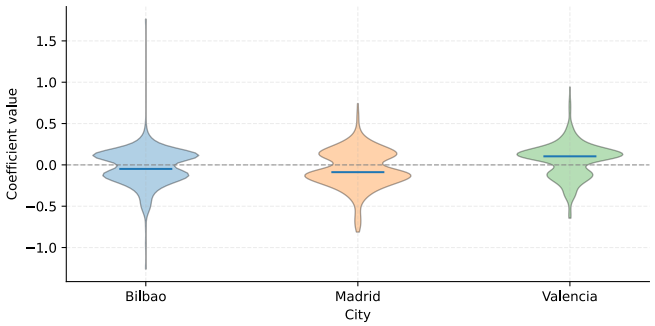


Figure 6. Price Coefficients by city

5.2 Distributional analysis

To further assess whether the observed heterogeneity in household-level estimates reflects systematic differences across consumption levels, we extend the analysis using a quantile regression framework based on the instrumented electricity prices. Figure 7 presents the distribution of price coefficients across contracts for selected quantiles ($\tau = 0.1, 0.5, 0.9$) and by city. Overall, the estimated price coefficients remain centered around zero across all quantiles, with no clear pattern of variation along the consumption distribution as shown in Table 6. While dispersion increases at the lower and upper quantiles (reflecting greater variability in consumption behavior during low- and high-demand periods) the median response remains close to zero in all cases. These results indicate that differences across quantiles are limited relative to the overall variability observed at the contract level.

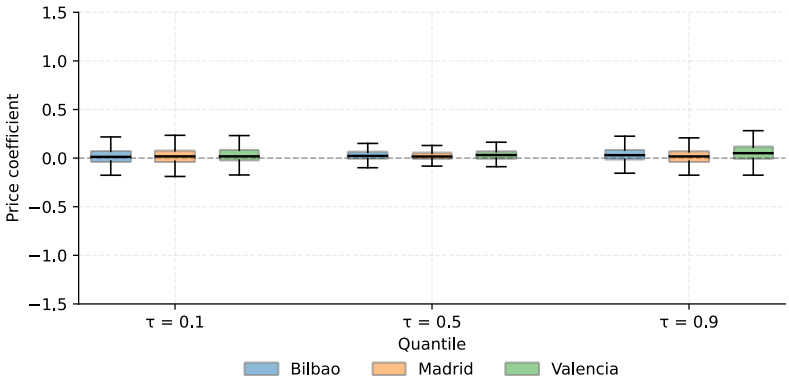


Figure 7. Price coefficients by quantile and city

Table 6 Results by quantiles and city

	Quantile	Mean	Median	SD	Min	Max	Skewness
Bilbao	**0.1**	0.03	0.04	0.16	-0.87	0.82	-0.09
	0.5	0.04	0.04	0.08	-0.22	0.42	0.30
	0.9	0.05	0.06	0.12	-0.73	0.55	-0.92
Madrid	**0.1**	0.03	0.04	0.16	-0.82	0.75	0.01
	0.5	0.04	0.04	0.08	-0.42	0.31	-0.53
	0.9	0.01	0.04	0.14	-0.87	0.53	-1.60
Valencia	**0.1**	0.05	0.04	0.14	-0.51	0.68	0.45
	0.5	0.05	0.05	0.07	-0.20	0.32	0.25
	0.9	0.07	0.09	0.12	-0.46	0.38	-0.97

6. Discussion

The empirical results of this study demonstrate that the short run price elasticity of residential demand in the Spanish PVPC market remains centered at zero, a finding that persists even under the significantly more volatile conditions of the 2023–2024 period. While [7] hypothesized that "steeper price gradients" might be a necessary condition to induce measurable behavioral changes, our data show that a 26% increase in mean prices and a threefold increase in price volatility compared to the 2016–2017 baseline were insufficient to cause a significant demand response. This suggests that the "rational inattention" identified in earlier literature remains a dominant barrier [6], [7]; for most households, the perceived financial gains from shifting consumption likely do not outweigh the cognitive and adjustment costs of monitoring hourly price fluctuations.

Furthermore, the heterogeneity observed in our violin plots (particularly the wider dispersion in Bilbao compared to Madrid and Valencia) indicates that while the median consumer is perfectly inelastic, there are individual variations in response that do not align into a consistent aggregate trend. Our findings are consistent with the recent evidence from [10], who argues that short-run aggregate responsiveness is often driven by storage systems rather than end-users, who remain fundamentally unresponsive to high-frequency price signals. In the absence of enabling technologies that automate the response, the mere exposure to real-time pricing (RTP) appears inadequate for transforming residential consumers into a source of system flexibility.

The quantile regression analysis reinforces these conclusions by showing that the absence of price responsiveness is not confined to average behavior but extends across the entire consumption distribution. Estimated price coefficients remain centered around zero for all quantiles ($\tau = 0.1, 0.5, 0.9$), with no systematic variation between low- and high-consumption periods. Although dispersion increases at the tails (reflecting greater variability in consumption patterns during very low- and peak-demand hours) this heterogeneity does not translate into consistent or statistically meaningful price responses. In particular, the lack of stronger elasticities at higher quantiles suggests that even during peak-consumption periods,

when the potential gains from load shifting are largest, households do not exhibit increased sensitivity to price signals.

Taken together, these results indicate that the limited responsiveness observed in the data is not driven by aggregation bias or by averaging across heterogeneous behaviors, but rather reflects a structural lack of responsiveness at the individual level. Even when exploiting exogenous price variation and allowing for heterogeneous effects across the consumption distribution, residential demand remains largely insensitive to short-run price fluctuations.

7. Conclusions

This paper concludes that the residential electricity demand under the Spanish PVPC tariff remains inelastic in the short run, regardless of the heightened price levels and volatility of the current energy landscape. By extending the 2SLS framework with a Quantile approach, we have shown that this lack of responsiveness is a consistent feature across the entire conditional distribution of consumption in major Spanish cities. The primary contribution of this research is the confirmation that increased "stakes" in the form of higher prices do not automatically overcome the structural barriers of lack of awareness and high adjustment costs

A critical factor in explaining the observed price inelasticity is the specific profile of PVPC households, who typically exhibit lower average consumption levels compared to consumers in the free market. This lower baseline consumption severely restricts the absolute magnitude of potential energy reductions available to these users. As the sources indicate, the financial incentives for such small-scale consumers are often insufficient to induce measurable behavioral changes, for instance, historical estimates suggested that even a fully flexible household could only achieve a maximum monthly saving of €1.91, while a more realistic 10% load shift would yield a negligible saving of approximately €0.19 [7]. These minimal financial stakes fail to offset the significant 'information burden' and the cognitive effort required to monitor hourly price fluctuations and adjust habits accordingly [6], [7].

In line with this evidence, our empirical results point in the same direction. Although we estimate somewhat higher potential savings (around €10 per month under full flexibility and approximately €2 per month under more realistic adjustment scenarios) these amounts remain modest in absolute terms. In particular, savings of around €2 per month are unlikely to provide sufficient incentives for households to actively modify their consumption habits. As a result, our findings ultimately reinforce those of Fabra et al. (2021), suggesting that the economic benefits associated with demand response under PVPC are too small to overcome the cognitive and behavioral frictions faced by consumers.

The lack of price responsiveness observed in our results can be further contextualized through the microeconomic framework established by [21], who demonstrate that household price elasticity is intrinsically linked to the composition of a family’s appliance portfolio. Their study identifies a stark contrast between households equipped with energy-intensive assets (such as central air conditioning or electric space heating) and those possessing only a 'regular

set' of electronic devices. While the former group exhibits significant price sensitivity due to the discretionary nature of high-power utilization, the latter often shows zero short-run demand sensitivity.

Given that the Spanish PVPC tariff is restricted to small consumers with a contracted power of less than 10 kW, the households in our sample predominantly fall into the category of users with a standard, non-intensive set of appliances. Lacking the 'swing' appliances necessary for substantial load shifting (such as large-scale HVAC systems or swimming pools) these consumers are structurally constrained to a near-zero elasticity baseline.

Our findings open several promising avenues for future research. First, the persistent zero-elasticity result across all quantiles of the consumption distribution and all price environments examined to date points to the structural nature of the barriers rather than to pricing design failures. A natural extension would be a field experiment component (a randomized controlled trial in which a sub-sample of PVPC households receive real-time price notifications via mobile applications or smart-home devices) to isolate the role of information frictions from high adjustment costs. The ongoing rollout of smart meters in Spain (mandated by EU Directive 2019/944) provides an institutional window for such a study.

Second, while this paper focuses on price responsiveness across the household's own consumption distribution (capturing potential intraday load-shifting) future research should examine whether the arrival of enabling technologies (home batteries, EV charging, smart thermostats) creates differential response at high-consumption hours. A time-comparison design using households that adopt smart devices could test whether the zero coefficients at high consumption quantiles ($\tau = 0.75, 0.90$) change once automation removes the cognitive cost of responding.

Third, the comparison across climatically distinct cities suggests that cooling-driven consumption (Valencia) may be structurally more flexible than heating-driven consumption (Madrid, Bilbao) due to the discretionary nature of air conditioning. Future work with a larger cross-section of cities could test whether climate zone moderates the distributional pattern of price responsiveness (specifically, whether households in hot-summer cities exhibit non-zero coefficients at high-consumption quantiles during summer months).

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