The Direct Rebound effect: People are living in the House.

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Introduction

Residential sector in developped countries :

- 45% of energy consumption
- 30% of GHG emissions

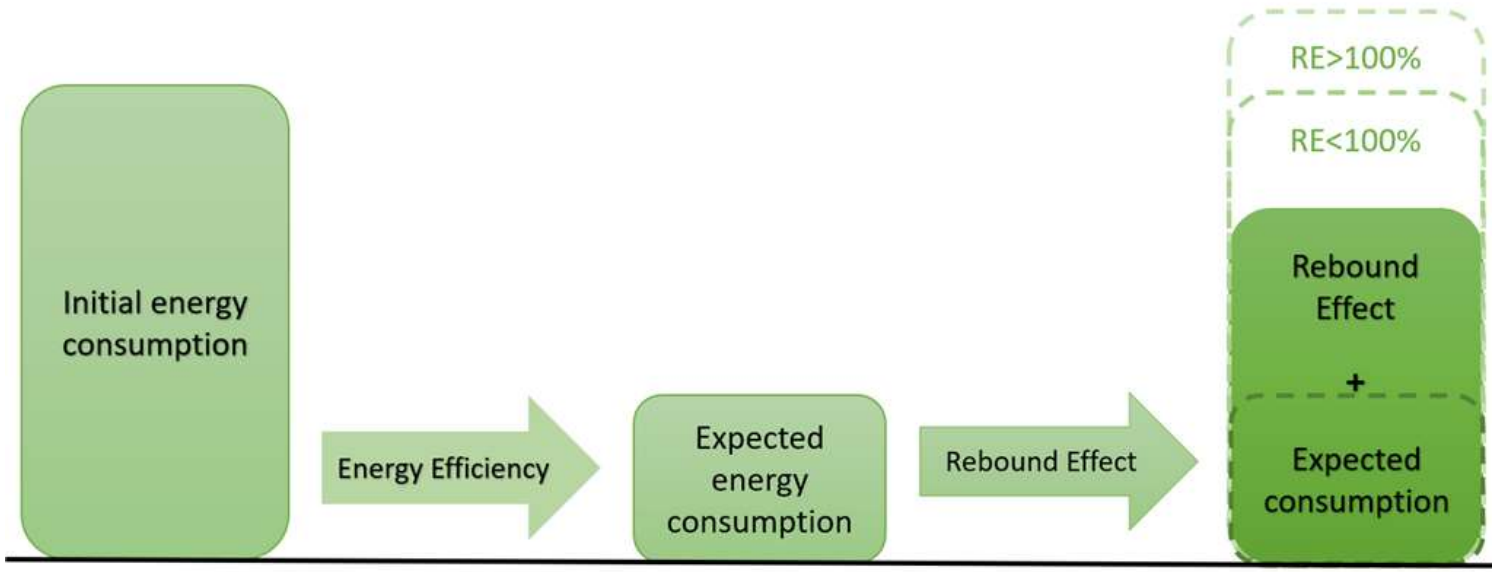
New Energy Efficiency Policies (in France) :

- Subsidies for energy efficiency - MaPrimeRénov 2022 ; White Certificat
- More restrictive buildings obligation - Thermal Regulation since 1972 ; new obligation regarding the Energy Performance Certificat (EPC)

Introduction

The impact of Energy Efficiency Improvement is ambigus :

- Governement expectation : EEI lead to the expected decrease in consumption
- Reality : EEI might lead to a reoptimization process of household. Actual consumption might be higher than expected - Rebound Effect (Jevons, 1866 ; Khazzoom, 1980 ; Chan and Gillingham, 2015)
  - $\nearrow$ energy efficiency $\Rightarrow$ $\searrow$ energy service price $\Rightarrow$ $\nearrow$ energy consumption



Research Statement

This paper examines :

- If energy efficiency improvement reduces energy consumption
- The intensity of the rebound effect
- If the rebound effect is homogeneous over the conditional distribution of the consumption

Why is this important :

- Ensuring the effectiveness of public policies

Relation to the Literature

Literature Gap

- Rebound effect between 5% and 60% (Sorrell and Dimitropoulos, 2008)
  - backfire effect (Du et al., 2021 ; Jafari et al., 2022)
  - no evidence of RE (Davis, 2008)

- Price elasticity vs Efficiency elasticity (Sorrell et al., 2009)
  - most paper assumption : similar reaction price decrease and EEI
  - Bounded rationality $\Rightarrow$ reaction is not similar (Linares and Labandeira, 2010) $\Rightarrow$ use of predicted energy consumption (EPC)

- Homogeneity vs Heterogeneity of the Rebound effect
  - Heterogeneity depending on the consumption level (Sorrell, 2018)
  - Heterogeneity depending on the energy-mix

- Households habits (Santarius and Soland, 2018)

Contents

Data

Cross-sectional data from the PHEBUS survey (2013) - Representative sample of the French market

Volet Clode : 5000 households

- Energy Consumption from bills / Actual Consumption
  - Overall
  - Gas
  - Electricity

Volet DPE : 2000 households

- Energy Performance Certificate / Predicted Consumption
  - Overall
  - Gas
  - Electricity

Control variables : Household characteristics (Number of children ; Age) - Household Habits (preference ; heating behavior) - Dwelling equipment - Dwelling Characteristics that are not including in the EPC.

Summary Statistics

	Overall	Gas	Electricity	t- test
Actual consumption	29,245	15,027	26,544	5.92***
Predicted Consumption	29,393	21,046	27,744	-9.2***
Income	40,045	42216.82	39983.82	-1.6*
Number of children	0.82	0.97	0.75	-3.6***
Durable Goods	2.09	2.07	2.09	1.43*
Index	1.039	1.025	1.04	1.15
Heating regulator	0.4856	0.66	0.33	-12.67***
Average time in home	1.59	1.63	1.64	0.162
Age	56.19	55.1	54.81	-0.35
Preference for comfort	2.116	2.13	2.21	1.05
Never lower heating in bedroom	0.33	0.34	0.31	-1.16
Auxiliary heater	0.345	0.23	0.37	5.37***

t-test refers to difference in means between the characteristics of gas and electricity sub-sample.
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table – Summary Statistics

Methodology

First step, model based on Aydin et al (2017) $\Rightarrow$ we use a log-log specification to estimate the efficiency elasticity.
Formally :

$$ln\left(T_i^a\right) = \beta_0 + \beta_1 ln\left(T_i^p\right) + \sum_{j=2}^{j} \beta_j Z_i + \epsilon_i$$

T_i^a the real energy consumption and T_i^p the predicted consumption
Z_i all the other control variables

The rebound effect is then equal to : $RE = 1 - \frac{\partial(T^a)}{\partial(T^p)}$

Methodology

Two issues we have to face :

- Endogeneity issue related to reverse causality - measurement errors (Engineer literature : 8%)
- Heterogeneity in the rebound effect

To overpass those issues, we use :

- IV-strategy :
  - Instrument : Thermal Regulation applied at the year of construction and wall thermal value (Aydin et al., 2017 ; Khayatian et al., 2016).
- Quantile-regression

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Results

OLS Regression

VARIABLES	(1) TOTAL	(2) GAS	(3) ELECTRICITY
Rebound Effect	0.585***	0.419***	0.54***
	(0.0268)	(0.0391)	(0.0407)
Income (log)	0.135***	0.171***	0.114***
	(0.0269)	(0.0430)	(0.0368)
Renter (1=yes)	-0.0612*	-0.0584	-0.0129
	(0.0343)	(0.0483)	(0.0567)
Average occupation time	-0.0971***	-0.0720**	-0.102***
	(0.0183)	(0.0279)	(0.0315)
Number of Children (log)	0.154***	0.0760	0.215***
	(0.0359)	(0.0506)	(0.0673)
AGE	-0.00112	0.00477***	-0.000288
	(0.00113)	(0.00168)	(0.00177)
Durable Goods (electronic) (log)	0.327***	0.347*	0.352**
	(0.100)	(0.186)	(0.140)
index	0.409***	0.317***	0.362***
	(0.0531)	(0.0825)	(0.0821)
Comfort Preference	0.0231***	0.0245*	0.0569***
	(0.00875)	(0.0144)	(0.0148)
Heating Regulator (1=yes)	0.0366	0.0680	0.129***
	(0.0268)	(0.0424)	(0.0441)
Never lower heating bedroom (1=yes)	0.0928***	0.0704*	0.108**
	(0.0263)	(0.0418)	(0.0452)
Auxiliary heaters (1=yes)	0.128***	-0.127***	-0.0316
	(0.0293)	(0.0472)	(0.0461)
Constant	3.904***	1.165**	3.518***
	(0.336)	(0.509)	(0.493)
Observations	1,831	637	672
R-squared	0.421	0.570	0.433

Notes :
Dependent variable : log(Actual Consumption).
Rebound Effect $= 1 - \log(\text{Predicted Consumption})$.
Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Results

IV-Regression

VARIABLES	(1) TOTAL	(2) GAS	(3) ELECTRICITY
Rebound Effect	0.774***	0.568***	0.719**
	(0.0726)	(0.0917)	(0.131)
Income (log)	0.161***	0.211***	0.151***
	(0.0288)	(0.0469)	(0.0472)
Renter (1=yes)	-0.0942**	-0.0896*	-0.0122
	(0.0387)	(0.0524)	(0.0589)
Average occupation time	-0.0958***	-0.0842***	-0.0952***
	(0.0187)	(0.0312)	(0.0323)
Number of Children (log)	0.168***	0.0764	0.234***
	(0.0383)	(0.0505)	(0.0690)
AGE	0.000363	0.00514***	0.00119
	(0.00140)	(0.00168)	(0.00217)
Durable Goods (electronic) (log)	0.386***	0.364**	0.408***
	(0.102)	(0.180)	(0.151)
index	0.427***	0.336***	0.373***
	(0.0505)	(0.0844)	(0.0775)
Comfort Preference	0.0196**	0.0250*	0.0540***
	(0.00917)	(0.0144)	(0.0152)
Heating Regulator (1=yes)	0.0111	0.0631	0.114***
	(0.0286)	(0.0424)	(0.0433)
Never lower heating bedroom (1=yes)	0.0903***	0.0813*	0.101**
	(0.0271)	(0.0426)	(0.0470)
Auxiliary heaters (1=yes)	0.168***	-0.128***	-0.0218
	(0.0313)	(0.0458)	(0.0441)
Constant	5.410***	2.172***	4.791***
	(0.659)	(0.781)	(1.047)
Endogeneity test	13.21***	5.42**	3.6*
Fstat	95.46***	64.18***	26.69***
Over-identification test	2.15	0.498	2.46
Observations	1,831	637	672
R-squared	0.388	0.554	0.391

Notes :
Dependent variable : log(Actual Consumption).
Rebound Effect $= 1 - \log$(Predicted Consumption).
Predicted Electricity Consumption is instrumented by the Thermal Regulation at the year of construction and the Thermal Coefficient.
Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Results

IV-Quantile Regression - Gas

	(1) 15^{th}	(2) 25^{th}	(3) 50^{th}	(4) 75^{th}	(5) 85^{th}	(6) 90^{th}
Rebound Effect	0.615***	0.689**	0.58***	0.534***	0.483***	0.461***
	(0.138)	(0.148)	(0.0922)	(0.111)	(0.104)	(0.0884)
Income (log)	0.221***	0.272***	0.236***	0.179***	0.141**	0.116*
	(0.0700)	(0.0765)	(0.0502)	(0.0555)	(0.0605)	(0.0652)
Renter (1=yes)	-0.106	-0.0499	-0.0532	-0.139**	-0.0946	-0.0693
	(0.0736)	(0.0843)	(0.0546)	(0.0642)	(0.0955)	(0.101)
Average occupation time	-0.132***	-0.108**	-0.0874***	-0.0597*	-0.0465	-0.0314
	(0.0476)	(0.0475)	(0.0333)	(0.0343)	(0.0310)	(0.0300)
Number of Children (log)	0.127**	0.0848	0.0382	0.0385	0.0758	0.0945
	(0.0508)	(0.0537)	(0.0678)	(0.0697)	(0.0640)	(0.0661)
AGE	0.00608**	0.00707***	0.00433**	0.00374**	0.00385**	0.00436**
	(0.00252)	(0.00253)	(0.00220)	(0.00183)	(0.00186)	(0.00189)
Durable Goods (electronic) (log)	0.401	0.483**	0.353*	0.282	0.403*	0.395*
	(0.300)	(0.217)	(0.208)	(0.288)	(0.238)	(0.218)
Index	0.478***	0.416***	0.243**	0.238**	0.254**	0.265**
	(0.105)	(0.101)	(0.117)	(0.105)	(0.115)	(0.117)
Comfort Preference	0.0356	0.0283	0.0207	0.0219	0.0236	0.0331*
	(0.0220)	(0.0226)	(0.0145)	(0.0156)	(0.0170)	(0.0177)
Heating Regulator (1=yes)	0.0720	0.0640	0.0564	0.0144	0.0456	0.0382
	(0.0596)	(0.0545)	(0.0577)	(0.0487)	(0.0515)	(0.0561)
Never lower heating bedroom (1=yes)	0.101*	0.0929*	0.0707	0.0575	0.118**	0.121**
	(0.0565)	(0.0484)	(0.0497)	(0.0531)	(0.0559)	(0.0515)
Auxiliary heaters (1=yes)	-0.0773	-0.0357	-0.103**	-0.118***	-0.146***	-0.147***
	(0.0769)	(0.0541)	(0.0486)	(0.0444)	(0.0496)	(0.0516)
Constant	1.911	2.159*	2.207***	2.906***	2.563***	2.605***
	(1.197)	(1.157)	(0.764)	(0.922)	(0.864)	(0.988)
Observations	637	637	637	637	637	637

Notes :
Dependent variable : log(Actual Gas Consumption).
Rebound Effect $= 1 -$ log(Predicted Consumption).
Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Results

IV-Quantile Regression - Electricity

	(1) 15^{th}	(2) 25^{th}	(3) 50^{th}	(4) 75^{th}	(5) 85^{th}	(6) 90^{th}
Rebound Effect	0.736**	0.67*	0.604**	0.705*	0.756*	0.772**
	(0.122)	(0.184)	(0.171)	(0.168)	(0.124)	(0.115)
Income (log)	0.163**	0.174*	0.141***	0.128***	0.136***	0.141***
	(0.0684)	(0.0915)	(0.0518)	(0.0488)	(0.0457)	(0.0424)
Renter (1=yes)	-0.0352	-0.0394	-0.00254	-0.0262	-0.0540	-0.0624
	(0.0824)	(0.0720)	(0.0701)	(0.0631)	(0.0554)	(0.0534)
Average occupation time	-0.143***	-0.102**	-0.0419	-0.0497	-0.0374	-0.0347
	(0.0457)	(0.0479)	(0.0418)	(0.0323)	(0.0297)	(0.0312)
Number of Children (log)	0.218***	0.194**	0.161**	0.121*	0.184**	0.235**
	(0.0815)	(0.0791)	(0.0645)	(0.0680)	(0.0893)	(0.116)
AGE	0.00169	0.00132	0.000853	-0.000534	0.000517	0.00115
	(0.00300)	(0.00338)	(0.00251)	(0.00231)	(0.00172)	(0.00161)
Durable Goods (electronic) (log)	0.516***	0.306	0.353**	0.308*	0.365*	0.432*
	(0.184)	(0.187)	(0.167)	(0.182)	(0.213)	(0.231)
Index	0.338***	0.381***	0.420***	0.385***	0.299***	0.278***
	(0.123)	(0.109)	(0.101)	(0.104)	(0.0854)	(0.0880)
Comfort Preference	0.0453*	0.0436**	0.0574***	0.0503***	0.0408**	0.0407**
	(0.0234)	(0.0203)	(0.0174)	(0.0169)	(0.0173)	(0.0173)
Heating Regulator (1=yes)	0.0738	0.0998	0.118**	0.0861*	0.0721	0.0654
	(0.0644)	(0.0645)	(0.0549)	(0.0464)	(0.0474)	(0.0492)
Never lower heating bedroom (1=yes)	0.117*	0.119*	0.112**	0.0613	0.0392	0.0425
	(0.0670)	(0.0658)	(0.0460)	(0.0556)	(0.0527)	(0.0547)
Auxiliary heaters (1=yes)	-0.0993*	-0.122*	-0.0604	0.0104	-0.00339	-0.00852
	(0.0599)	(0.0627)	(0.0585)	(0.0531)	(0.0451)	(0.0471)
Constant	4.445***	3.940***	3.731**	5.336***	5.912***	6.025***
	(0.640)	(0.917)	(1.621)	(1.622)	(1.223)	(1.076)
Observations	672	672	672	672	672	672

Notes :
Dependent variable : log(Actual Electricity Consumption).
Rebound Effect $= 1 -$ log(Predicted Consumption).
Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Results

IV-Quantile Regression - Overall

	(1) 15^{th}	(2) 25^{th}	(3) 50^{th}	(4) 75^{th}	(5) 85^{th}	(6) 90^{th}
Rebound Effect	0.807*	0.751**	0.697***	0.673***	0.725***	0.727***
	(0.104)	(0.105)	(0.0717)	(0.0757)	(0.0659)	(0.0570)
Income (log)	0.207***	0.210***	0.147***	0.141***	0.144***	0.148***
	(0.0381)	(0.0424)	(0.0352)	(0.0337)	(0.0347)	(0.0414)
Renter (1=yes)	-0.0774	-0.0627	-0.0740*	-0.0925**	-0.0939**	-0.105**
	(0.0580)	(0.0540)	(0.0395)	(0.0427)	(0.0401)	(0.0412)
Average occupation time	-0.126***	-0.119***	-0.0704***	-0.0510**	-0.0558***	-0.0519**
	(0.0265)	(0.0270)	(0.0208)	(0.0212)	(0.0215)	(0.0239)
Number of Children (log)	0.213***	0.182***	0.113***	0.111***	0.112***	0.114***
	(0.0562)	(0.0392)	(0.0374)	(0.0397)	(0.0415)	(0.0433)
AGE	0.00159	0.00198	-0.000212	-0.000527	-0.000143	0.000626
	(0.00198)	(0.00177)	(0.00128)	(0.00126)	(0.00113)	(0.00115)
Durable Goods (electronic) (log)	0.446***	0.509***	0.351***	0.335***	0.363***	0.357***
	(0.153)	(0.0910)	(0.107)	(0.0885)	(0.109)	(0.123)
Index	0.514***	0.523***	0.447***	0.295***	0.281***	0.248***
	(0.0699)	(0.0675)	(0.0534)	(0.0545)	(0.0617)	(0.0724)
Comfort Preference	0.0223*	0.0254**	0.0250**	0.0174*	0.0119	0.0213*
	(0.0133)	(0.0118)	(0.0107)	(0.00999)	(0.0109)	(0.0120)
Heating Regulator (1=yes)	-0.0101	-0.00624	-0.00761	0.0286	0.0199	0.0140
	(0.0420)	(0.0343)	(0.0281)	(0.0296)	(0.0318)	(0.0377)
Never lower heating bedroom (1=yes)	0.0947**	0.0601*	0.0659**	0.0760**	0.0596*	0.0474
	(0.0369)	(0.0362)	(0.0302)	(0.0299)	(0.0336)	(0.0344)
Auxiliary heaters (1=yes)	0.123**	0.125***	0.144***	0.151***	0.167***	0.201***
	(0.0548)	(0.0455)	(0.0292)	(0.0274)	(0.0383)	(0.0432)
Constant	4.680***	4.170***	4.834***	5.052***	5.704***	5.735***
	(0.750)	(0.748)	(0.649)	(0.782)	(0.685)	(0.568)
Observations	1,831	1,831	1,831	1,831	1,831	1,831

Notes :
Dependent variable : log(Actual Overall Consumption).
Rebound Effect $= 1 -$ log(Predicted Consumption).
Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

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Conclusion

- Rebound Effect between 0.77 and 0.46
- Rebound Effect is heterogeneous
  - Rebound effect : linear for gas -> from 0.689 to 0.461
  - Rebound effect : U-shape for electricity and overall consumption
    - Overall : From 0.8 to 0.671 to 0.727
    - Electricity : From 0.736 to 0.604 to 0.712
- Importance of consumption habits

Governements have to consider the heterogeneous effect of EEI as well as consumption habits

Thank you

Robustness

Thermal Regulation - Maximal U-value

VARIABLES	(1) TOTAL	(2) GAS	(3) ELECTRICITY
Predicted Consumption (log)	0.174**	0.404***	0.238*
	(0.0759)	(0.0948)	(0.133)
Income (log)	0.168***	0.219***	0.159***
	(0.0296)	(0.0471)	(0.0485)
Renter (1=yes)	-0.106***	-0.0957*	-0.0169
	(0.0396)	(0.0532)	(0.0596)
Average occupation time	-0.0961***	-0.0867***	-0.0938***
	(0.0190)	(0.0313)	(0.0327)
Number of Children (log)	0.172***	0.0766	0.235***
	(0.0388)	(0.0507)	(0.0692)
AGE	0.000768	0.00521***	0.00147
	(0.00142)	(0.00169)	(0.00219)
Durable Goods (electronic) (log)	0.402***	0.367**	0.423***
	(0.103)	(0.179)	(0.153)
index	0.435***	0.339***	0.379***
	(0.0510)	(0.0851)	(0.0785)
Comfort Preference	0.0183*	0.0250*	0.0524***
	(0.00939)	(0.0144)	(0.0155)
Heating Regulator (1=yes)	0.00559	0.0622	0.114***
	(0.0289)	(0.0426)	(0.0437)
Never lower heating bedroom (1=yes)	0.0902***	0.0833*	0.100**
	(0.0277)	(0.0427)	(0.0480)
Auxiliary heaters (1=yes)	0.177***	-0.129***	-0.0217
	(0.0318)	(0.0458)	(0.0445)
Constant	5.834***	2.366***	5.107***
	(0.689)	(0.802)	(1.080)
Endogeneity test	19.6159***	19.96***	5.57674**
Over-identification Test	.016586	1.90138	.783359
Fstat	84.9127***	7.21543***	25.2849 ***
Observations	1,832	637	673
R-squared	0.371	0.548	0.376

Notes :
Dependent variable : log(Actual Consumption).
Predicted Electricity Consumption is instrumented by the thermal regulation and the maximal U-value.
Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Robustness

Mean of Predicted consumption by EPC level

VARIABLES	(1) TOTAL	(2) GAS	(3) ELECTRICITY
Predicted Consumption (log)	0.226***	0.424***	0.308***
	(0.0410)	(0.0583)	(0.0769)
Income (log)	0.157***	0.213***	0.139***
	(0.0281)	(0.0450)	(0.0400)
Renter (1=yes)	-0.101***	-0.0921*	-0.0226
	(0.0372)	(0.0489)	(0.0574)
Average occupation time	-0.0996***	-0.0856***	-0.0995***
	(0.0189)	(0.0297)	(0.0318)
Number of Children (log)	0.173***	0.0770	0.231***
	(0.0372)	(0.0505)	(0.0682)
AGE	0.000482	0.00513***	0.00103
	(0.00121)	(0.00167)	(0.00197)
Durable Goods (electronic) (log)	0.384***	0.364**	0.407***
	(0.0973)	(0.179)	(0.139)
index	0.449***	0.337***	0.405***
	(0.0567)	(0.0831)	(0.0866)
Comfort Preference	0.0195**	0.0247*	0.0540***
	(0.00912)	(0.0144)	(0.0151)
Heating Regulator (1=yes)	0.0154	0.0633	0.123***
	(0.0270)	(0.0424)	(0.0436)
Never lower heating bedroom (1=yes)	0.0940***	0.0812*	0.108**
	(0.0272)	(0.0416)	(0.0467)
Auxiliary heaters (1=yes)	0.158***	-0.129***	-0.0401
	(0.0291)	(0.0460)	(0.0476)
Constant	5.431***	2.227***	4.633***
	(0.459)	(0.578)	(0.745)
Endogeneity test	63.566***	19.96***	11.1452***
Fstat	679.543***	272.687***	209.04 ***
Observations	1,839	638	676
R-squared	0.395	0.553	0.415

Notes :
Dependent variable : log(Actual Consumption).
Predicted Electricity Consumption is instrumented by the average predicted consumption by housing groups.
Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Robustness

OLS Regression with energy price

VARIABLES	TOTAL		ELEC	
Predicted Consumption (log)	0.415***	0.394***	0.460***	0.423***
	(0.0268)	(0.0260)	(0.0407)	(0.0407)
Electricity price (log)		-0.354***		-0.350***
		(0.0423)		(0.0666)
Gas price (log)				
Income (log)	0.135***	0.123***	0.114***	0.103***
	(0.0269)	(0.0258)	(0.0368)	(0.0349)
Renter (1=yes)	-0.0612*	-0.0584*	-0.0129	0.00115
	(0.0343)	(0.0326)	(0.0567)	(0.0542)
Average occupation time	-0.0971***	-0.0934***	-0.102***	-0.0926***
	(0.0183)	(0.0174)	(0.0315)	(0.0293)
Number of Children (log)	0.154***	0.148***	0.215***	0.229***
	(0.0359)	(0.0340)	(0.0673)	(0.0652)
AGE	-0.00112	-0.000684	-0.000288	-7.33e-05
	(0.00113)	(0.00108)	(0.00177)	(0.00171)
Durable Goods (electronic) (log)	0.327***	0.321***	0.352**	0.295***
	(0.100)	(0.0914)	(0.140)	(0.112)
index	0.409***	0.370***	0.362***	0.316***
	(0.0531)	(0.0507)	(0.0821)	(0.0807)
Comfort Preference	0.0231***	0.0185**	0.0569***	0.0517***
	(0.00875)	(0.00832)	(0.0148)	(0.0137)
Heating Regulator (1=yes)	0.0366	0.0498*	0.129***	0.127***
	(0.0268)	(0.0257)	(0.0441)	(0.0424)
Never lower heating bedroom (1=yes)	0.0928***	0.0973***	0.108**	0.118***
	(0.0263)	(0.0253)	(0.0452)	(0.0437)
Auxiliary heaters (1=yes)	0.128***	0.140***	-0.0316	-0.00390
	(0.0293)	(0.0283)	(0.0461)	(0.0455)
Constant	3.904***	3.552***	3.518***	3.322***
	(0.336)	(0.328)	(0.493)	(0.472)
Observations	1,839	1,839	676	676
R-squared	0.421	0.466	0.433	0.489

Notes :
Dependent variable : log(Actual Consumption).
Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

The rebound effect for residential heating (DHW & Heater) :

$$\lambda = \frac{\ln(H)}{\ln(\mu)} \tag{1}$$

H : the overall heating needed to ensure household comfort
μ : the overall efficiency of the heating system.
The heating efficiency can be expressed using the heating level achieved using one unit of energy (either electricity, gas or fuel).

$$\mu = \frac{H_r}{T^*} \tag{2}$$

It follows :

$$H = H_r(\frac{T^a}{T^*}) \tag{3}$$

using the previous equation, we can rewrite λ as :

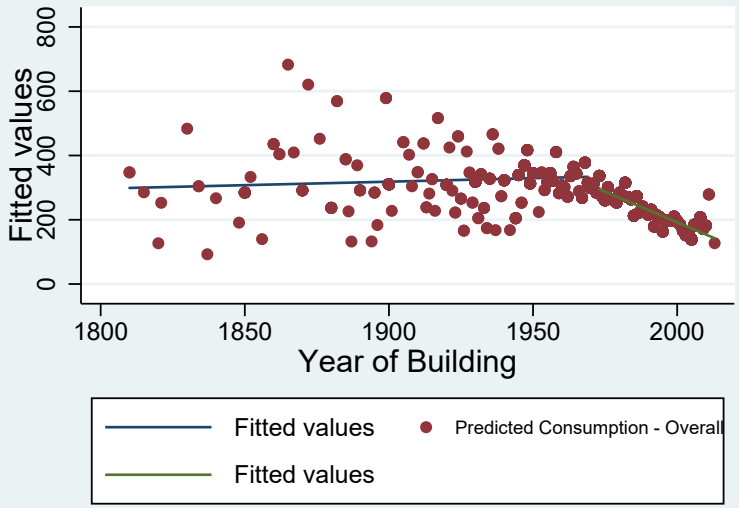
$$\lambda = \frac{\ln(H_r(T^a/T^*))}{\ln(H_r/T^*)} \tag{4}$$

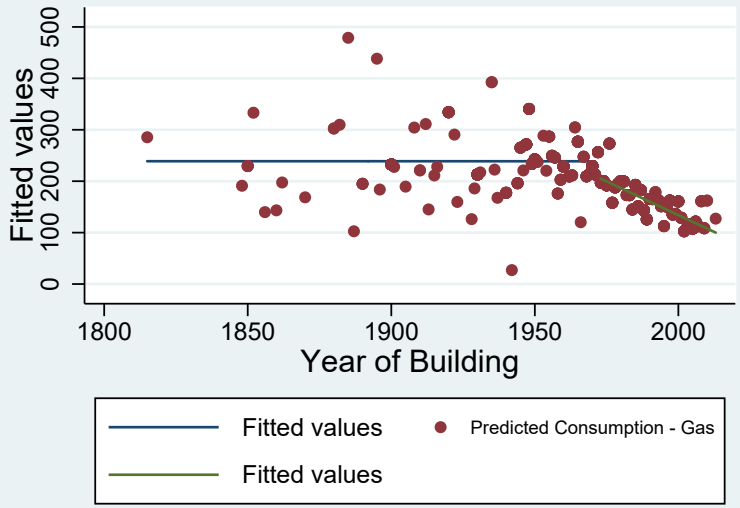
Assuming H_r fixed :

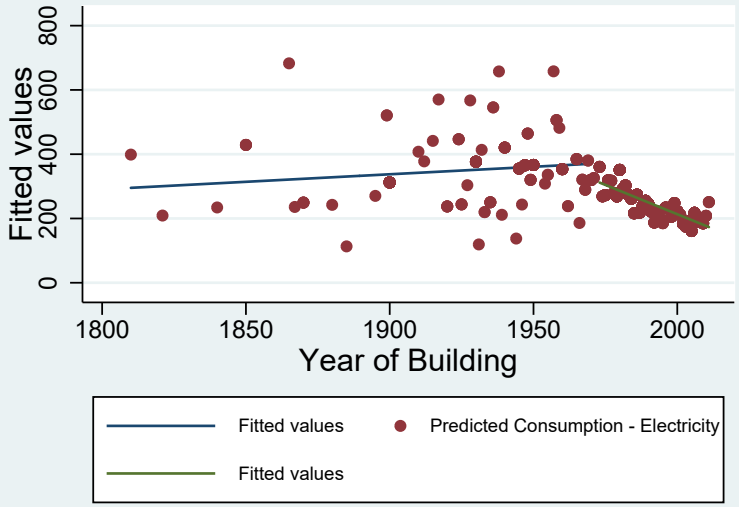
$$\lambda = 1 - \frac{\partial \ln(T^a)}{\partial \ln(T^*)} \tag{5}$$

Methodology

Measurement errors and Heterogeneity







Methodology

Measurement errors and Heterogeneity