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WORKING PAPER

Outside the Comfort Zone: Non-Linear Link Between Energy Efficiency and Consumption

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We show that residential energy use responds non-linearly to modeled efficiency. Using about 126,000 French homes with both bill-based and model-based Energy Performance Certificates, we find that actual energy use in poorly efficient dwellings lies well below modeled need (a prebound effect), while efficient homes track more closely models. Leveraging shifts in building thermal norms as quasi-exogenous variation in modeled need, we estimate local energy efficiency-elasticities. In inefficient homes, shallow upgrades mainly relax comfort constraints ; deep renovations deliver measurable savings. Recognizing these non-linear behavioral responses is essential for evaluating retrofit benefits and setting renovation thresholds.

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KEYWORDS

Energy efficiency | Energy consumption | Rebound effect | Prebound effect | Residential sector

Executive summary

Energy retrofits are central to Europe's decarbonization plans. Energy Performance Certificates (EPCs) have been made mandatory to inform households about energy efficiency levels, and policies to stimulate energy retrofits have widespread. Yet, evaluations of renovation programs have contrasted results, several pointing realized savings that fall short of modeled projections, a phenomenon labelled as "energy performance gap." This paper quantifies the behavioral component of that gap in French housing. Using about 126,000 dwellings that have both a bill-based EPC (pre-2021) and a model-based EPC (post-2021, 3CL), we estimate how actual energy use responds to modeled energy need. While in the literature most rebound evidence infers behavior from price elasticities, we directly estimate local energy efficiency–elasticities with a credible identification strategy that relies on shifts in national thermal norms. We document that behavioral responses vary sharply with initial efficiency, a key input for fair and effective retrofit policy. We show that the energy efficiency-elasticity of consumption is strongly non-linear: in inefficient homes, efficiency gains are largely spent on comfort catch-up (prebound), while in efficient homes they translate mostly into savings.

Key Findings

- Prebound dominates in inefficient homes: in the least efficient decile, actual use is about 49% below modeled need. Modeled savings from a marginal reduction in energy needs are offset at 90% by the behavioral adjustment.
- Efficient homes track models. In mid-to-high-efficiency homes, the rebound effect remains below one third: modeled gains mostly materialize as energy savings.
- Instrumental variables (IV) design strengthens non-linearity evidence. Relative to OLS, the IV estimate raises the elasticity level and makes curvature more negative (concavity stronger), confirming endogeneity in naive estimates.
- Prebound is stronger in low-income areas, even though houses are bigger in high-income areas (offering thus more options for selective heating). Heating restraint in inefficient homes is stronger among poorer households.

Policy Implications

1. Use modeled final energy need, and not primary-energy/m² labels, for performance measure and targeting.
2. Measure performance pre/post retrofit (modeled need), and not consumption alone, to separate comfort catch-up from quality shortfalls.
3. Prioritize deep renovations in inefficient homes to yield energy savings; shallow upgrades mostly raise comfort.
4. Pair targeting with income-sensitive support to reduce cold-home risks and address distributional concerns.

1 Introduction

Since Fowlie et al. (2018), the effectiveness of energy retrofits in achieving actual savings has come under scrutiny. Engineering models predict sizable reductions in consumption, yet evaluations often find modest gains (Zivin and Novan, 2016; Baba Moussa et al., 2025). The canonical explanation for this "energy performance gap" is rebound: efficiency lowers the cost of energy services and raises use among households (Jevons, 1865; Khazzoom, 1980). For housing, Galvin and Sunikka-Blank (2016) distinguishes two cases behind this mechanism: rebound, when improved efficiency enables households to consume beyond a modeled basic need, and prebound, when initial consumption falls below that need and improved efficiency permits catch-up toward it.

Most estimates of the rebound effect (see review by Schütt et al., 2025) rely on the price elasticity of energy consumption, due to limited data on energy performance. This strategy comes at the cost of confounding users' behavioral responses with structural constraints due to home characteristics (Sorrell and Dimitropoulos, 2008; Hache et al., 2017; Belaïd et al., 2018). Few studies directly estimate the energy efficiency-elasticity of consumption, which is a measure better suited for understanding behavioral effects.

We estimate such an elasticity for the French residential sector using a dataset of more than 126,000 houses. We compare actual energy consumption (from bills) with modeled need (from a thermal model) and document a strongly non-linear relationship. In low-efficiency homes, actual use lies well below modeled need, consistent with the prebound hypothesis, while responsiveness rises with efficiency. This challenges the common assumption of constant energy efficiency-elasticity of consumption. Identification relies on an instrumental variables (IV) strategy that instruments modeled need with construction period dummies, capturing exogenous shifts from successive thermal regulations (Laprie, 2024). Our results indicate that shallow retrofits mainly relax comfort constraints in inefficient homes, and that deep renovations are required for energy savings.

2 Data

Following a 2002 European directive, France requires an Energy Performance Certificate (EPC) when renting or selling a dwelling. Until mid-2021, French EPCs were either model-based (3CL thermal method, estimating energy needs to maintain a 19°C indoor temperature, along with hot water and lighting year-round) or bill-based (previous 12 months of consumption). Both report kWh/m^2 (primary)[1]. We analyze final energy consumption as the dependent variable. EPC labels are expressed in primary energy per m^2, which does not map one-to-one to final modeled need; we focus on final energy because it is the quantity households pay and decide on.

[1]See Ministère de la Transition Écologique (2024) for EPC policy details.

The 2021 Climate and Resilience Law banned bill-based EPCs (due to their dependence on occupant behavior) and required their renewal using the 3CL model. We exploit this change to assemble a dataset of 126,749 houses with both a pre-2021 bill-based EPC (2013–2021) and a post-2021 model-based EPC (2021–2024). Records from the French national energy agency[2] are matched on geographic coordinates. Table I reports descriptive statistics.

Post-2021 EPCs provide modeled final energy need and dwelling characteristics (floor area, number of floors, construction period, heating energy mix). Multiple heating sources are common, with separate systems for hot water and specific uses. Pre-2021 EPCs report annual final energy use from bills. We construct a house-specific price index by weighting fuel prices by each fuel's share in modeled need and using prices in the 12 months preceding the pre-2021 EPC.[3]

To capture socioeconomic and climatic heterogeneity, we add municipal median income (proxy for household income across France's 36,000 communes) and department-year heating degree days (HDD), a key predictor of residential use (Bruguet et al., 2025). Although occupancy and household size are unavailable (a standard limitation), the structural and contextual variables explain substantial variation in consumption.

Figures 1 and 2 summarize the relationship between modeled and actual use. Figure 1 shows wide dispersion around the 45° line, indicating substantial heterogeneity for similar modeled needs. Figure 2 bins modeled need and plots mean actual use, revealing a non-linear pattern: consumption rises less than proportionally, motivating our quadratic specification. The histogram in the background shows EPC classes, which are based on normalized primary energy per m^2; their distribution does not align exactly with final modeled need, reinforcing our choice of final consumption as the suitable dependent variable.

3 Empirical approach

Let C_i be the annual final energy consumption of house i, and N_i its modeled energy need (3CL). We estimate

$$\log C_i = \alpha + \beta_1 \cdot \log N_i + \beta_2 \cdot (\log N_i)^2 + \gamma \cdot Z_i + e_i, \qquad (1)$$

where Z_i includes floor area, number of floors, the house-specific energy price index, heating degree days, municipal median income, the main heating energy type, and the time elapsed between the two EPCs[4]. Coefficients on logged regressors are elasticities. Figure 2

[2] ADEME (2025).

[3] Price series: Service des Données et Études Statistiques (SDES) (2025).

[4] Dummies enter in levels; continuous variables in logs.

indicates a less-than-proportional rise of actual use with modeled need. The quadratic term allows the energy efficiency-elasticity to vary along the performance spectrum rather than remain constant.

Modeled need may be endogenous: households facing high bills could retrofit before the post-2021 EPC, reducing N_i while leaving earlier billed use unchanged, biasing OLS estimation. We therefore use an instrumental variables (IV) strategy with construction period dummies as instruments for $\log N_i$ and $(\log N_i)^2$. These periods trace major shifts in French thermal regulations that tightened insulation standards (Laprie, 2024). Because construction year is fixed and regulatory changes are exogenous, the instruments shift modeled need but, conditional on Z_i, affect actual consumption only through efficiency.

The local energy efficiency-elasticity is thus

$$\varepsilon(N_i) \equiv \frac{\partial \log C_i}{\partial \log N_i} = \beta_1 + 2\beta_2 \log N_i. \tag{2}$$

For a marginal efficiency improvement (a decrease in N_i), the realized share of modeled savings is $\varepsilon(N_i)$; the unrealized share is $1 - \varepsilon(N_i)$. We classify this unrealized share as prebound when the implied adjustment moves actual use toward the modeled basic need, and as rebound when it implies use above that need.

4 Results and Discussion

4.1 IV estimation

Table II reports OLS and IV results. Construction-period dummies are highly relevant instruments for $\log N_i$ and $(\log N_i)^2$ (first-stage $F > 1,000$). Exogeneity of OLS is strongly rejected (Wu–Hausman $p < 2 \times 10^{-16}$), and overidentification restrictions are not rejected (Sargan $p = 0.97$).

IV alters both the level and the curvature of the relationship. Relative to OLS, the linear coefficient on $\log N_i$ is significantly larger while the quadratic coefficient is more negative, implying a higher energy efficiency-elasticity at the mean and stronger concavity. Thus, the IV estimates point to a strongly non-linear link between modeled need and actual use. The negative coefficient on $(\log N_i)^2$ implies that local elasticity declines when modeled need rises; in inefficient dwellings, further increases in N_i translate into relatively small rises in use, consistent with budget-driven heating restraint.

Estimated coefficients for control variables are consistent across different models and match expectations. Price elasticity is significant and negative (–0.77), indicating that households reduce consumption when energy prices rise. This aligns with long-run cross-sectional estimates (Auray et al., 2019; Miller and Alberini, 2016; Labandeira et al., 2017). Surface area shows a positive yet below one elasticity (0.63), indicating economies of scale in heating or selective space use. The slightly negative impact of the number of floors may reflect more compact layouts or targeted heating. Climate, represented by heating degree days, is positively linked to consumption. Finally, municipal median income shows a positive correlation with consumption (0.22), consistent with increased comfort demand in wealthier areas (Csereklyei, 2020). The minor positive effect of the time elapsed between EPCs may indicate a potential for renovation. Fixed effects for the main heating energy source control for structural differences in technology usage patterns.

4.2 Local energy efficiency-elasticities

Figure 3 has two panels. The top panel shows, by decile of modeled need, the relative gap between IV-predicted use and modeled need. The bottom panel reports the local energy efficiency-elasticity ε and the corresponding unrealized share of modeled savings $1-\varepsilon$ (our rebound/prebound metric, following Sorrell and Dimitropoulos 2008). We compute ε from the IV coefficients and evaluate it by decile; deciles are ordered so that D10 denotes the least efficient homes (highest modeled need) and D1 the most efficient ones.

The pattern is asymmetric. In high to mid-efficiency dwellings (D1–D5), IV-predicted use is close to or slightly above modeled need (up to +16%), so efficiency gains largely convert into savings; unrealized shares are below one third. Moving toward less efficient dwellings, gaps turn strongly negative: in D10, IV-predicted use is 49% below modeled need (consistent with the pattern observed in Figure 2) and the unrealized share when need falls is about 90%. This indicates pronounced prebound: actual use lies below modeled need and efficiency improvements are mainly spent on comfort catch-up.

To probe the mechanism, Figure 4 contrasts municipalities in the top and bottom 5% of median income. Climate exposure (HDD) is similar across groups; homes in the higher-income municipalities are larger on average (117 vs. 91 m^2), allowing more selective heating. Yet, for a given modeled need, homes in higher-income areas consume more, supporting the interpretation that budget constraints drive heating restraint, a key mechanism behind prebound.

5 Conclusion

We document a strongly non-linear relationship between energy efficiency and consumption: IV estimates indicate that prebound dominates rebound. In poorly efficient, and often low-income, homes, efficiency gains are largely absorbed as comfort catch-up rather than realized as savings. To achieve energy savings while addressing distributional concerns, policy-makers should prioritize deep renovations in inefficient dwellings over shallow upgrades.

Figures

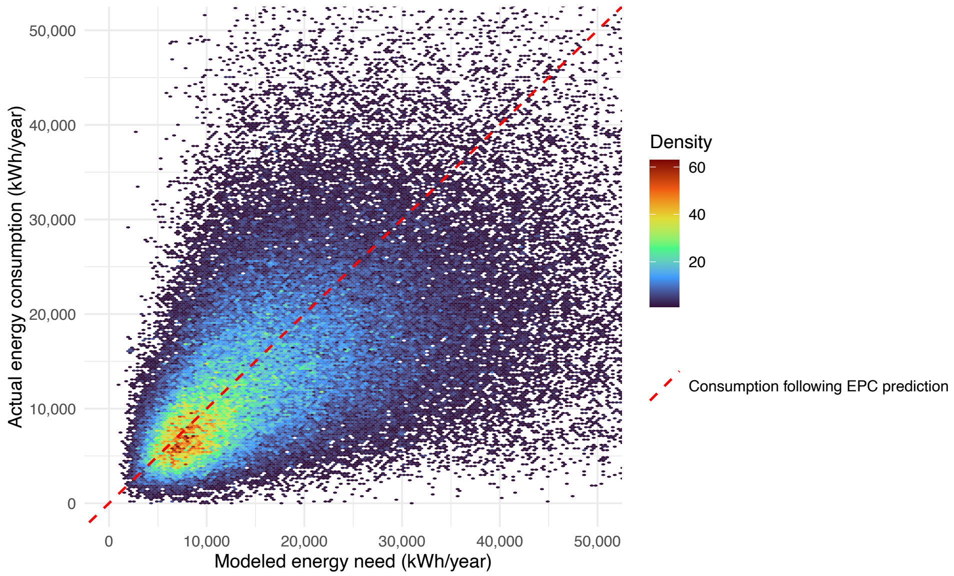

Figure 1: Heatmap of Actual vs. Modeled Energy Use

Note: This figure plots actual residential energy use (y-axis) versus modeled energy needs (x-axis) for all homes in the sample. Colors represent observation density, from low (blue) to high (red). The red dashed line represents the 45° "no-gap" line where actual consumption equals modeled consumption. Authors' calculations using French EPC microdata from ADEME.

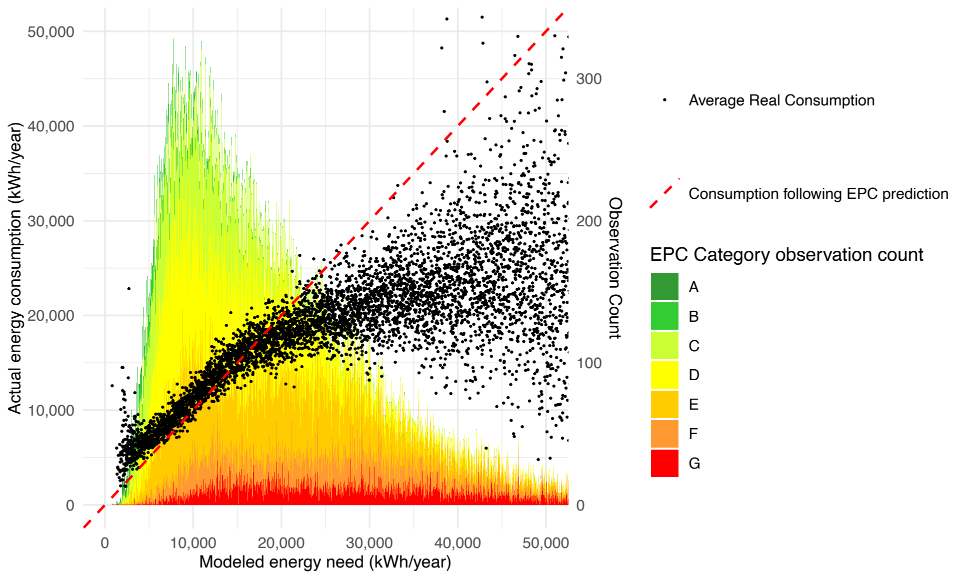

Figure 2: Average Actual Energy Use by Modeled Energy Need

Note: This figure plots average actual energy consumption (black points) against modeled energy need, calculated in 10 kWh/year bins. The red dashed line is the 45° "no-gap" line where actual equals modeled consumption. The colored background histogram displays the distribution of EPC categories (from A to G) by the same bins of modeled need. Authors' calculations using French EPC microdata from ADEME.

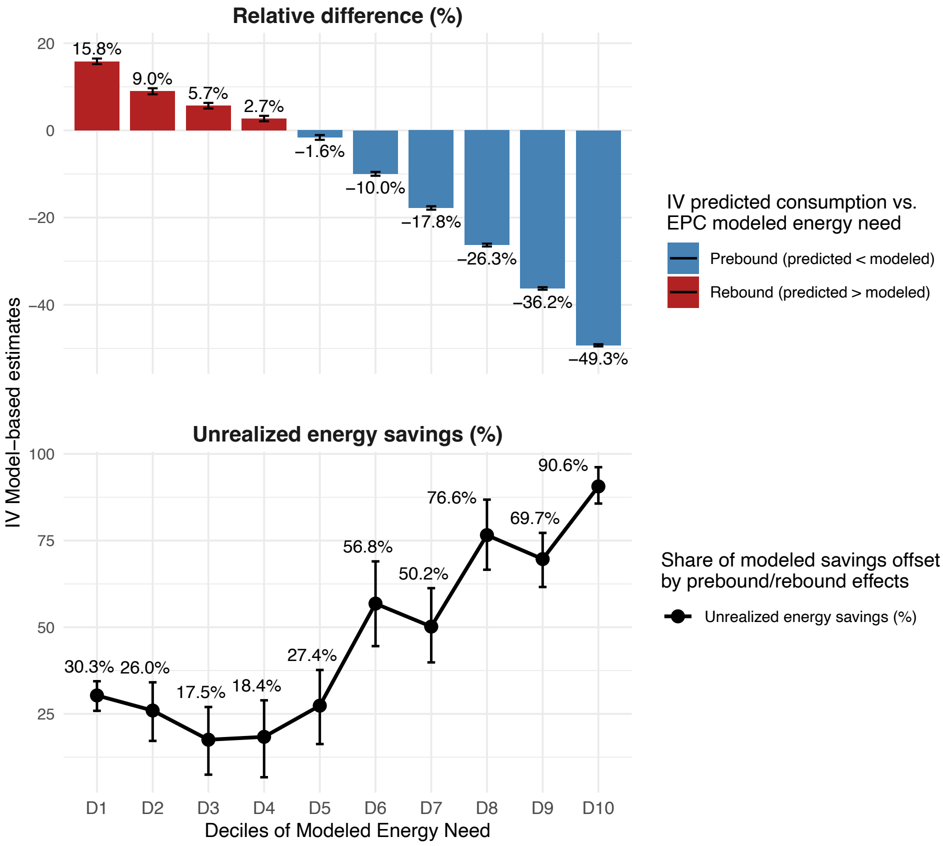

Figure 3: Unrealized Modeled Savings by Efficiency Decile

Note: This figure shows the relationship between modeled and IV-predicted energy use across deciles of modeled energy need in our sample (D1 = most efficient, D10 = least efficient). Upper panel (bars) reports the mean relative difference between IV-predicted use and EPC-modeled need. Lower panel (dots) displays the share of modeled savings that are not realized as actual savings when modeled need decreases. Unrealized savings are computed as one minus the local IV-based elasticity of actual use with respect to modeled need. Whiskers in both panels indicate bootstrapped 95% confidence intervals. Authors' calculations using French EPC microdata from ADEME.

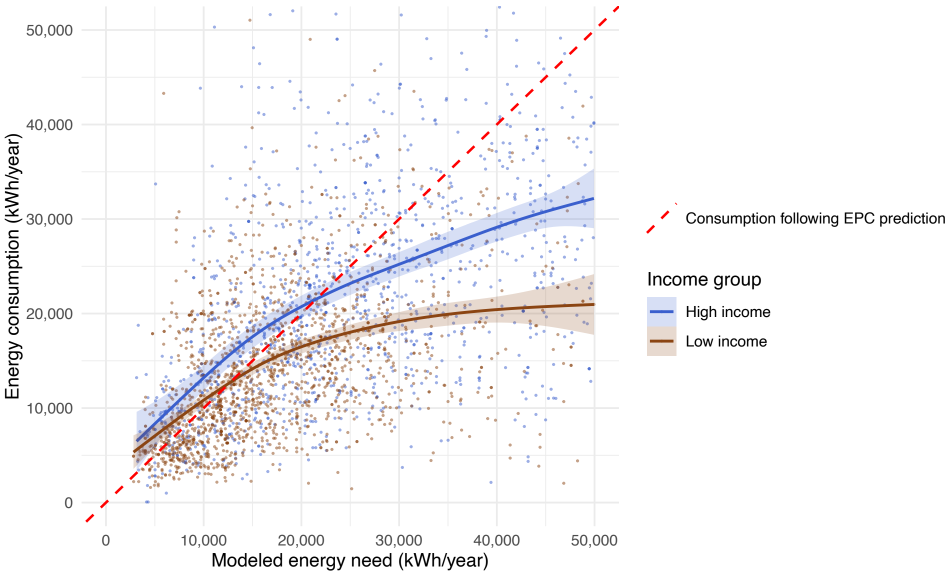

Figure 4: Actual vs. Modeled Energy Use by Municipal Income Group

Note: This figure shows average actual energy use compared to modeled energy need for households in municipalities where residents' median incomes are in the top and bottom 5% of our sample. Solid lines are generalized additive model (GAM) fits with 95% confidence bands; the red dashed line is the 45° "no-gap" line where actual use equals modeled need. Authors' calculations using French EPC microdata from ADEME.

Tables

Table I: Summary Statistics

Variable	Level / Statistic	Value
EPC label (post 2021)	A	231 (0.2%)
	B	3,299 (2.6%)
	C	23,573 (18.6%)
	D	37,974 (30.1%)
	E	34,961 (27.5%)
	F	16,394 (12.9%)
	G	10,317 (8.1%)
Energy consumption (kWh/year)	Mean (SD)	15,970 (9,847)
	Q1 – Median – Q3	8,628 – 13,963 – 21,038
Modeled Energy Need (kWh/year)	Mean (SD)	19,803 (13,002)
	Q1 – Median – Q3	10,319 – 16,585 – 25,768
Surface area (m^2)	Mean (SD)	97.2 (35)
	Q1 – Median – Q3	73.6 – 91 – 114.3
Main heating energy	Natural gas	58,188 (46%)
	Electricity	48,164 (37.9%)
	Domestic fuel oil	10,979 (8.6%)
	Wood logs	5,681 (4.5%)
	Wood pellets	2,385 (1.9%)
	Industrial wood chips	10 (0%)
	Forest wood chips	22 (0%)
	Butane	7 (0%)
	Coal	169 (0.1%)
	LPG	797 (0.6%)
	Propane	190 (0.1%)
	District heating	157 (0.1%)
Household-specific energy price (ct€/kWh)	Mean (SD)	11 (4)
	Q1 – Median – Q3	7.7 – 8.8 – 15.8
Number of floors	Mean (SD)	1.9 (0.8)
	Q1 – Median – Q3	1 – 2 – 2
Heating Degree Days (°C.days)	Mean (SD)	1,910 (322)
	Q1 – Median – Q3	1,714 – 1,933 – 2,077
Municipal median income (€)	Mean (SD)	20,182 (3,372)
	Q1 – Median – Q3	18,027 – 19,557 – 21,568
Time between EPCs (years)	Mean (SD)	5.3 (2.5)
	Q1 – Median – Q3	3.3 – 5.3 – 7.3
Construction period	Before 1948	84,902 (67%)
	1948–1974	26,432 (20.8%)
	1975–1977	1,700 (1.3%)
	1978–1982	2,552 (2.0%)
	1983–1988	2,236 (1.8%)
	1989–2000	3,883 (3.1%)
	2001–2005	1,883 (1.5%)
	2006–2012	3,161 (2.5%)

Note: This table reports descriptive statistics for the sample of 126,749 houses with both a pre-2021 EPC based on actual energy bills and a post-2021 EPC computed with the 3CL thermal model. Actual consumption and modeled need are in final energy; EPC labels are in primary energy/m^2. Records were matched on identical geographic coordinates; duplicates are dropped by keeping the closest date pair. Authors' calculations using French EPC microdata from ADEME.

Table II: OLS and IV Estimates

	Dependent variable: log(Energy consumption)	
	(1) – *OLS*	(2) – *IV*
log(Modeled energy need)	0.537***	1.738***
	(0.045)	(0.604)
log(Modeled energy need)^2	−0.024***	−0.090***
	(0.002)	(0.031)
log(House-specific energy price)	−0.736***	−0.775***
	(0.009)	(0.019)
log(Surface area)	0.570***	0.632***
	(0.004)	(0.011)
log(Heating Degree Days)	0.249***	0.273***
	(0.007)	(0.011)
Number of floors	−0.020***	−0.028***
	(0.002)	(0.002)
log(Municipal median income)	0.204***	0.221***
	(0.008)	(0.009)
log(Years elapsed between EPCs)	0.019***	0.010***
	(0.002)	(0.002)
Constant	1.796***	−4.084
	(0.242)	(2.942)
Main heating energy type	Yes	Yes
Observations	126,749	126,749
R^2	0.540	0.533
Adjusted R^2	0.540	0.533
Residual Std. Error (df = 126,729)	0.441	0.444
F Statistic	7,832.389***	
IV Diagnostic tests		
• First-stage F-stat. *log(Modeled energy need)*		1,031.087***
• First-stage F-stat. *log(Modeled energy need)^2*		1,033.619***
• Wu-Hausman statistic		36.999***
• Sargan statistic		0.948

Note: This table reports coefficients from ordinary least squares (OLS) and instrumental variables (IV) regressions of the logarithm of actual final energy consumption on modeled energy need and dwelling, climate, and socioeconomic controls. The dependent variable is the logarithm of annual final energy consumption in kWh. The IV specification instruments for both the linear and quadratic terms in modeled energy need using construction period dummies, with first-stage F-statistics reported at the bottom of the table. All regressions control for main heating energy type. Robust standard errors are shown in parentheses. Statistical significance is denoted by *p<0.1, **p<0.05, ***p<0.01. Authors' calculations using French EPC microdata from ADEME.

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