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A green value beyond energy savings?

Capitalization of energy labels versus Techno-economic assessment of energy renovations in the French housing market.

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Abstract

While a growing number of studies evidence the existence of a green value associated to energy labels, these studies disagree on the magnitude of this green premium and lack comparison with associated renovation costs and expected savings for households. This paper investigates the green value of French houses in two areas: one urban, the Lyon metropolis, and one rural, the Brest area in Brittany. The traditional hedonic analysis of transaction prices in those regions is coupled with Geographic Information Systems to regress both on the intrinsic characteristics of dwellings and on the distance to various public amenities, such as parks, city center or public transports. Moreover, a spatial econometric model is estimated to control for neighborhood effects. Results evidence a significant green value in both areas. If relative premium is higher in Brittany, switching to absolute terms evidence tantamount green values in the two regions, about 35,000€. Using a dataset on renovation costs, I find that the green premium matches with the investment required to improve energy efficiency. Green value is then the capitalization of renovation costs. Nevertheless, the use of empirical discount rates evidenced by the economic literature suggests that this green value is significantly higher than expected savings on the energy bill. Co-benefits of a more efficient house, such as improved thermal comfort, could then be more efficient drivers of the renovation decision than usual discourse on energy savings.

Keywords: Hedonic pricing ; Green Value ; Energy efficiency ; Spatial econometrics.
JEL classification: R21; Q40; L15.

1 Introduction

Since the introduction of real estate energy labels during the last decade, economic literature has regained interest in the application of hedonic methods to the housing market. Indeed, if those labels meet their goal, namely reducing information asymmetry between buyers and sellers on energy quality of traded houses, we should be able to observe a capitalization of the energy savings associated to a 'greener' house. The Energy Performance Certificate (EPC), progressively introduced in the European Union since 2002, is especially interesting: on the contrary to Energy Star label or LEED certification in the United States, it has to be realized for any building sold or rented out. The EPC, which came into force a decade ago for most Member States, ranks houses in 7 classes, each of them identified by a letter, from A for almost zero consumption houses to G for houses energy-greedy.

Most of recent hedonic investigations have a found a significant green premium for energy-efficient buildings. In the United States, Kahn and Kok (2014) evidenced a small premium for green-labelled houses in California, and Eichholtz et al. (2010) found also increased selling prices for energy-efficient office buildings. In Europe, hedonic analyzes have been applied in several countries, estimating the sales premium at a few percents of a house price: Brounen and Kok (2011) identified a premium of 3.7% in the Netherlands, Hyland et al. (2013) found a premium of 9% in Ireland, just as Fuerst et al. (2015) in England. In Germany, Cajias and Piazolo (2013) estimated that a 1% increase in energy efficiency lead to a 0.45% increase of the market value. In France, working paper by Leboullenger et al. (2018) identifies also a premium between 1 and 3% for green houses. However those hedonic approaches of the green value lack a detailed description of associated costs and savings. Indeed the 'engineer' approach of the green value suggests that the premium should be more important, and is generally calculated in absolute terms rather than in percentage of the market value, see for instance the techno-economic optimization of renovations made by Ferrara et al. (2013) .

The present paper innovates from the existing literature on two aspects: first we analyze separately two different real estate markets, one urban (the Lyon metropolis, center of France) and one rural (the Brest region, in Brittany) with strongly different levels of prices. Second, we couple the analysis of the green premium with a dataset on renovation costs, and with a thermal model enabling the estimation of associated of energy savings. Results evidence that the 'green premium' should be considered in absolute terms rather than relative to the house price: indeed, absolute premium are closely similar in the two regions investigated, despite the important differences between each market. Moreover, if this premium corresponds to the renovation costs, suggesting that green value results from a Bertrand-type competition between sellers, it appears that this premium largely exceeds expected energy savings. This finding suggests that the green label captures many benefits derived from an energy-efficient house, beyond energy savings.

Section 2 details the hedonic method employed and the specification used for the spatial error model. Summary statistics of the datasets used are also presented: characteristics of traded houses, material and labor costs for the energy renovation and energy costs. A thermal model is also built to assess renovation costs to upgrade a house and the associated energy savings. Section 3 presents the econometric evaluation of houses prices and of the green premium. The green value of a B-labelled house compared to a F-labelled house *ceteris paribus* is estimated at 29.7% of the price in the Brest region, against 11.1% of selling price is the Lyon metropolis. In absolute terms, both green premium amounts about 34,000€. Section 4 evidences that this consistent green value in both regions corresponds to the required investments to renovate a house from the F-class to the B-class. Follows a comparison with expected energy savings: if those vary greatly with time horizon, discount rate and rebound effect, the sum of expected energy savings computed with usual discount rates elicited for households in the literature accounts for only half of the green value. Section 5 concludes with the main findings and potential extensions.

2 Data and methods

2.1 Hedonic regression and spatial error model

I use a hedonic model in order to evaluate the effect of Energy Performance Certificate on house prices. Hedonic regression is a widespread method to evaluate the drivers of complex goods pricing. Indeed, as goods with multiple and heterogeneous characteristics offer various services to consumers, pricing of a given good will then depend on the level of each service it can provide. Following the seminal contribution of Rosen (1974), this method has been extensively used to estimate the role of various characteristics in house prices, as underlined by the review of Sirmans et al. (2005). Indeed, households vary multiple intrinsic characteristics of houses (such as size, number of rooms, presence of a pool...) but also locational advantages (proximity to the city centre, to environmental amenities, attractiveness of the neighborhood...). More recently, this method is also used by the papers addressing the issue of the green value in the residential sector, see Brounen and Kok (2011), Hyland et al. (2013), Kahn and Kok (2014), Fuerst et al. (2015) or Ramos et al. (2015).

To test the impact of energy label's various classes on house prices, I regress the logarithm of transaction price on the characteristics of houses by the estimation of the following equation :

$$ln(P_i) = \alpha + \beta * X_i + \gamma * L_i + \delta * EPC_i + \xi_i \quad (1)$$

$$\xi_i = \lambda * W * \xi_i + \epsilon_i \quad (2)$$

In equation 1, P_i is the transaction price of the house. X_i and L_i are respectively vectors of intrinsic characteristics (size, number of rooms, construction period, etc.) and of locational variables (distance to city centre, to the nearest underground station, to the seaboard, etc.) of the house i. EPC_i is a categorical variable indicating to which Energy Performance Certificate class the dwelling i belongs. Those variables are either available in our transactions dataset (for X_i and EPC_i) or built using Geographic Information Systems (for L_i). α, β, γ and δ are vectors of estimated coefficients. δ is then our interest vector of coefficients. By ξ_i I specify a spatial error model (see equation 2). I build W, the spatial weights matrix, as a distance matrix to describe the pattern of spatial interactions: two transaction prices P_i and P_j will be more linked as their underlying houses i and j get geographically closer. More precisely, the the interaction coefficient between i and j will be $w_{ij} = exp(-dist_{ij})$, with $dist_{ij}$ being the geographic distance between i and j expressed in kilometers. In the hypothetical case where two houses share the exact same location, we have then $w_{ij} = 1$. The spatial weights matrix W is normalized. This spatial specification of errors in our model aims at capturing the effects of unobserved spatial variables, such as neighborhood effects.

2.2 Transaction prices, houses characteristics and geographic variables

I apply the previously detailed model over two French regions: first the Brest area in Brittany, gathering about 430,000 people over 2,100 km^2, and second the Lyon metropolis, gathering almost 1,400,000 inhabitants over 553 km^2. The '*Pays de Brest*' is then a mostly rural area, while '*Grand Lyon*' is a dense and urban area. Those two regions were specifically chosen in order to compare the green value in two real estate markets unevenly tense, but with similar heating needs. Indeed the $D_{h.ref}$, a climatic indicator which measures the number of degrees-hour needed to heat a dwelling during a year, are similar in those regions: respectively $D_{h.ref}^{Brest} = 55000$ and $D_{h.ref}^{Lyon} = 54000$, while $D_{h.ref}$ ranges from $30,000$ to $71,000$ K in France.

Another advantage of treating those areas is that their respective local authorities have made publicly available an important volume of geographic data. It enables a detailed geographic analysis of the role of various environmental and public amenities in the price formation.

Transaction details were acquired through the French association of notaries, PERVAL. Those datasets include the precise dwelling location, transaction price, and many characteristics of the house, including total floor area, garden area, number of rooms, construction period, presence of a swimming pool, presence of a parking, month of the transaction, and the Energy Performance Certificate of the dwelling. Our dataset covers 70% of the transactions realized in 2016 in the two areas of interest. Transactions of "exceptional properties", such as castles, are removed from the sample. In the end, the Brest sample gathered 1,242 houses transactions, with a mean price of 160,636€, and the Lyon one 1,094 houses transactions with a mean price of 365,481€.

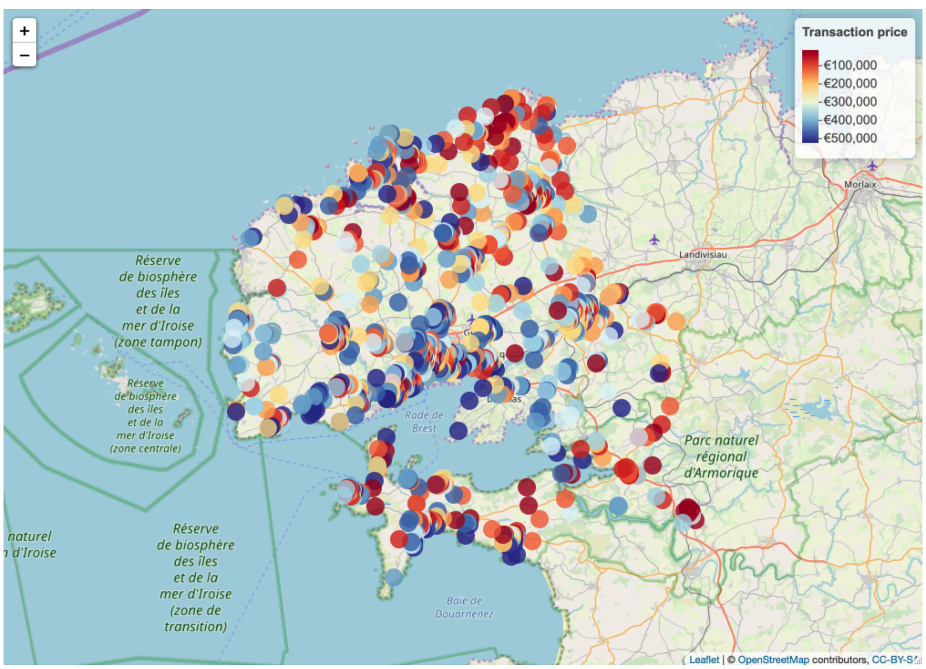

Figure 1: Map of observed transactions in the Brest region

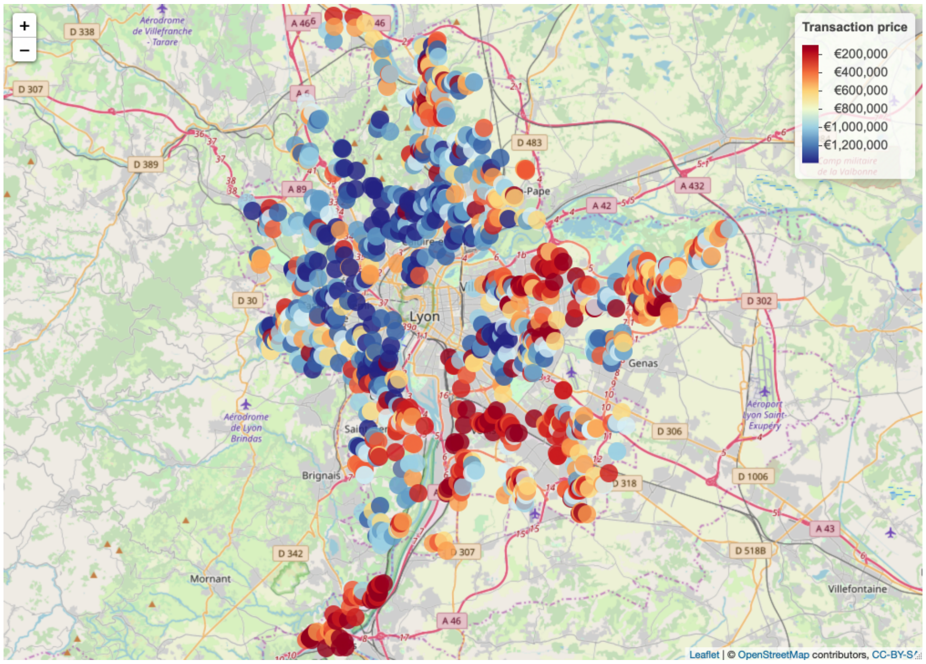

Figure 2: Map of observed transactions in Lyon metropolis

Location and prices of transactions investigated are plotted in Figure 1 for Brest area and in Figure 2 for Lyon's one. We can already observe that neighborhood is a key driver of prices in the Lyon metropolis, while prices seem less dependent to location in the Brest region. I use the location of dwellings in order to compute several geographical variables for each dwelling. Datasets on public amenities are available on the websites of the two local authorities, respectively `https://geo.pays-de-brest.fr/` for the Brest region and `https://data.grandlyon.com/` for the Lyon metropolis. Using the R software and Quantum GIS, a geographic information system, I compute geographical distances (in kilometers) or travel time through the street/road network (in minutes), according to which is the more relevant. When the public amenity present more than one point of interest, the closest one to the dwelling is selected: for instance, the travel time to the underground in Lyon will be the travel time to the nearest metro station.

Tables 1 and 2 describe statistical distributions of the samples key variables. As expected, the housing market is more tense in the urban area, with transaction prices over two times superior on average in the Lyon metropolis than in Brest region. One can note that distribution of energy labels in the two areas are similar, and that A-labelled houses represent a very small part of the samples (3 in Lyon and 3 in Brest). The construction period variable have some missing values (7% of the sample in Lyon, 4% for Brest), other key variables are complete. Two variables describe the house size, respectively the total floor area and the number of rooms. Regarding geographic variables, in both areas I compute the travel time to the city center, to the nearest train station and to the nearest tramway station. For Lyon specifically, I add the travel time to the nearest park and metro station. For Brest, I add the distance to the seaboard, distance to the nearest wind turbine and distance to the nearest hamlet.

Table 1: Summary statistics, key variables for Brest region (n = 1,242)

Continuous variable	Mean	St. Dev.	Min	Max
Price	160,636	61,766	16,000	520,000
Total floor area	110.501	32.143	34	252
Total land area	1,053	1,346	28	13,674
Number of rooms	5.465	1.387	1	12
Travel time to Brest center	26.974	13.060	3.000	65.800
Travel time to the nearest tramway station	19.081	13.364	1.100	60.200
Travel time to the nearest train station	19.645	11.020	0.200	46.300
Distance to the seaboard	3.262	2.768	0.000	11.727
Distance to the nearest wind turbine	7.932	4.016	0.788	19.476
Distance to the nearest hamlet	3.890	2.683	0.000	13.200

Categorical variable	Categories	Number
Construction period	Unknown	53
	Before 1850	0
	1850 / 1913	18
	1914 / 1947	119
	1948 / 1969	318
	1970 / 1980	315
	1981 / 1991	148
	1992 / 2000	63
	2001 / 2010	194
	2011 / 2020	14
Energy performance Certificate	A	3
	B	32
	C	189
	D	455
	E	382
	F	132
	G	49

Table 2: Summary statistics, key variables for Lyon metropolis (n = 1,094)

Continuous variable	Mean	St. Dev.	Min	Max
Price	365,481	161,135	100,000	1,387,300
Total floor area	123.777	43.167	39	300
Total land area	802.237	718.665	27	5,757
Number of rooms	5.207	1.434	1	12
Travel time to Lyon center	23.634	5.010	9.400	35.500
Travel time to the nearest metro station	13.132	5.761	0.400	27.600
Travel time to the nearest park	7.517	3.078	0.200	17.700
Travel time to the nearest tramway station	11.471	6.887	0.400	28.700
Travel time to the nearest train station	8.346	4.911	0.100	25.000

Categorical variable	Categories	Number
Construction period	Unknown	83
	Before 1850	4
	1850 / 1913	15
	1914 / 1947	124
	1948 / 1969	206
	1970 / 1980	202
	1981 / 1991	169
	1992 / 2000	113
	2001 / 2010	151
	2011 / 2020	27
Energy performance Certificate	A	3
	B	27
	C	304
	D	390
	E	259
	F	76
	G	35
Swimming pool	Yes	181
	No	913

2.3 Renovation costs and expected energy savings

In order to compare costs and benefits of energy efficiency, a technical-economic analysis is built using a description of French houses, a thermal model, a dataset on mature technologies and their costs for thermal renovations, and energy costs. This approach enables an estimation of the investment required to renovate a house and upgrade its EPC class. It also estimates energy savings associated to those insulation improvements.

2.3.1 Typical houses

An archetype of French houses is defined using Insee (2015) statistics. Architectural characteristics and initial efficiency of each component of this typical house are described in table 3. If all French houses share the same architectural characteristics in the model, they are differentiated according to their construction period. U-value is the heat transfer coefficient, expressed in $[W.m^{-2}.K^{-1}]$; a component's U-value is then a measure of the quantity of heat leaked by this material. When insulating a component, its U-value decreases. As thermal norms have become more demanding since their appearance in 1974, the U-values of building materials have become smaller, inducing less heat losses for more recent houses, hence smaller energy consumptions and better initial EPC classes. For instance old houses built before 1974 and not retrofitted have a mean U-value about $2.5W/(K.m^2)$, which corresponds to a primary energy consumption over $400kWh/(m^2.an)$ and an EPC class F. On the contrary, recent houses built after the introduction of 2005 French thermal norms have a mean U-value of $0.6W/(K.m^2)$, and consume less than $100kWh/(m^2.an)$ for space heating (corresponding EPC class is C).

Table 3: Architecture and performance of French typical houses

Characteristic	Value
Total floor area	$112m^2$
Number of floors	2
Height per floor	$2.5m$
Percentage of external walls covered by glass	30%

Construction period	<1974	74-81	82-89	90-2000	2001-2005	2006-2014
Share of the housing stock	53.29%	11.2%	10.3%	11.2%	5.9%	8.1%
Uwalls	2.5	1	0.8	0.5	0.47	0.36
Uwindows	4	3	3	3	2.3	2.1
Uroof	2.5	0.5	0.32	0.26	0.25	0.2
Ufloor	1.2	1.2	0.74	0.5	0.36	0.27

2.3.2 Dataset on material and labor costs for renovation

To evaluate investment costs for dwelling thermal renovation, we use Bâtiprix (2015), a French data base on prices in construction, including both material and labor costs, with a set of academic articles and official reports dealing with the costs of renovation (see Lechtenböhmer and Schüring (2011) and Ferrara et al. (2013)). We select mature technologies, widely available on the French market. All available options and associated costs are presented in table 4. Costs are given with a VAT of 5.5%, which is the VAT applicable in France for thermal renovations, and include both material and labor costs.

For walls, the main technologies available are interior thermal insulation (ITI), using various thicknesses of glass wool, and exterior thermal insulation (ETI), using various thicknesses of rock wool or expanded polystyrene with coating. Interior insulation is less expensive, but also less efficient. The best solution for wall insulation is a combination of interior and exterior insulation. The program gives the possibility of not acting on the walls (*statu quo*) : the price is then zero and the U-value is not modified. For windows, four options are available, including the *statu quo*: double-glazed windows, double-glazed windows with argon, and triple-glazed windows. Prices are significantly higher for these technologies. For the floor, the technology is an insulation with different thicknesses of rock wool, typically used on the underside of floor slabs. For the roof, house attics are considered as non-inhabitable. Main technologies available for these houses are rolls of mineral wool (with various thicknesses) and blown granulated rock wool.

Table 4: Mature technologies to insulate houses

Component	Technologies	U-value ($W/m^2.K$)	Prices (€/m^2)
Walls	Statu Quo	Unchanged	0
	ITI Glass wool 4cm	0.77	71.74
	ITI Glass wool 6cm	0.5	73.85
	ITI Glass wool 8cm	0.38	75.96
	ITI Glass wool 10cm	0.3	78.07
	ETI Exp. Polyst. with coating 14cm	0.27	180.405
	ETI Exp. Polyst. with coating 15cm	0.26	183.57
	ETI Rock wool with coating 16cm	0.23	200.45
	ETI(rock 20cm) + ITI(mineral 10cm)	0.11	288.015
Windows	Statu Quo	Unchanged	0
	4/16/4 double-glazing	2	380
	4/16/4 double-glazing argon	1.7	420
	4/16/4/16/4 triple-glazing	1.2	480
Roof	Statu Quo	Unchanged	0
	Mineral wool rolls 20cm	0.2	20.045
	Mineral wool rolls 30cm	0.13	22.155
	Blown rock wool 20.5cm	0.22	34.815
	Blown rock wool 29.5cm	0.15	53.805
	Mineral wool between herringbones 10cm	0.35	85.455
	Mineral wool between herringbones 12cm	0.29	86.51
	Mineral wool between herringbones 16cm	0.22	87.565
Floor	Statu quo	Unchanged	0
	Rock wool slab underside 10cm	0.34	128.71
	Rock wool slab underside 12cm	0.29	133.985
	Rock wool slab underside 14cm	0.25	139.26

2.3.3 Minimized renovation costs

For increasing efficiency targets (and then decreasing primary energy consumptions), available technologies are combined to minimize investment costs. This optimization is performed for each construction period, starting from house's initial performance (*i.e.* all the *statu quo* solutions are chosen, for a cost of 0 €), up to the best performance achievable (*i.e.* investment in the most efficient technology to insulate all envelope's components). Underlying thermal model is described in Appendix A.1. For each house type, a curve of minimized investment costs to reach a primary energy consumption level is then obtained (see section 4).

2.3.4 Heating energy prices

Table 5 gives the distribution of the various energies used for space heating in French houses, and their associated costs (data for the year 2016 drawn from CEREN, 2018). The average energy cost in €/kWh of houses built before 1974 is lower than the global average cost for French houses: this is explained by a smaller share of those houses heated by electricity, in favor of natural gas and heating oil. In order to compare expected energy savings between a theoretic consumption and the real one (including a 'rebound effect'), the thermal model described in Appendix A.1 also includes a behavioral adaptation through the intermittence factor. In theory this factor is supposed to be constant regardless of the energy performance of the house. In reality, households living in poorly efficient houses limit their own consumption, while households living in efficient houses consume more than the theoretical prediction.

Table 5: Heating energy of French houses and associated costs in 2016

Energy	Share of all houses	Share of houses built before 1974	Costs (Cts of €/kWh)
Natural gas	34.5 %	41.1%	6.96
Electricity	39.1 %	23.8%	16.48
Heating oil	18.1 %	26.4%	9.17
Wood	7.4 %	7.8%	5.8
Heating coal	0.4 %	0.7%	17.0
Urban heating	0.5 %	0.2%	10.31
Weighted average of energy costs	11.1	9.8	-

3 Econometric evaluation of the Green Value

Table 6 presents results from the estimation of the two spatial econometric models. Linear regression models estimated with the same variables present fair explanatory powers (pseudo-R squared between 63 and 65%), but the Moran's test evidences spatial autocorrelation of residuals both for Lyon and Brest. Geographical variables used are then not sufficient to control for spatial effects, justifying the use of a spatial error model. In table 6, we can distinguish the effects of three kind of variables: the ones describing the intrinsic characteristics of houses, the ones related to their location, and the interest variable, namely the Energy Performance Certificate.

First, both in the Brest region and in the Lyon metropolis, we find as expected a strong significance and a positive impact of size variables: the total floor area, the total land area but also the number of rooms and of floors increase the price. Moreover in Lyon, the presence of a basement and especially the one of a swimming-pool increases as well the price. Among the intrinsic characteristics of houses, we also control for the construction period. It is important to control for this variable as it may be linked to the energy performance of the house. Indeed, after the first oil shock in 1974, the French government enforced thermal norms, which has been gradually tightened since then. Thus, as houses get more recent, they are naturally more efficient. However, house age captures also other effects, for instance it might be a proxy for the house condition. Identified effects are consistent with this hypothesis: houses built since the eighties are gradually more expensive, while houses built before the seventies are less. Nevertheless, this effect is not systematically stronger as houses get older, probably due to a 'vintage effect'.

Second, geographical variables also appear to have an important impact on houses prices in both areas. The travel time to the city center impacts negatively the price, evidencing a premium for houses nearer to the city center, even though this effect is less significant in Lyon. The negative effect of the travel time to the nearest metrostation is stronger in Lyon. An alternative indicator of centrality in the Brest region has a more unexpected effect: it is the travel time to the nearest hamlet. When this time increases, house's price increase as well. This suggests that in this rural zone, households value more houses located out of small town centers when keeping the same distance to the bigger city center. The travel time to the nearest rail station has a positive effect on prices in both areas, meaning that households prefer to be further from a train station. If this effect can be counter intuitive at first sight, the ambiguous effect of rail station on real estate prices has been deeply studied by Bowes and Ihlanfeldt (2001). They show that positive effects of train stations, such as reduced commuting costs or attraction for some retail activity, can be offset by several negative externality: primary the noise, and secondly an increase in criminality in the direct neighborhood. In those two particular cases, I hypothesize that positive effect of reduced everyday commuting time can be small. Indeed those areas are well served by various public transports (many bus lines are available for instance), and then those train stations are more used to travel out of the region. However, the noise externality associated to trains remains important, and might explain this overall negative effect of distance to the nearest train station. This rationale is especially relevant for the Lyon metropolis, and consistent with the hedonic result. The travel time to the nearest tramway station has a poorly significant effect: in the Lyon metropolis this effect is not evidenced, in line with some literature results about the impact of tramway on prices (see Papon et al. (2015) study on the associated gains of light rail line for real estate in Paris). In the Brest region, this effect is significantly positive, meaning that households value more houses which are further from tramway stations. Similar drivers of the impact of train station can be summoned to explain this effect. One could shade this explanation by underlying that this effect could be different for houses and flats: indeed, tramways installation in cities takes up space on roads previously dedicated to cars. Households owning a car, as most households living in houses, might then fear an increase in travel time by car in the surroundings of tramway stations.

Regarding environmental amenities, interpretations of travel times are more straightforward, as a smaller distance to the seaboard is associated to a greater price in the Brest area, and a smaller travel time to a park is also associated to a greater price in Lyon. Last geographic variable added in the Brest estimation is the distance to the nearest wind turbine, which evidences a highly significant and positive effect on price: households penalize houses close to wind farms. This effect is consistent with the results of Gibbons (2015) who showed that wind turbines impacted negatively housing sales prices in England and Wales.

Last, I evidence a significant effect of Energy Performance Certificate class on houses prices on both areas. The D-label is used as a reference category. On the one hand, lower classes (namely E, F and G labels) evidence significant negative effect on price, with a stronger effect as the label worsens. On the other hand, classes better than D gradually increase house value, with the exception of the A-labelled houses which stands out in both areas. In the Brest region, the A-label does not have a significant effect compared to the D-label, and its effect is even negative in the Lyon metropolis. This effect roots in two possible sources: first our sample of A-labelled houses is extremely small (3 in both areas). Second, and more importantly, the French law allows to estimate the Energy Performance Certificate upon energy bills of the occupier for old houses. UFC, the national association of consumers in France, has shown that in some cases, poorly insulated houses get a A-label if they are not occupied and then energy bills are nearly equal to zero.

Table 6: Hedonic spatial estimation for the Brest region and the Lyon metropolis

	Dependent variable: log(Price)	
	Brest region	**Lyon metropolis**
Energy Performance Certificate		
Class A	−0.010	**−0.335****
	(0.145)	(0.115)
Class B	**0.116****	**0.036****
	(0.048)	(0.022)
Class C	**0.032***	0.012
	(0.022)	(0.016)
Class D	Hold-out	Hold-out
Class E	**−0.090*****	**−0.055*****
	(0.018)	(0.016)
Class F	**−0.145*****	**−0.069*****
	(0.026)	(0.026)
Class G	**−0.280*****	**−0.073****
	(0.041)	(0.036)
Total floor area	**0.005*****	**0.003*****
	(0.0003)	(0.0002)
Total land area	**0.00004*****	**0.0001*****
	(0.00001)	(0.00001)
Number of rooms	**0.016****	**0.035*****
	(0.007)	(0.005)
Presence of a basement	0.029	**0.035****
	(0.018)	(0.014)
Presence of a swimming-pool	0.078	**0.143*****
	(0.102)	(0.017)
Construction Period		
Unknown	Hold-out	Hold-out
Before 1850	-	**−0.192***
		(0.101)
1850 / 1913	−0.003	−0.035
	(0.069)	(0.056)
1914 / 1947	−0.047	**−0.062****
	(0.042)	(0.029)
1948 / 1969	−0.061	**−0.070*****
	(0.038)	(0.027)
1970 / 1980	0.040	0.009
	(0.038)	(0.027)
1981 / 1991	**0.146*****	0.009
	(0.041)	(0.028)
1992 / 2000	**0.245*****	0.034
	(0.048)	(0.030)
2001 / 2010	**0.276*****	**0.071****
	(0.040)	(0.028)
2011 / 2020	**0.387*****	0.052
	(0.077)	(0.047)
Travel time to Brest/Lyon center	**−0.014*****	**−0.006***
	(0.005)	(0.005)
Travel time to the nearest hamlet (Brest) / Metrostation (Lyon)	**0.013*****	**−0.016****
	(0.004)	(0.006)
Travel time to the nearest train station	**0.004****	**0.012*****
	(0.002)	(0.004)
Travel time to the nearest tramway station	**0.008***	0.008
	(0.004)	(0.005)
Travel time to the seaboard (Brest) / nearest park (Lyon)	**−0.017*****	**−0.009****
	(0.005)	(0.004)
Distance to the nearest wind turbine (Brest)	**0.009*****	-
	(0.003)	
Constant	**11.314*****	**11.952*****
	(0.080)	(0.122)
Other control variables		
Month of the transaction	Not significant	Significant **
Number of floors	Significant *	Significant *
Observations	1,242	1,094
Log Likelihood	−32.929	195.213
σ^2	0.061	0.039
Akaike Inf. Crit.	147.859	−304.426
Wald Test	50.284*** (df = 1)	1,590.116*** (df = 1)
LR Test	45.138*** (df = 1)	323.638*** (df = 1)
Note:		*p<0.1; **p<0.05; ***p<0.01

To estimate the green premium of efficient houses, I will then consider the B-label as the Energy Performance Certificate of 'green houses'. This is a legitimate assumption as policy-makers in France have set the B-label as the 2050 target for the whole housing stock, designing both A and B-labelled houses as low consumption buildings. Owners of B-labelled houses comply then with the most demanding norms for energy efficiency for the next decades. The 'red' reference (*i.e.* inefficient houses) chosen for estimating the green premium is the F-label rather the G-label. I choose the before last label for two reasons, even if it reduces the estimated green premium (as G-label is in both regions less valued than F one). First, classes of the Energy Performance Certificate cover varying intervals of estimated primary energy consumption (see Appendix A.2). The case of the G-label stands out as it has no upper limit on consumption, and G-labelled houses can then present important heterogeneity in their respective performances. The second reason leading to the choice of the F label roots in the theoretic primary energy consumption of typical houses built since 1974. As shown in the following section 4, a typical French house built before the introduction of thermal norms should not be have a performance worse than F. The G label then indicates the presence of important defects or architectural characteristics not referenced in our database and affecting the energy quality of the house, such as a pierced roof or a glass canopy. Measuring the green premium from this category of dwellings would be deceptive, capturing other effects than house insulation.

In relative terms, the green premium associated to the B label compared to the F label amounts to 29.7% in the Brest region and to 11.1% in the Lyon metropolis. However, energy costs are homogeneous between our two regions of interest: in France electricity price is the same across the country for households thanks to tariff equalization, while heating oil and natural gas prices are closely similar in the two regions (price differences respectively below 1% and 2%). As the two regions share similar heating needs (see section 2.2), energy bills and expected savings associated to a more performant house should be similar as well, even if the urban market of Lyon is tighter than the rural one of Brest. It is then more relevant to estimate the green premium in absolute terms. Switching to absolute values, I find that the green premium in Brest amounts to $35,300$€, while in Lyon it equals $32,300$€. Those two real estate markets, structurally different but sharing similar heating needs and costs, reveal close capitalizations of the green label. This kind of result is consistent with the 'engineer' approaches of the green value, which compare investment costs and expected savings associated to energy renovations. The following section crosses this hedonic estimation of the green value with a techno-economic assessment of energy renovation.

4 Techno-economic analysis of energy renovation

4.1 Renovation investment costs

Using the description of thermal and architectural characteristics of a French typical house built before 1974 (over the half of France housing stock), a dataset on material and labor costs for renovation, and the thermal model previously described, I represent the optimized renovation curve of F-labelled houses on Figure 3. On the abscissa is represented the level of investment in the thermal renovation. On the ordinate is represented the primary energy consumption which can be achieved by a renovation of this investment level. I add on this axis the range of the various energy classes of the Energy Performance Certificate to highlight investment levels enabling to upgrade the energy label. Then, initial performance of the house corresponds to an investment level of 0€, meaning that the house has not been retrofitted and consume over $400kWh/m^2/year$ of primary energy. This consumption lies in the range of the F-label. As investment level grows, primary energy consumption decreases. We can observe some important steps which correspond to the point where increasing the energy performance requires to insulate another component of house's envelope, or to switch to a more efficient but also expensive technology. The merit order of renovation actions starts with the insulation of the roof. Indeed, the roof is responsible for approximatively 30% of heat losses, and insulation technologies are relatively cheap. Then follows the internal wall insulation and floor insulation. Replacement of windows by double-glazed ones only occurs in the fourth position of the merit order, and last technology to be chosen is external wall insulation, highly efficient but also much more expensive. Smaller steps of the renovation curve indicate that the same set of components are insulated, but with gradually more efficient technologies (*e.g.* switching from double-glazed windows to double-glazed with argon windows).

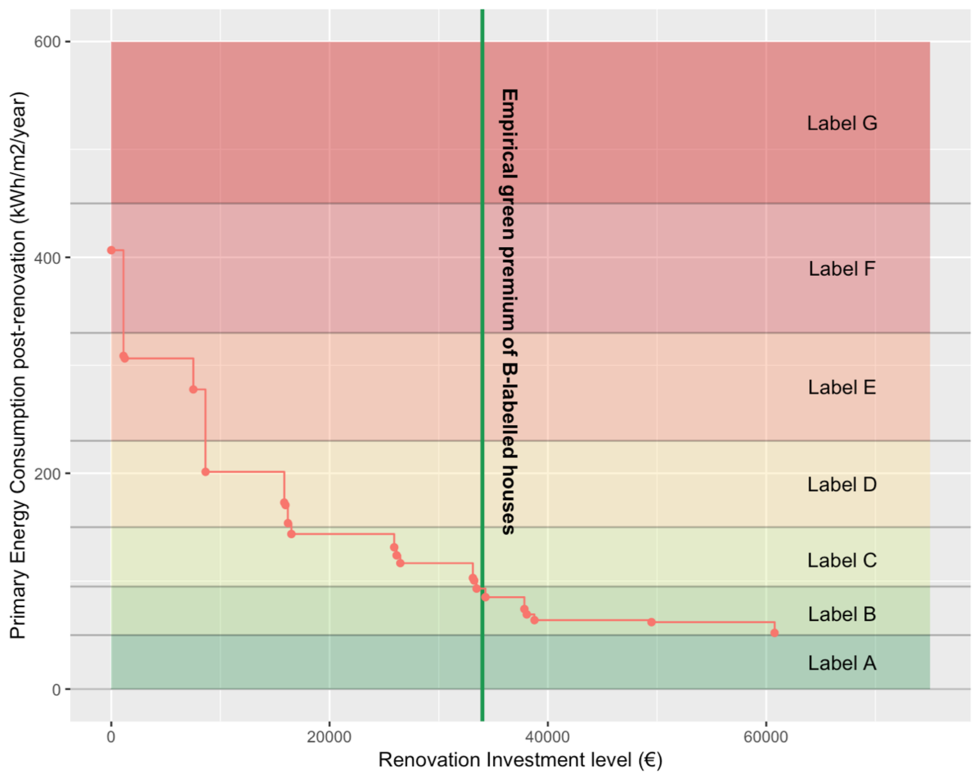

Figure 3: Renovation of a typical house built before 1974

Figure 3 also displays the empirical capitalization of B-labelled houses compared to F-ones identified in the spatial econometrics section. This evidences that the green premium associated to low-consumption houses matches closely with the renovation investment level required to reach this performance level. Indeed, turning a typical house built before 1974 into a B-labelled ones requires an investment of 32,000€, while the green premium estimated in the previous section amounts abount 34,000€. A potential explanation of these very close estimates is that houses sellers compete *'à la Bertrand'* in prices on the energy quality component of the house value: the production cost of energy efficiency, *i.e.* the required investment to turn an inefficient house into a low-consumption one, is homogeneous and charging more than this amount will lead buyers either to choose another seller proposing a B-labelled house at a lower price or to buy an inefficient house and invest themselves in the renovation. This hypothesis is also consistent with the premium difference observed between the Brest region and the Lyon metropolis. Indeed, a previous study on the French market has found that, outside the Paris region, renovation costs are similar across the country, but slightly superior in the rural area compared to the urban ones (more precisely, observed prices are about 5% superior in the rural areas, see OCRE, 2015). If the premium of B-labelled houses can be explained by a Bertrand type competition on energy quality, next section explores the associated energy savings that households can expect from a low-consumption house.

4.2 Discounted energy savings

In order to compare expected savings on the energy bill with the green premium of B-labelled houses, I represent on Figure 4 the sum of discounted energy savings (in €) by living in a B house rather than a not retrofitted house built before the thermal norms of 1974. Using the thermal model, I distinguish the case of a household forecasting energy savings only on the theoretic energy consumption (dotted curves) to the case of a household taking into account the rebound effect (solid curves). Rebound effect has a double effect in cutting excepted savings: first households living in poorly efficient houses restrict their energy consumption, and second households living in low-consumption houses over-consume compared to the theory. I discriminate also two time horizons which could be used by households to compute expected savings. The first one, 15 years (red curves), corresponds to the expected time the owner household will live in the house (our dataset provides this information, revealing a mean period of ownership of 13 years in Brest and of 14 years in Lyon). The second time horizon chosen, 30 years (blue curves), corresponds to the expected lifetime of energy efficiency investments. On the abscissa is represented the discount rate, and on the ordinate is represented the sum of discounted energy savings. Like in section 4.1, Figure 4 also displays the green premium of B-labelled houses.

When the time horizon is considered as 15 years, the green premium is always superior to the sum of discounted savings. In the case of a 30 years time horizon, these savings can fully explain the green premium only of discount rates are low enough: in the case where subjects do not take into account the rebound effect, green premium is superior to discounted savings for any discount rate above 5%. This result is even more striking when rebound effect is taken into account: sum of discounted savings is then inferior to the green premium for any discount rate above 2%.

If the discount rate used by households is superior 7%, no matter the time horizon or if the rebound effect is taken into account or not, the green premium is at least 35% superior to energy savings. Many academic studies have shown that discount rates used by households are largely superior to what standard economic assumes as rational, namely the real interest market rate, about 3%. Hausman et al. (1979), Coller and Williams (1999) and Harrison et al. (2002), while using different empirical approaches, all reveal discount rates largely superior to 10% for households and a large heterogeneity. In a recently published paper by the American Economic

Review, De Groote et al. (2018) evidenced with a large sample of Belgian households that over 90% of implicit discount rates used by households to invest in photovoltaic panels fall within the range of 13% to 16%. This investment decision in energy production can be compared to the investment decision in energy renovation as return-on-investment time are similar. Using this range of discount rates, in all the scenarios considered (15 or 30 years time horizon, rebound effect taken or not into account), Figure 4 tends to demonstrate that energy savings explain half or less of the green premium.

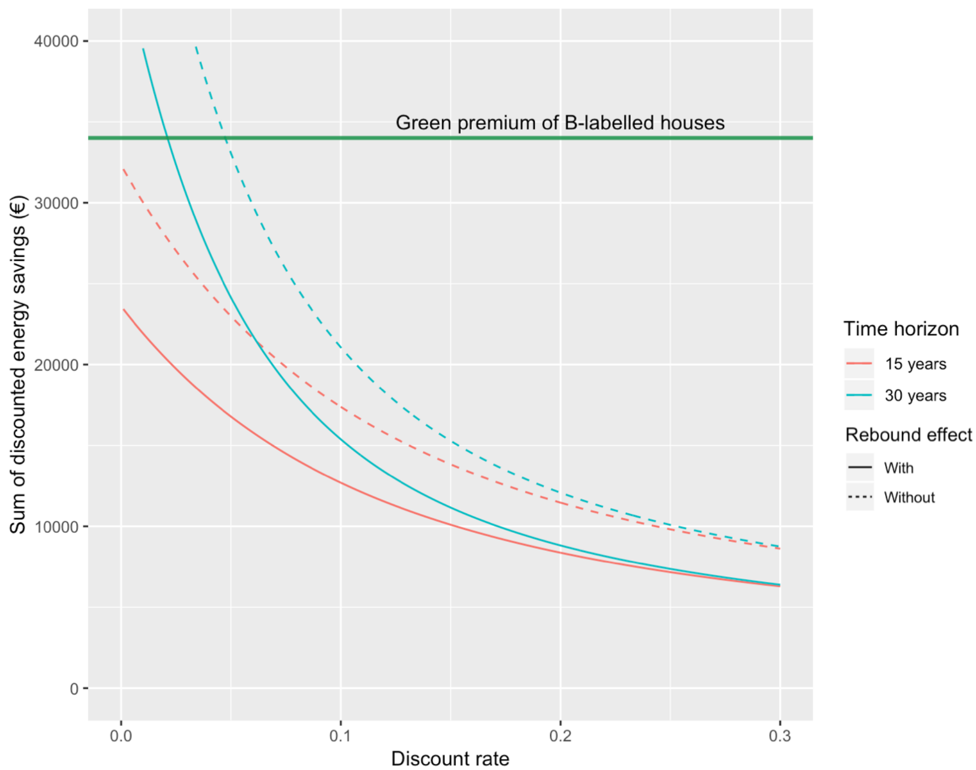

Figure 4: Discounted energy savings versus Green premium

We can raise several potential explanations of this green value beyond energy savings: first energy savings are not the only benefits of an energy renovation. Ancillary benefits, such as improved thermal comfort, reduced exposition to external noise and moisture issues, were targeted by the study of Jakob (2006) who hypothesized that they could represent utility gains to the same order of magnitude as energy savings. My results strengthen this hypothesis: co-benefits could be as much valuable as energy savings for households.

Another advantage of owning a house labelled as 'low-consumption' lies in the protection against future changes in the public policies. French policy-makers have set the target for the whole building stock to be labelled as 'low-consumption' at the 2050 horizon. This target is not legally binding for now, policy-makers favoring rather incentives such as subsidies and zero-interest loans to motivate owners. However, a first attempt was made to make renovations mandatory for inefficient houses in the 2015 French law for the energy transition. If this article of the 2015 law was then censored by the constitutional council due to imperfect specifications, it remains an important signal that policy makers might, in the next decade, enforce a legislation on this topic to constrain owners of poorly efficient houses to invest in a renovation. Then, buying a house already labelled as 'low-consumption' is an efficient way to protect your investment from the uncertainty related to policy changes.

One last potential root of the green premium is the 'moral value' of living in a more environmentally friendly house. Brounen and Kok (2011) showed in the Netherlands that the proportion of green voters in a given neighborhood modifies households' behavior regarding the Energy Performance Certificate, suggesting that the Willingness-to-Pay for energy efficiency could vary among households according to their environmental beliefs.

5 Conclusion

Existing literature on energy efficiency has often opposed the economic approach and the engineer approach. This opposition is has been extensively documented in the studies on the energy efficiency gap and on the energy paradox, underlining differences between technologists', economists' and social optimal level of energy efficiency (see the recent review by Gerarden et al, 2017). In this article I suggest that the two approaches are not irreconcilable. Using a dataset on houses transactions in two French regions, I evidence that 'low-consumption' houses benefit from of a significant green premium on the real estate market. If the capitalization of energy label information is more important in relative terms in the rural area, in absolute terms rural and urban green premiums are similar, about 35,000€. These tantamount absolute green values correspond to the required investment in mature technologies to improve energy efficiency: a legitimate assumption is that a Bertrand-type competition occurs between sellers on the energy quality component of houses, preventing them from selling a low-consumption higher than its renovation cost. On the buyer side, I find that this green value largely exceeds the expected energy savings associated to a low-consumption house when using the discount rates elicited in the literature for households investments.

Relevant extensions of this work would focus on disentangling the relative importance of the various co-benefits that could explain the 'green surplus' of efficient houses. First, in order to measure thermal comfort gains, it would be interesting to couple the analysis of Brest and Lyon with another French region with different heating needs. Second, the protection from the legislation hazard could be estimated by comparing the green premium granted to houses with an intermediate level of renovation to the premium of low-consumption ones.

Acknowledgments

A Appendix

A.1 Thermal model

On the basis of a thermal model inspired by the 3CL-DPE method, a French official method to estimate building energy consumption for space heating (MEDDE (2012), MEDDE (2009)) and using the PhD thesis realized by Allibe (2012), I link the performance of the envelope (represented by the mean U-value = U_G) to the primary energy consumption for space heating: $Cons_{peh}$ expressed in $[kWh/(m^2.an)]$. This conventional consumption in primary energy for heating is the value used to attribute an EPC class to a house. Relation is stated in Eq. (3).

$$Cons_{peh}(U_G) = K_{final \to primary} * \frac{U_G * A_{envelope} * D_{h.ref} * I}{Boil_{eff} * L_s} \tag{3}$$

In the previous equation, U_G is the mean U-value of the building $[W/(K.m^2)]$, and main variable. It is calculated by algorithm on the basis of the architecture and materials of each building.

Other parameters are fixed. $A_{envelope}$ is the total area of the building envelope $[m^2]$. It is calculated by the program thanks to information on building's architecture. L_s is the total floor area $[m^2]$. In order to estimate the need per m^2, the total living space area in the house needs to be provided. $Boil_{eff}$ refers to the boiler efficiency. It depends on the particular heating system of the dwelling. The efficiency of a regular boiler is usually between 0.85 and 0.95 ; for this paper we will assume that this efficiency is equal to 0.9 for all houses. $K_{final \to primary}$ is computed as the mean standard transformation coefficient of final energy into primary energy. Given the distribution of heating energies in the French houses stock, we use $K = 1.6$. For more details on heating energy in French houses, see ADEME (2013).

$D_{h.ref}$ is the number of degrees - hour needed to heat up the space during a year (depending on the climate) $[K.h]$. The 3CL-DPE method provides $D_{h.ref}$ for all French metropolitan departments ; these numbers are estimated to reach a temperature of 18^{o}C with the heating system, considering that other contributions (lighting, biological heat) will be enough to reach the set-point temperature of 19^{o}C. In the model we use the average value between French metropolitan departments of Lyon and Brest, which have similar heating needs as detailed in section 2.2. The $D_{h.ref}$ used is then 54500 $K.h$.

I is the factor of intermittence. As a house is not continuously occupied during the year, especially during working hours, heating systems can be turned off. The factor of intermittence is between 0 and 1, the reference value for houses is $I_0 = 0.85$. On the contrary to the conventional consumption prediction model ($Cons_{feh}^{theoretic}$, which is used to estimate the EPC class of the house), the behavioral consumption model I compute ($Cons_{feh}^{behavioral}$) integrates the behavior of households by allowing the variation of intermittence. On the one hand, when U_G is high, the intermittence is lower: households adopt strategies to reduce their consumption (decrease temperature setpoint in bedrooms, or turn off heating at night). But on the other hand, when U_G is small, the intermittence will be close to 1: a better insulated dwelling allows to choose a higher temperature setpoint higher. It is the "rebound effect": a gain in energy efficiency implies a lower cost for the same energy service and then demand for that service may increase. The expression of this $I = f(U_G)$ is inspired by Allibe (2012):

$$I(U_G) = \frac{I_0}{1 + 0.1 * (\frac{U_G}{U_{G_0}} * \frac{A_{envelope}}{L_s} * \frac{H_{c0}}{H_c} - 1)} \tag{4}$$

Where H_c is the ceiling height per floor (in $[m]$), $H_{c_0} = 2\ m$ and $U_{G_0} = 1\ W/(K.m^2)$ This thermal model is used to estimate the theoretical and behavioral consumption of a typical house. When comparing these consumptions to average observed ones in France (RAGE (2012)), it appears that the behavioral model gives a fair estimation of real consumption rates.

For instance, its prediction of total French energy consumption for residential heating is $30.6 Mtoe$. This estimation is obtained by combining the thermal model to the description of French housing stock (see tables 3 and 5). According to official figures given by the CEREN (2018), residential energy consumption in 2016 for space heating was $28.1 Mtoe$. The real energy consumption is then 8% inferior to the calculated one. Two main factors explain this over-estimation: firstly, I do not take into account already refurbished buildings; secondly, in the last thirty years, the average area of houses has strongly increased, from $96m^2$ in 1984 to $112m^2$ in 2014 (see Insee, 2015). But this evolution is not represented in the model, resulting in an overestimation of the total area of old houses, which consume more, and an underestimation of the total area of recent houses, which consume less. This gap between predicted and real consumption is still significantly smaller than the ones found in the literature until now for space heating in France (22% for Mata et al. (2014), 18% for Ribas Portella (2012)).

A.2 Energy Performance certificate design

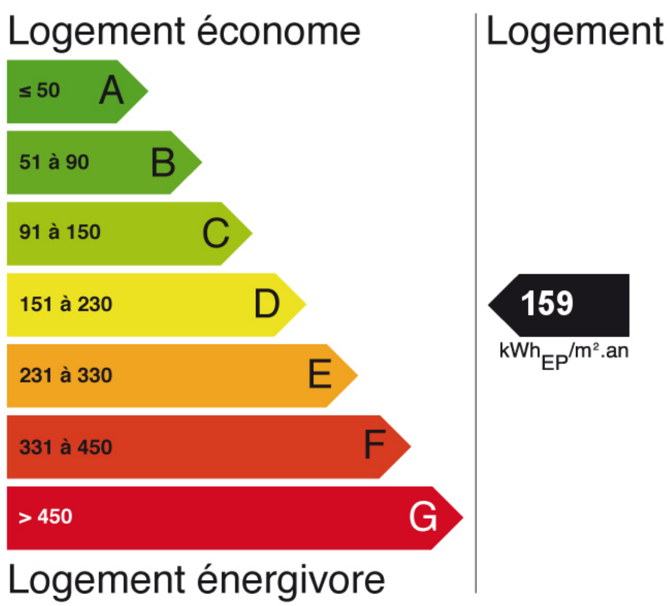

Figure 5: EPC classes cover various range of energy consumption

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