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How heterogeneous is the impact of energy efficiency on dwelling prices? Evidence from the application of the unconditional quantile hedonic model to the Portuguese residential market

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ABSTRACT

This paper studies the impact of energy efficiency on the unconditional distribution of residential property prices in Portugal. Using a dataset of more than 256,000 residential property sales from 2009 to 2013, a period that covers an economic depression, unconditional quantile regression analysis reveals that the responsiveness to energy efficiency improvements is different not only as we move from low- to high-priced residential units but also between apartments and houses. While apartments show a downward trend in the magnitude of energy efficiency coefficient estimates, the opposite occurs for houses. This last property type exhibits clear price discounts at the lowest quantiles of the price distribution, something that is not observable through conditional mean and quantile regression analysis. Our results suggest the existence of a different level of responsiveness to energy efficiency improvements in the Lisbon region when compared to the rest of the country and that the impact of the Energy Performance Certificate label increases throughout time across all price quantiles. As a by-product of this paper, an unconditional quantile price index shows how the impact of the crisis was not the same across different market segments, with more severe price decreases for low- than high-priced properties.

1. Introduction

The impact of energy efficiency on the price of residential properties has long been investigated though hedonic models (Rosen, 1974) in which the property price is regressed against a measure of energy efficiency and other price-determining property attributes. The focus of the use of this revealed preference method in this research context, for which a comprehensive survey is available in Zhang et al. (2018), has been on quantifying the impact of energy efficiency over the conditional mean price estimated by standard ordinary least squares (OLS). By and large, the overwhelming majority of study results suggest the existence of price premiums associated with energy efficiency as measured by the Energy Performance Certificate (EPC) and other energy labels.[1]

Rather than focusing on the conditional mean effects, a more recent line of research explores the heterogeneity of the impact of dwelling characteristics across the residential property price distribution. Mak et al. (2010) and Wen et al. (2019) are two examples that assess the impact of key price-determining attributes, such as size, age, comfort and location factors (e.g. parking facilities, access to public goods), at different points on the price distribution. Notwithstanding these recent developments, the assessment of the impact of energy efficiency at various points on the price distribution is restricted to two recent papers. While Liao and Zhao (2019) analyse the impact on transaction prices of a residential unit located in a certified (green) building in Singapore, Evangelista et al. (2020) focus on the individual residential unit certification level and provide evidence that the market reaction to the EPC label in the Portuguese market is relatively stable across the price distribution.

This strand of study involves applying the standard conditional quantile regression (CQR) method, which draws on the seminal paper of Koenker and Basset (1978). Liao and Zhao (2019) constitute a notable exception, where the recent unconditional quantile regression (UQR)

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[1] The European Union introduced the EPC label in the Energy Performance of Buildings Directive (EPBD) in 2002, which was later recasted in Directive 2010/31/EU. In Portugal, EPCs were first implemented in June 2007 as a consequence of the partial transposition of the EPBD into national law.

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approach proposed by Firpo (2007) is used. While conditional and unconditional quantile approaches provide valid results, it should be noted that they refer to different concepts, with the former evaluating the partial effects along a theoretical or conditional price distribution, and the latter assessing the overall impact on the unconditional price distribution. To highlight the difference between these two approaches it could be said that that, while a property with high energy efficiency may be located in the upper range of the (conditional) price distribution of the properties with the same area, age and other observable characteristics, this may be located in the lower section of the overall (or unconditional) dwelling price distribution. Firpo et al. (2009) present examples of differences in the magnitude and sign of the two types of partial effects.

This paper provides comprehensive analysis of the relationship between energy efficiency and prices in the residential property market according to the UQR framework. The results derive from the dataset used by Evangelista et al. (2020), which covers more than 256,000 residential property transactions. The data largely overlaps with a period when the market was depressed and provides a rich set of information on energy efficiency and other dwelling attributes at the individual unit level. The comprehensiveness of the data benefits from EPC certification becoming mandatory in all transactions from the start of 2009 onwards.

This paper adds to the literature in three ways. Firstly, as this assesses the impact of energy efficiency along the distribution of prices at the unit level according to various aggregations of the EPC scale, the findings provide far more detailed analysis than that provided by Liao and Zhao (2019), which draws their conclusions from information taken from a dichotomous energy efficiency evaluation system designed for green buildings. Secondly, the paper presents a wide range of results studying the potential heterogeneity of energy efficiency partial effects not only across the distribution of prices but also according to dwelling type (apartment, house, new and existing), throughout time and the main regions of Portugal. Finally, the results include an unconditional quantile hedonic price index, enabling an evaluation of whether depressed market conditions impact equally across the different price quantiles of the residential market in Portugal.

The organisation of this paper is as follows. Section 2 reviews the literature and highlights the key aspects associated with the estimation of energy efficiency quantile partial effects. Section 3 describes the available dataset and provides analysis of the features of these data. Section 4 presents and discusses the results. Finally, section 5 concludes.

2. Energy efficiency quantile partial effects

The impact of energy efficiency on property prices has essentially been studied from the conditional mean perspective. However, having information on this impact across the entire price distribution spectrum is important not only to carrying out robustness checks (e.g., comparing the mean and median values) but also to providing a clearer view of the impact of energy efficiency improvements in different price market segments. Within this framework, quantile regression emerges as an appropriate technique able to help provide a full picture of the impact of energy efficiency and as an important instrument for all those interested in tailoring policy measures according to the different segments of the residential property market.

2.1. Use of conditional and unconditional quantile partial effects

The literature providing evidence on the impact of residential property market attributes across the price distribution is relatively scarce, focused on small homogeneous markets, and essentially restricted to the use of the CQR framework. One early example is Zietz et al. (2008), who focus their analysis on a particular region of Utah, US. Further examples come from Mak et al. (2010) and Wen et al. (2019), respectively addressing the Hong Kong and Hanzhou markets in China. Fuest and Warren-Myers (2018) also apply conditional quantile regression models to assess the effect of energy rating non-disclosure across the distribution of rents in the Australian Capital Territory. More recently, Evangelista et al. (2020) provide evidence on the conditional quantile energy efficiency partial effects in the sales market for Portugal.

As mentioned above, the CQR framework provides a particular interpretation of quantile impact changes on the distribution of the dependent variable as these remain conditional on the values of the model's covariates. As highlighted by Borah and Basu (2013), this prevents the generalisation of CQR results to a policy or population context. In fact, while the OLS conditional mean partial effects are susceptible to interpretation as unconditional (or generalizable) partial effects through the law of iterated expectations, this does not hold for CQR. Examples of the application of the UQR framework include Peeters et al. (2017) and Seya et al. (2020), who deal with farmland prices in Belgium and parking lot prices in Japan. Although in a stated preference context, Lang and Lanz (2021) also make usage of the unconditional quantile framework to investigate whether the tenant's willingness to pay for energy efficiency improvements is homogeneous across the distribution of potential rent increases.

Liao and Zhao (2019) constitute the only example providing evidence on conditional and unconditional quantile energy efficiency partial effects. These authors report fundamental differences in the conditional and unconditional estimates of the effect of individual residential units located in certified green buildings in Singapore. Two points are worth highlighting in relation to this study. Firstly, given that certification is concentrated in certain locations, types of properties, and developers, the study included the need to address the issue of sample selection. Secondly, while the quantile evaluation takes place at the residential unit level, green certification is only captured at the aggregated building level. This fact precludes a finer study of the effects of energy efficiency as there is no information at the residential unit level.

The case of Portugal avoids sample selection as the EPC label was made obligatory for all residential market transactions in January 2009 and compliance with this obligation has always been high. Moreover, the national evaluation system providing the data applied in this paper includes energy performance information at the individual unit level across Portugal, which allows for the full application of the energy scale used to evaluate properties. Fuest and Warren-Myers (2018) provide an example of the advantages taken from similar data conditions in which the analysis of the effects of several levels of EPC labelling on housing transaction prices in a mandatory labelling system for conditional mean models is carried out for the Australian Capital Territory. Finally, we would note that the present study is the first to apply the UQR framework to an entire country. Modelling this heterogeneity is a challenging issue to address, which becomes possible due to the size of the dataset and to the number of variables present in it (see section 3 for more on the data).

2.2. Inclusion of EPC information in quantile hedonic models

The appropriation of the information provided by the EPC label by the quantile hedonic models considered in this paper builds on the approach to OLS and CQR estimators applied by Evangelista et al. (2020). In order to explore all levels of the EPC scale and to provide a clearer view of the impact of this label on dwelling prices, three different ways of incorporating the rating system used in Portugal into the hedonic models are considered.[2] Table 1 provides a brief description on

[2] In Portugal, the EPC rating in effect until November 2013 consisted of a nine-level scale (A^+, A, B, B^-, C, D, E, F, and G). In this system, the A^+ and A ratings represent 0% to 50% of annual energy consumption needs relative to the reference values, B and B^- 51% to 100%, and the G rating 301% or more of these same standard values. The change that took effect from December 2013 onwards eliminated the G rating.

Table 1
Definition of the energy efficiency measures considered.

Energy efficiency measure	Variable description
AB	Dummy variable = 1 when the EPC of the residential unit is either A^+, A, B or B^-
(A^+, A), B, B^-, C, D, E, and (F, G)	Set of six dummy variables identifying the EPC label issued to the property (omitted category: D)
EED	Discrete variable which translates the 9-level EPC scale used in Portugal, {A^+,A, B, B^-, …, F, G}, into the values {9,8,7, 6, …2, 1}

these three alternative measures.

The first follows Evangelista et al. (2020) in that it relies on the inclusion of a binary variable, designated as *AB*, which assumes the value 1 for the four most energy efficient ratings (A^+, A, B, B^-), and the value 0 otherwise. According to the EPC system used in Portugal, these four ratings identify all residential units registering annual consumption energy needs that are the same as or lower than those of the reference standard consumption level (i.e., identifying all properties that perform the same as or better than a standard energy efficiency performance).

The second adopts a seven-level scale, representing the (A^+, A), B, B^-, C, D, E, and (F, G) EPC ratings. In this setting the extreme ratings are grouped due to the fact that these account for a low number of transactions (see section 3 for more details) and the D rating serves as the reference.

Finally, the third measurement procedure consists of the inclusion of a discrete variable, defined as *EED*, which translates the nine-level Portuguese EPC scale, i.e., the {A+, A, B, B-, …, F, G}, into the {9, 8, 7, 6, …2, 1} values. Following Lyons et al. (2013), this discrete approach of measuring the effect of energy efficiency was applied in Evangelista et al. (2020) in OLS models. To the best of our knowledge, there are no other empirical applications of this way of modelling the energy efficiency scale in housing markets (see Zhang et al., 2021, for an application of a three-level discrete energy efficiency variable in the explanation of the price of air conditioners). This approach has not been used in quantile regression analysis in this research context despite the appealing feature of circumventing the estimation problem associated with having too few observations for the many energy efficiency ratings at some price quantiles.

2.3. Methodology and estimation strategy

The core relevance of this paper stems from understanding the effects of energy efficiency (*EE*), as measured by each of the three alternative forms defined in the previous subsection, on the dwelling price at the τth quantile of its distribution, $0 < \tau < 1$. Following Koenker and Basset (1978), the conditional effect of *EE* on the transaction price *P* at the τth price quantile, $\frac{dQ_\tau(P|z)}{dEE}$, $z = (EE, x)$, can be derived as the argument that minimises the following sum of weighted absolute residuals:

$$\widehat{\beta}_{\tau,CQR} \equiv \underset{\beta}{arg\ min} \sum_{i=1}^{n} \rho_\tau . \left(P_i - z_i^{'}\beta_\tau\right) \quad (1)$$

where $\rho_\tau = u_i.(\tau - \mathbb{I}\{u_i < 0\})$ corresponds to the reweighting (*alias* check) function of the residuals u_i,and $\mathbb{I}$ is an indicator function assuming the value 1 when the condition between brackets holds, and 0 otherwise. The x corresponds to the k property attributes that, in addition to *EE*, are included in the hedonic model specification establishing a functional relationship between prices and dwelling attributes. With the exception of $\tau = 0.5$,which corresponds to the least absolute deviation regression case, the reweighting of residuals by the check function takes place asymmetrically for all price quantiles.

The estimation adopts the same baseline OLS and CQR models as Evangelista et al. (2020) in the sense that the same x vector of hedonic covariates serves to estimate the impact of energy efficiency in existing apartments, new apartments, existing houses and new houses. The description of these variables is available in the supplemental paper appendix. As in this study, the dependent variable also represents the natural logarithm of residential property prices.

The unconditional partial effect of *EE*, $\frac{dQ_\tau(P)}{dEE}$, is estimated according to two different approaches, which depend on the respective specification of energy efficiency. The first approach, considered when *EE* is defined as a dummy variable (*AB* or the labels on the seven-level scale), applies the estimator proposed by Firpo (2007). This case assumes that the data generating mechanism of *EE* is governed by the set of x observable characteristics, and use an estimator based on propensity scores (Rosenbaum and Rubin, 1983), which acts to reweight the sum of check functions in Koenker and Basset's (1978) minimisation procedure presented above. In this approach, the effect of a change at the τth price quantile from 0 to 1 in *EE* on *P*, $\widehat{\Delta}_\tau \equiv \widehat{P}_{1,\tau} - \widehat{P}_{0,\tau}$, reflects the difference between the distributions of the most and the least energy efficient transacted properties, where the $\widehat{P}_{l,\tau}$, $l = (0,1)$ are obtained from:

$$\widehat{P}_{l,\tau} \equiv \underset{\beta}{arg\ min} \sum_{i=1}^{n} \omega_{l,i} . \rho_\tau . \left(P_i - z_i^{'}\beta_\tau\right) \quad (2)$$

where $z_i{'}\beta_\tau = P_{l,\ \tau}$ and $\widehat{\omega}_{1,i}$ and $\widehat{\omega}_{0,i}$ are the estimated propensity score weightings, calculated as $\frac{EE_i}{n\widehat{pr}(x_i)}$ and $\frac{1-EE_i}{n(1-\widehat{pr}(x_i))}$, respectively.

In the second approach, in which *EE* assumes the discrete form *EED*, the estimation of the energy efficiency partial effect at the τth unconditional quantile is done following the Firpo et al. (2009) method. In this framework, the partial effect corresponds to that emerging from the OLS regression of the covariates on the (re-centered) influence function of the unconditional quantile on the explanatory variables.[3] The re-centered version of this function is given by:

$$RIF(P_i, Q_\tau) = \alpha_{1,\tau}\mathbb{I}\{P_i < Q_\tau\} + \alpha_{2,\tau} \quad (3)$$

where $\alpha_{1,\tau} = {}^{1}/_{f_P(Q_\tau)}$ and $\alpha_{2,\ \tau} = Q_\tau - (1 - \tau)\alpha_{1,\ \tau}$, and $f_P(Q_\tau)$ is the marginal density of *P*, which has a conditional expectation given the covariates linear on the covariates.

The design of the estimation exercise consisted of applying OLS, CQR and two versions of the UQR estimators for the three different *EE* variables to four different market segments (existing apartments, new apartments, existing houses and new houses) with the results obtained through StataCorp (2017) software. The Firpo et al. (2009) estimator is available in this software through the *rifreg* command and the Firpo (2007) estimator is implemented in accordance with the approach adopted by Frölich and Melly (2010).

3. Data

The dataset used in this paper reports information on the prices and characteristics of more than 256,000 residential property transactions carried out in Portugal between 2009 and 2013. The dataset results from combining the transfer and property tax records with those obtained from the EPC label supervisory body in Portugal. The data are the same as those used by Evangelista et al. (2020) for the derivation of OLS and CQR results. A detailed description of the data matching process for these three sources of information is available in the paper's supplemental appendix.

Table 2 provides the descriptive statistics for some key attributes of the properties and for the nine levels of the EPC energy efficiency scale. Furthermore, following Evangelista et al. (2020), there is the division of

[3] An influence function, which has an unconditional expectation of zero, is used in the literature dealing with robust statistics to assess the influence of removing or adding an observation on the value of a statistics.

Table 2
Descriptive statistics of a group of selected variables.

	All (N = 256,145)				Existing apart. (N = 149,920)				New apartments (N = 59,410)				Existing houses (N = 33,282)				New houses (N = 13,533)			
Variable:	*0.1th*	*0.5th*	*0.9th*	*Avg*	*0.1th*	*0.5th*	*0.9th*	*Avg*	*0.1th*	*0.5th*	*0.9th*	*Avg*	*0.1th*	*0.5th*	*0.9th*	*Avg*	*0.1th*	*0.5th*	*0.9th*	*Avg*
Transaction value (€)	46,760	96,200	205,400	119,888	44,500	80,000	165,000	97,695	75,000	129,000	238,000	149,007	40,000	112,000	250,000	143,783	60,000	150,000	300,000	179,155
Gross floor area (m^2)	61	100.6	170.0	110.6	58.2	91.6	137.0	96.0	67.9	110.0	158.0	113.1	64.1	135.8	240.0	148.3	85.0	167.0	242.7	168.6
Dep. floor area (m^2)	0	20.3	72.8	31.1	0	13.8	42.0	18.6	12.0	30.5	67.2	36.1	0	40	146.2	60.2	0	62.0	157.0	75.4
Uncov. land area (m^2)	0	0	162.5	78.2	0	0	0	2.9	0	0	0	4.9	0	178.3	938.0	411.0	22.1	196.0	917.9	415.6
No. bedrooms (#)	1	2	4	2.5	1	2	3	2.3	1	2	3	2.3	2	3	5	3.5	2	3	4	3.3

Energy rating:	*Transaction value tertile group*				*Transaction value tertile group*				*Transaction value tertile group*				*Transaction value tertile group*				*Transaction value tertile group*			
	1st	*2nd*	*3rd*	*Glob.*	*1st*	*2nd*	*3rd*	*Glob.*	*1st*	*2nd*	*3rd*	*Glob.*	*1st*	*2nd*	*3rd*	*Glob.*	*1st*	*2nd*	*3rd*	*Glob.*
A^+	0.001	0.004	0.016	0.007	0.000	0.001	0.005	0.002	0.007	0.018	0.036	0.020	0.005	0.002	0.006	0.005	0.005	0.008	0.015	0.009
A	0.006	0.030	0.090	0.041	0.001	0.005	0.037	0.014	0.055	0.117	0.184	0.118	0.022	0.012	0.030	0.021	0.029	0.054	0.100	0.061
B	0.073	0.213	0.325	0.202	0.048	0.141	0.294	0.159	0.299	0.408	0.474	0.393	0.045	0.055	0.118	0.073	0.072	0.164	0.235	0.157
B^-	0.092	0.144	0.150	0.128	0.083	0.129	0.148	0.120	0.167	0.180	0.125	0.157	0.059	0.099	0.173	0.110	0.101	0.156	0.169	0.142
C	0.457	0.387	0.240	0.363	0.522	0.508	0.370	0.468	0.331	0.221	0.131	0.228	0.130	0.202	0.222	0.185	0.174	0.263	0.229	0.222
D	0.192	0.137	0.112	0.148	0.177	0.128	0.090	0.132	0.104	0.044	0.038	0.062	0.357	0.372	0.261	0.330	0.340	0.234	0.170	0.248
E	0.142	0.066	0.047	0.086	0.152	0.080	0.050	0.095	0.034	0.010	0.010	0.018	0.210	0.153	0.115	0.160	0.163	0.075	0.059	0.099
F	0.030	0.016	0.016	0.021	0.015	0.008	0.005	0.009	0.004	0.001	0.002	0.002	0.132	0.086	0.061	0.093	0.087	0.038	0.020	0.048
G	0.007	0.003	0.004	0.005	0.001	0.001	0.001	0.001	0.000	0.000	0.001	0.000	0.039	0.019	0.014	0.024	0.030	0.008	0.004	0.014
Year:																				
2009	0.194	0.258	0.255	0.235	0.171	0.241	0.239	0.217	0.255	0.299	0.282	0.279	0.216	0.228	0.225	0.223	0.258	0.274	0.284	0.272
2010	0.234	0.301	0.320	0.285	0.217	0.298	0.315	0.276	0.272	0.333	0.339	0.315	0.235	0.261	0.296	0.264	0.268	0.316	0.301	0.295
2011	0.204	0.189	0.187	0.204	0.206	0.194	0.188	0.196	0.202	0.182	0.185	0.190	0.194	0.188	0.180	0.188	0.197	0.194	0.196	0.196
2012	0.181	0.127	0.118	0.181	0.196	0.133	0.120	0.150	0.150	0.101	0.103	0.118	0.169	0.156	0.147	0.157	0.151	0.119	0.121	0.130
2013	0.187	0.125	0.120	0.187	0.209	0.135	0.137	0.160	0.120	0.084	0.090	0.098	0.187	0.167	0.152	0.168	0.125	0.097	0.098	0.107
Region:																				
North	0.122	0.117	0.060	0.100	0.107	0.095	0.039	0.081	0.186	0.102	0.036	0.108	0.169	0.177	0.077	0.141	0.249	0.228	0.057	0.178
Oporto	0.262	0.192	0.160	0.206	0.294	0.224	0.166	0.229	0.238	0.165	0.165	0.189	0.141	0.183	0.170	0.165	0.094	0.126	0.147	0.122
Center	0.210	0.214	0.143	0.190	0.164	0.175	0.106	0.149	0.289	0.223	0.103	0.205	0.376	0.314	0.175	0.289	0.404	0.388	0.186	0.326
Lisbon	0.305	0.323	0.464	0.363	0.365	0.393	0.546	0.433	0.13	0.311	0.525	0.322	0.090	0.159	0.356	0.202	0.051	0.102	0.323	0.159
Alentejo	0.033	0.033	0.022	0.029	0.013	0.021	0.016	0.017	0.025	0.028	0.013	0.022	0.142	0.075	0.036	0.085	0.111	0.051	0.037	0.066
Algarve	0.059	0.100	0.128	0.095	0.052	0.081	0.109	0.08	0.102	0.140	0.131	0.124	0.063	0.070	0.163	0.098	0.064	0.072	0.215	0.117
Islands	0.009	0.021	0.023	0.018	0.005	0.012	0.017	0.011	0.029	0.030	0.028	0.029	0.018	0.022	0.022	0.021	0.027	0.032	0.035	0.031

Portugal into seven territorial units to obtain the regions. Apart from two exceptions, these follow the official nomenclature. Given its market transaction relevance, the Oporto metropolitan area was isolated from the North region. Conversely, the Azores and Madeira islands were grouped together into a single category due to the low number of transactions in these regions. The Table 2 data description takes into account the separation between apartments and houses and between new and existing dwellings. However, as this paper extends the analysis of the impact of energy efficiency to the whole spectrum of price distribution, the dwelling attributes are summarised at the 0.1th, 0.5th and 0.9th price quantiles as well as for all observations. For the nine levels of the EPC energy scale, this also presents the proportion of each energy label according to each transaction value tertile group.

Table 2 reports how over 50% of the transactions refer to existing apartments, followed by new apartments (23.2%), existing houses (13.0%) and new houses (5.3%). The average and median transaction prices are €119,888 € and €96,200, respectively. Unsurprisingly, houses display higher average and median prices relative to apartments and new builds account for higher average and median prices than existing units. Interestingly, the greatest heterogeneity in houses is revealed when the 0.1th and 0.9th price quantiles are compared with those of apartments. While at the 0.1th price quantile, the average price for houses is lower than for apartments, the opposite happens at the 0.9th price quantile, thus suggesting the existence of a wider amplitude of values for the former dwelling type. As expected, new properties display larger average gross and dependent floor areas and register a higher average number of bedrooms than existing properties.

The highest number of transactions takes place in 2009 and 2010, which account respectively for 23.5% and 28.5% of all transactions available in the dataset. The following years record a lower number of transactions, reflecting the period of time in which the Portuguese residential property market was depressed. Furthermore, the urban region of Lisbon, followed by the Oporto metropolitan area, account for the highest number of transactions (36.3% and 20.6%, respectively). At the other extreme, the Alentejo region and the Azores and Madeira islands together represent less than 5% of all transactions. One prominent feature of the Lisbon region is the fact that it accounts for more than 50% (30%) of the transactions of the most expensive apartments (houses) in the 0.9th price quantile. Conversely, the Oporto metropolitan area and the Centre region, concentrate the highest percentages of transactions at the lowest quantiles in the price distribution.

Fig. 1 provides another perspective on the frequency of the EPC ratings over the different price distribution quantiles. This figure highlights four points. Firstly, the proportion of the most efficient labels increases as the price quantile increases. One example of this is the fact that most efficient ratings (A^+, A, B and B^-) account for less than 20% of the properties in the 0.1th price quantile. However, these same ratings represent around 40% and 60% of the most expensive houses and apartments, respectively. This reflects an expected outcome suggesting the existence of a positive relationship between efficiency levels and property prices.

Secondly, the energy efficiency rating for apartments is generally higher than for houses. While the most common rating for apartments is C, followed by B, for houses the most frequent label is D, followed by C. This difference may stem from physical and engineering differences between the two dwelling types. For instance, while the building envelope of a house (i.e., what separates the indoor and outdoor environments) does not usually include shared walls, an apartment is often concomitant to other dwellings included in a bigger envelope. For this reason, the latter are often less exposed to the external environment than the former and it is consequently technically more difficult to ensure high energy efficiency standards in houses than in apartments. Thirdly, the figure details how new properties register higher energy efficiency performances than existing properties. This difference is more

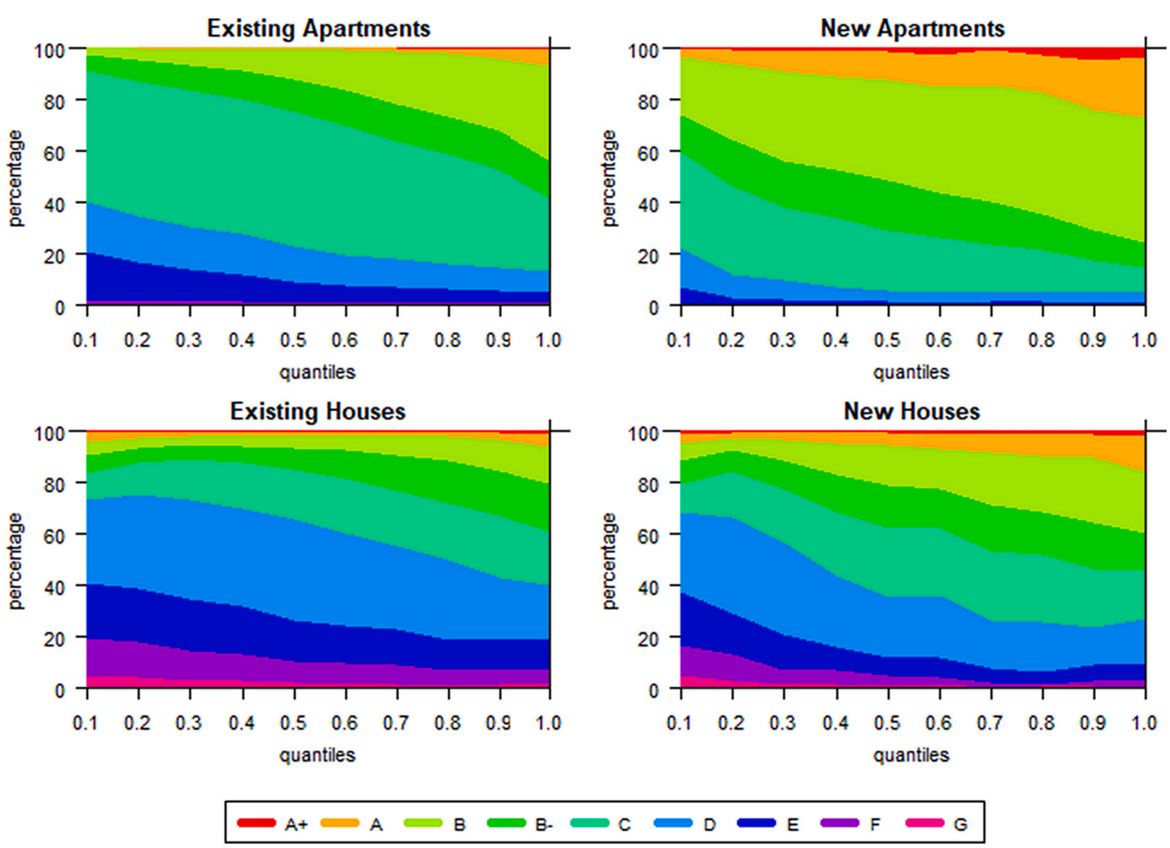

Fig. 1. Relative importance of EPC labels (%) at different price percentiles.

pronounced than that reported for apartments and houses. The adoption throughout time of building codes with better energy saving requirements may help in explaining this outcome.

Finally, the figure reveals how the percentage of transacted dwellings is rather low at both extremes of the EPC scale. In fact, when grouped together, the A^{+} and A ratings account for only 4.8% of the transactions. Similarly, the F and G ratings represent only 2.6% of all observations. This situation has conditioned the interpretation of the quantile regression results when incorporating a disaggregated energy efficiency scale and restricted the reading of the energy efficiency partial effect results to those located at the centre of the EPC scale (i.e., the B, B^{-}, C, D ratings).

4. Results

This section presents and discusses the energy efficiency partial effects of UQR over the price distribution. OLS and, in some cases, CQR results are also provided as a reference. Three sets of partial effects are analysed. The first considers different forms of including the EPC label in the hedonic model. The second details the time and regional effects by considering the discrete *EED* scale. The third set of results additionally presents a quantile house price index for Portugal.

4.1. Measuring the impact of the EPC label through applying different scales

Table 3 displays the results for the 0.1th, 0.5th and 0.9th quantiles and Figs. 2 to 4 detail a wide variety of quantile results, displaying the 0.05th to 0.95th quantiles for both the discrete *EED* (Fig. 2) and AB (Fig. 3) scales or, in the case of the seven-level energy efficiency scale, the 0.25th to 0.75th quantiles (Fig. 4). In addition to quantile regression, the table and figures also show OLS results and the 95% confidence intervals for all of the point estimates.

Evangelista et al. (2020) revealed significant but relatively stable CQR results across the price quantiles of the EPC labelling (as measured by the binary scale *AB*). Despite some differences relative to OLS, which are more evident in apartments, the very moderate quantile effects consubstantiate a modest added value of the CQR approach relative to OLS. The CQR results in Fig. 2 for the discrete *EED* scale confirm the previously observed stability pattern. However, the UQR results unveil a more heterogeneous impact of the EPC label. These differences emerge in a scenario where UQR reflects a higher volatility when compared to OLS and CQR, and are explicit not only in terms of magnitude but also in the direction of the partial effects in some cases.

The higher variability of UQR relative to the CQR and OLS results has been observed in previous papers in other areas; see, inter alia, Peeters et al. (2017) and Fournier and Koske (2013). The literature acknowledges this increased variability, see Firpo et al. (2009), as stemming from the nature of UQR. While CQR coefficients reflect a *within-group* impact from changing from less to more energy efficient standards - where in our case the *within-group* consists of the set of dwellings with the same values for all covariates (other than energy efficiency), UQR coefficients provide an overall impact change estimate, which reflects, in addition to the *within-group* variation, the *between-group* variation. It is furthermore worth noting that, as Figs. 2 and 3 register, the width of the UQR point estimate confidence intervals is generally larger at the lower and upper quantiles of the price distribution and, as detailed in Fig. 4, inflated when deploying the seven-level scale, especially for most (least) energy efficient labels at the lowest (highest) quantiles of the price distribution. In accordance with expectations and as set out in the lower section of Table 2, these refer to situations in which the percentage of transactions for that energy efficiency label is low.

Despite the figures sometimes displaying relatively high degrees of dispersion, important quantile effects emerge from the UQR results, something that reflects the differentiated responses of buyers at different price quantiles to improvements in energy efficiency property features. Responses to energy efficiency gains are so diverse that apartment and house markets exhibit quantiles with opposite trends as the price

Table 3
Effects of improving one level in the EPC scale, OLS, CQR, and UQR results.

Energy efficiency measure	Apartments							Houses						
	OLS	0.1th		0.5th		0.9th		OLS	0.1th		0.5th		0.9th	
		CQR	UQR	CQR	UQR	CQR	UQR		CQR	UQR	CQR	UQR	CQR	UQR
							Existing							
EED	*0.043**	*0.057**	*0.048**	*0.044**	*0.051**	*0.033**	*0.023**	*0.015**	*0.013**	*−0.013**	*0.017**	*0.022**	*0.017**	*0.024**
	(0.001)	*(0.002)*	*(0.002)*	*(0.001)*	*(0.001)*	*(0.001)*	*(0.002)*	*(0.002)*	*(0.003)*	*(0.005)*	*(0.002)*	*(0.002)*	*(0.002)*	*(0.004)*
AB	*0.118**	*0.138**	*0.131**	*0.117**	*0.105**	*0.105**	*0.042**	*0.045**	*0.021*	*−0.182**	*0.049**	*0.087**	*0.077**	*0.095**
	(0.002)	*(0.004)*	*(0.007)*	*(0.002)*	*(0.005)*	*(0.003)*	*(0.010)*	*(0.006)*	*(0.012)*	*(0.031)*	*(0.007)*	*(0.019)*	*(0.009)*	*(0.023)*
B	*0.164**	*0.211**	*0.178**	*0.161**	*0.119**	*0.127**	*−0.161**	*0.042**	*−0.000*	*−0.401**	*0.052**	*0.066*	*0.088**	*0.142**
	(0.003)	*(0.007)*	*(0.017)*	*(0.004)*	*(0.0160)*	*(0.005)*	*(0.048)*	*(0.010)*	*(0.019)*	*(0.050)*	*(0.011)*	*(0.037)*	*(0.015)*	*(0.036)*
B^{-}	*0.089**	*0.126**	*0.161**	*0.086**	*0.113**	*0.055**	*−0.031*	*0.055**	*0.029*	*−0.118**	*0.054**	*0.127**	*0.087**	*0.076**
	(0.003)	*(0.007)*	*(0.010)*	*(0.004)*	*(0.008)*	*(0.005)*	*(0.016)*	*(0.008)*	*(0.016)*	*(0.043)*	*(0.009)*	*(0.023)*	*(0.013)*	*(0.034)*
C	*0.014**	*0.045**	*0.072**	*0.013**	*0.027**	*−0.013**	*−0.069**	*0.033**	*0.023*	*0.079**	*0.029**	*0.062**	*0.041**	*0.021*
	(0.003)	*(0.005)*	*(0.007)*	*(0.003)*	*(0.006)*	*(0.004)*	*(0.011)*	*(0.007)*	*(0.013)*	*(0.025)*	*(0.007)*	*(0.015)*	*(0.011)*	*(0.011)*
N. Obs.				149,920							*33,282*			
							New							
EED	0.054*	*0.062**	*0.085**	*0.054**	*0.052**	*0.046**	*0.029**	*0.022**	*0.026**	*−0.006*	*0.025**	*0.030**	*0.025**	*0.020**
	(0.001)	*(0.002)*	*(0.003)*	*(0.001)*	*(0.001)*	*(0.001)*	*(0.003)*	*(0.002)*	*(0.003)*	*(0.008)*	*(0.002)*	*(0.003)*	*(0.003)*	*(0.005)*
AB	*0.123**	*0.132**	*0.163*	*0.118**	*0.116**	*0.112**	*0.094**	*0.055**	*0.063**	*−0.182**	*0.060**	*0.052**	*0.068**	*0.034*
	(0.002)	*(0.004)*	*(0.009)*	*(0.003)*	*(0.007)*	*(0.004)*	*(0.019)*	*(0.006)*	*(0.011)*	*(0.045)*	*(0.007)*	*(0.015)*	*(0.010)*	*(0.030)*
B	*0.121**	*0.172**	*0.148**	*0.128**	*0.084**	*0.056**	*−0.016*	*0.067**	*0.074**	*−0.320**	*0.069**	*0.098**	*0.101**	*0.037*
	(0.005)	*(0.008)*	*(0.018)*	*(0.005)*	*(0.021)*	*(0.007)*	*(0.078)*	*(0.009)*	*(0.018)*	*(0.085)*	*(0.010)*	*(0.028)*	*(0.014)*	*(0.055)*
B^{-}	*0.043**	*0.095**	*0.116**	*0.054**	*0.060**	*−0.023**	*−0.095**	*0.027**	*0.048**	*−0.153**	*0.034**	*0.069**	*0.051**	*0.000*
	(0.006)	*(0.009)*	*(0.019)*	*(0.006)*	*(0.016)*	*(0.007)*	*(0.034)*	*(0.009)*	*(0.018)*	*(0.068)*	*(0.010)*	*(0.024)*	*(0.014)*	*(0.043)*
C	*−0.014**	*0.035**	*0.005*	*−0.001*	*0.005*	*−0.080**	*−0.078**	*0.018**	*0.029*	*0.080*	*0.016*	*0.055**	*0.034**	*−0.032*
	(0.006)	*(0.008)*	*(0.016)*	*(0.005)*	*(0.015)*	*(0.007)*	*(0.022)*	*(0.008)*	*(0.016)*	*(0.047)*	*(0.009)*	*(0.019)*	*(0.012)*	*(0.035)*
N. Obs.				*59,410*							*13,533*			

Notes: The dependent variable of the models is the logarithm of transaction value. Standard errors are in parenthesis. The * sign represents the statistical significance at the 0.05 level. Results for UQR are displayed in Fig. 2 (EED), 3 (AB) and 4 (B, B-, C). Results for CQR for EED are displayed in Fig. 2. Additional results available from the authors upon request.

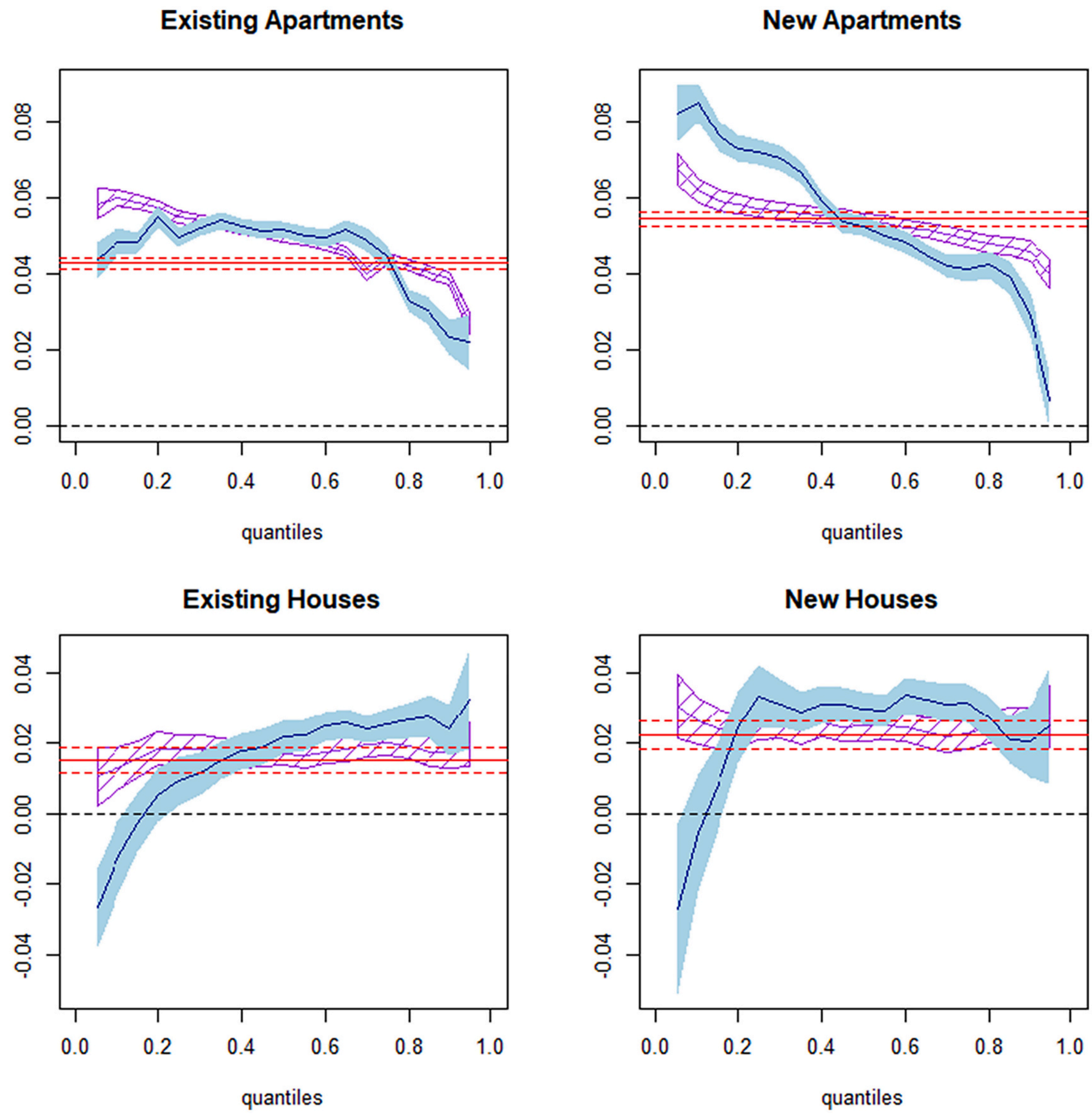

Fig. 2. EPC effect on transaction prices (discrete scale EED) - CQR (dashed purple) and UQR (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

quantile increases, the former displaying clearly decreasing premiums and with the latter recording a moderate increase in effect. This difference is naturally exacerbated at the lower price quantiles where the responsiveness in terms of premium is at the highest level for apartments (especially new) and at the minimum, and actually sometimes negative, level for houses. This is apparent both in the discrete *EED* and the *AB* variables in Figs. 2 and 3, with the latter displaying the impacts of a larger magnitude due to the measurement of a global effect of the aggregate *AB* of 4 letters relative to the set of D-G ratings below reference.

The way energy efficiency is rewarded across the price distribution clearly differs between apartments and houses, not only in terms of quantile shape but also because the former receive, in general, higher price premiums when compared to the latter. The OLS results of Evangelista et al. (2020) had already featured this: for example, the premium for *AB* energy efficiency labels was 12.3% for new apartments and 5.5% for new houses. Despite revealing similar differences for those properties at the central location (the median) of the price distribution (respectively, 11.6 and 5.2%), UQR unveils new patterns of responsiveness of apartment and house buyers as discussed in the previous paragraph, behaviours that the CQR estimates, given their stability and closeness to the OLS results, do not capture. In particular, we would note that the high rewards for low priced apartments, especially for new properties where there is an upgrade reward of 8.5% per EPC letter (16.3% for the *AB* classification), contrasting with the low or almost inexistent reward at high prices. The potential energy saving disregard at the high end of the price distribution may stem from how good energy efficiency performances are standard for most expensive apartments. On the other hand, homebuyers of houses, which are on average less responsive to energy saving features, for price quantiles higher than the 0.4th on the discrete scale and the 0.2nd on the AB scale, probably due to increases in the housing area and the consequent increase in energy costs, tend to respond positively and stably to energy saving labels. In contrast, for low priced houses, one letter increases in energy efficiency tend to be either mostly penalized by price discounts or irrelevant for existing and new properties, respectively. Buyers in this market segment appear to overweigh the costs involved in energy saving devices relative to the potential reductions in the energy bill. This feature was missed by both the OLS and CQR results, essentially because the former merely captures the response at the mean level and the latter provides results conditional on housing characteristics.

By comparing the energy partial effects for existing and new

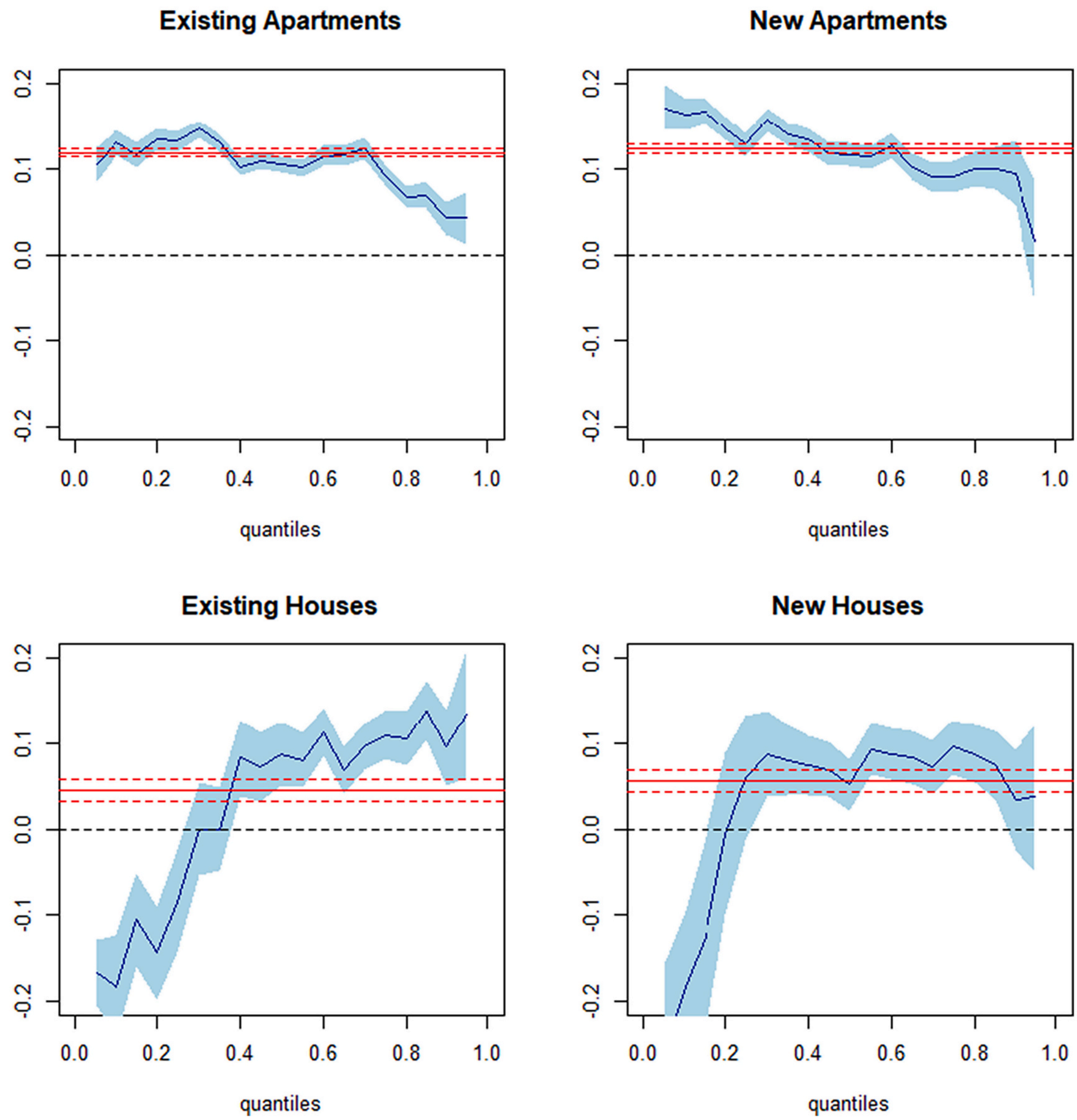

Fig. 3. EPC effect on transaction prices (AB scale).

dwellings, it is possible to verify that, although the conditional mean effect tends to be slightly higher for new properties, it is not generally possible to identify a clear higher energy efficiency price reward for this type of properties when compared with existing properties. This is seen through Figs. 2 and 3, where energy efficiency partial effects for new and existing dwellings usually share a common pattern for almost all of the quantiles of the price distribution. Low priced apartments constitute the exception to this pattern, where new apartments show larger energy efficiency price premiums than the one obtained for existing apartments. For instance, new apartments show an energy efficiency price premium that almost doubles the one obtained for existing apartments in the 0.1th quantile.

Despite the high variability, analysis of the results for the seven-level scale (Fig. 4) suggests some additional conclusions. First, in both the OLS and quantile confidence intervals, excessive overlapping is observed for houses while the differences in responsiveness for apartments are clear. The overlap in existing houses is more relevant in the OLS results while for new houses is more evident in UQR where variability occurs at the highest levels. In particular, for new houses an OLS premium of B relative to D of around 6.7% more than doubles that of B^-, while C presents a smaller premium of 1.8%. On the other hand, for existing (new) apartments OLS premiums of 16.4% (12.1%) for B, are followed by 8.9% (4.3%) for B^- and with a far less relevant difference for C across both dwelling categories. The UQR results reflect the descending global quantile shape of both *EED* and *AB* according to the apartments price, with the novelty that, at high price quantiles, discounts are sometimes observed. We would note that the discounts on low priced houses already detected through *EED* and *AB* also clearly emerge in this scale and increase for the highest labels.

In general, the application of three alternative measurements of the EPC scale results in rich analytical results as different types of price responses are measured. In particular, two major aspects emerge. Firstly, the *AB* scale appears as an effective way of examining the robustness of the results of the central EPC measure *EED*, as the estimated quantile patterns are very similar (despite their different magnitudes). Secondly, the seven-level scale based on dummy variables allowed a complementary and more detailed characterization of price responses to particular ratings. For the remainder of this paper, the analysis focuses on the discrete *EED* scale. On the one hand, the calculation of disaggregated effects by year and by region separating EPC ratings is unsuitable, due to the scarcity of observations and the limitations already identified with this scale. On the other hand, the *AB* binary approach patterns mimic those of the discrete measurement *EED*.

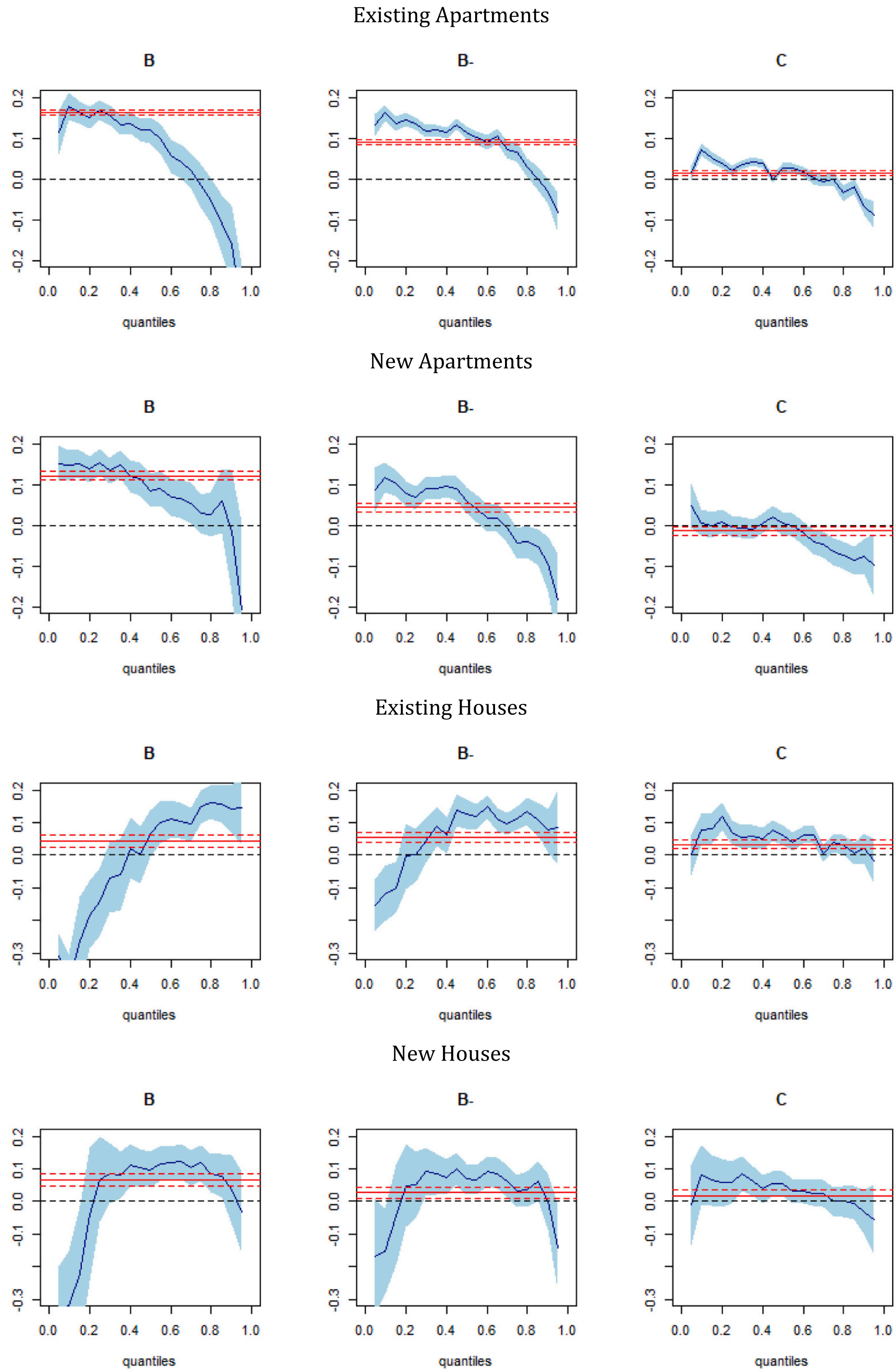

Fig. 4. EPC effect on transaction prices (disaggregated scale).

4.2. *The time and regional effects of the EPC label*

Fig. 5 presents the evolution of the energy efficiency partial effects throughout the quantiles of the unconditional price distribution of residential properties for each one of the five years considered in this study. As in the previous section, Fig. 5 also provides the OLS results and 95% confidence intervals.

As the results demonstrate, the average energy efficiency partial effects remain relatively stable across time for apartments and houses. This is more evident for houses where there are overlapping confidence intervals among the different estimates that do not preclude the hypothesis of being the same for every year. However, this relative stability contrasts with the results returned by the quantile partial effects that display a variety of patterns throughout the years and for the different market segments.

The overall patterns of the previous section for 2009–2013, which

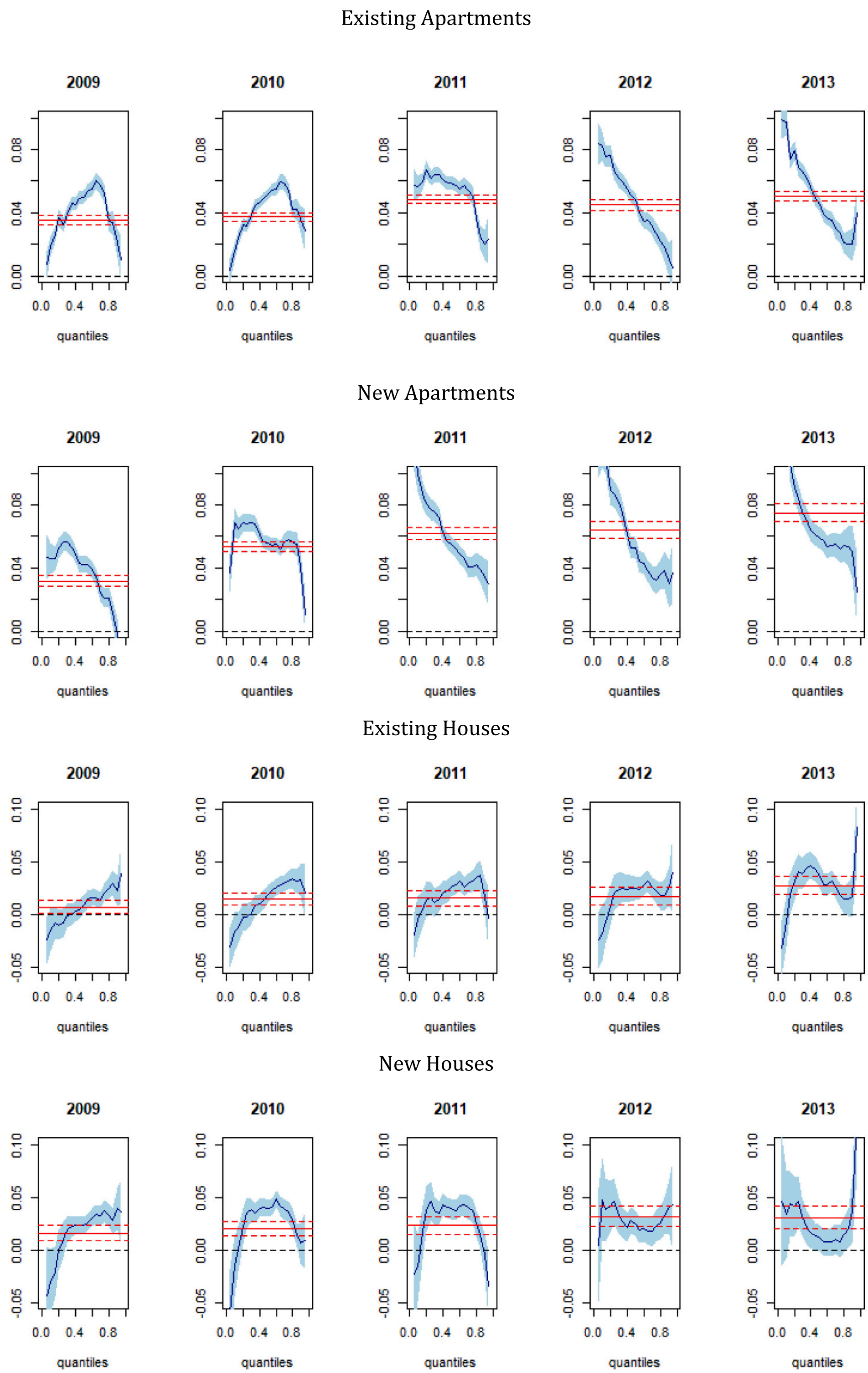

Fig. 5. EPC effect on transaction prices — disaggregation by year.

display decreasing premiums for EPC upgrades as the prices of apartments increase and discounts at low priced houses followed by stable or slightly increasing effects for houses, are not reflected in the yearly behaviour. For apartments, decreasing premiums occur in the last two years under analysis (2012 and 2013). However, in previous years, the responses to the label changed substantially, especially for the low-priced segment where homebuyers of existing (new) properties, in 2009 and 2010, award a smaller (similar) reward to an EPC rating upgrade than those in the central quantiles of the price distribution. This pattern changed in 2011, when there was a significant fall in the proportion of transactions observed; see section 3. In 2011, homebuyers of existing (new) apartments start to provide a similar (larger) reward to those in the median quantiles, which was then amplified in the subsequent years. For houses, in a scenario of increased variability, it is worth noting that discounts or irrelevant responses in the low price quantiles declined over the years for new properties. In general, an increasing effect with the price in 2009, is followed by a nonlinear quantile behaviour in 2010 and 2011 and a somewhat random and volatile pattern in 2012 and 2013, which may interconnect with the drop in the number of transactions in these years.

Overall, we may state that the market price premium responsiveness to energy efficiency improvements has risen over the years. This suggests that in the case of Portugal, the market required a certain period of time to incorporate the benefits of a property registering the most energy efficient EPC ratings. This rising level of awareness is particularly promising as it occurred in a time span impacted by crisis, which was reflected in our dataset by a reduction in the number of transactions, see also the results on the price indexes in section 4.3. Finally, despite being promising, the scenario clearly calls for policies aimed at increasing the responsiveness of homebuyers to high (low) price apartments (houses).

Fig. 6 provides results for each of the seven regions considered by the hedonic models.

The regional responsiveness to energy efficiency improvements is very heterogeneous. However, we may summarise the results in four main points. Firstly, due to the low number of transactions in the Alentejo region and the Azores and Madeira archipelagos, the OLS and UQR results are particularly volatile and show wide confidence intervals. As such, the results of these regions have not been subject to

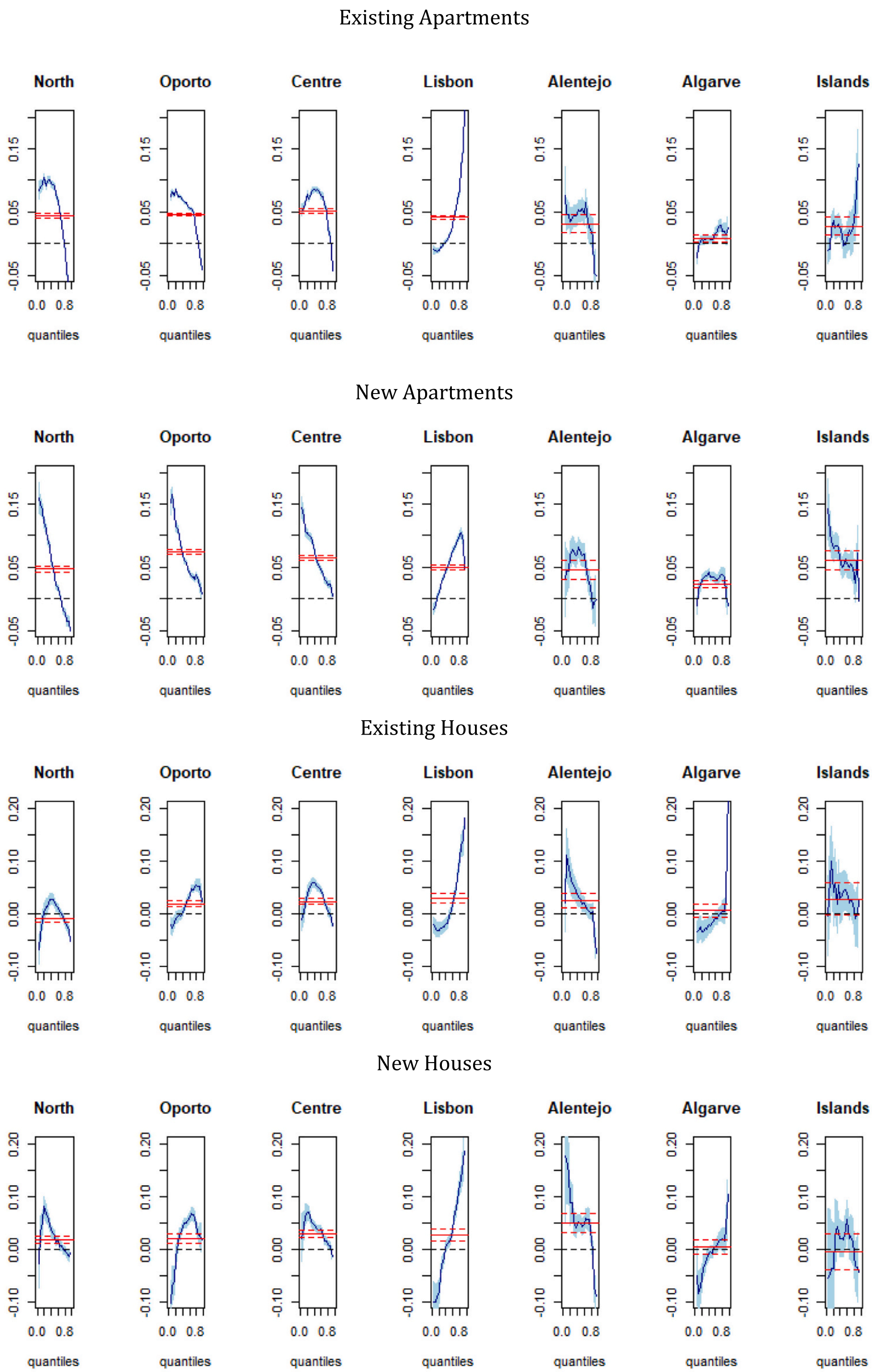

Fig. 6. EPC effect on transaction prices — disaggregation by region.

analysis. Secondly, in the Algarve region, the effects of the EPC label are either statistically irrelevant for houses or, in the case of apartments, much lower than in other regions. One possible explanation may derive from how the Algarve is a tourist region in which many properties are bought as secondary or temporary residences, with energy efficiency potentially not perceived as an important attribute. Thirdly, the results identify how Lisbon displays a distinctive behaviour when compared to the rest of the regions. This translates into price discounts at the lower price quantiles and higher price premiums for the most expensive properties. Although there is no clear-cut explanation for these facts, the attractiveness and concentration of the transactions of the most expensive properties in Lisbon (see Table 2), may help in explaining, at least for the upper end of the market, why the region exhibits a price pattern different from the rest of the country. Finally, the energy efficiency market responsiveness found for Oporto, North and Centre regions are very similar and closely resemble that displayed in Fig. 2. Moreover, when compared with these results, energy efficiency price discounts emerge not only in the lower price quantiles for houses but also for most expensive apartments in the North and Oporto regions and for existing apartments in the Centre region.

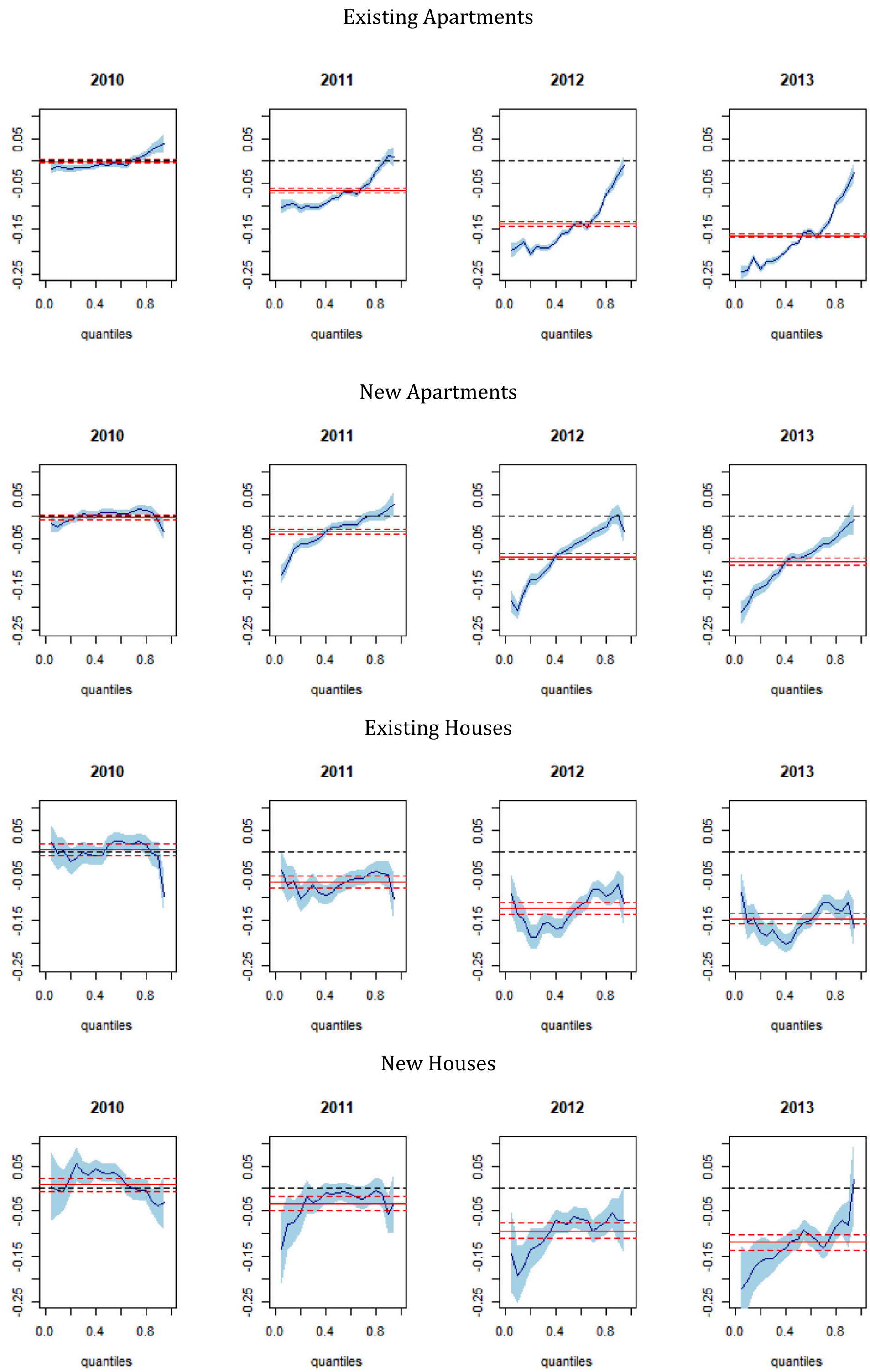

Fig. 7. Residential price indexes (fixed base at 2009).

4.3. An unconditional quantile price index

This section extends the quantile regression analysis carried out in the previous sections to study how prices behaved in the Portuguese residential property market across the distribution of dwelling sales between 2009 and 2013, a period influenced by economic crisis and a slump in housing prices. More concretely, we estimate a time dummy quantile hedonic price index by taking the anti-log of the coefficient estimates of the yearly time-dummy variables included in the models for the four market segments presented in this paper; see Hill (2013) for details on the construction of time-dummy price indexes.

Although using quantile regression for the analysis of residential price changes is not a novelty, evidence on this topic is not abundant and, where available, it is derived using the CQR framework (see, for example, Coulson and McMillen, 2007; Zhang and Yi, 2017). While the construction of conditional quantile price indices focuses on the theoretical conditional price distribution of dwellings, the usage of the unconditional quantile regression framework allows researchers to evaluate inflation at any point on the price distribution without any conditionality constraints. By using UQR, we are not only able to analyse the general evolution of dwelling prices across the different market segments (e.g., high, medium and low segments) but also to assess their plausibility against the results for the mean of the price distribution provided by the official price index for Portugal (Instituto Nacional de Estatística, 2014).

Fig. 7 below displays the estimated yearly price changes for the four markets in Portugal from 2010 to 2013 according to the UQR and OLS estimators, obtained from the models in Section 4.1, based on the *EED* measure applied to produce Fig. 2. The values are expressed as the cumulative price changes adopting 2009 as the base year.

Fig. 7 reports the OLS and UQR results that portray an overall decline in residential prices over the period considered in this paper. Although more evident in 2011 and 2012, this also extends into 2013, something that is in line with the figures published by the official house price index for Portugal. In effect, when compared to 2009, the official price index for Portugal reports annual price drops of 4.17%, 10.95%, and 12.63% in 2011, 2012, and 2013, respectively. For 2010, this indicator records a marginal price increase of 0.77%.

More importantly, Fig. 7 reveals relevant differences in the way prices change across the whole spectrum of price distribution, with the overall decline in prices impacting less prominently for the most expensive properties than for the less expensive properties. This is particularly evident for apartments from 2011 to 2013, for new houses from 2012 to 2013 and for the central price quantiles (0.4th to 0.6th quantiles) of existing houses. In contrast, for apartments in 2010, and for houses in 2010 and 2011, the quantile results do not align with this pattern except for in the higher quantiles and the most expensive existing apartments, where there is a clearly increasing trend in price premiums.

Overall, the results highlight the importance of carrying out quantile regression analysis to gain a broader view of the trends in residential property prices. In this particular case, they convey how the impact of the financial crisis, captured by the overall drop in the mean price of properties, was not homogeneous across the distribution of dwelling prices. While the lower end of the residential property market tends to exhibit price decreases, high-priced properties seemed to be more resistant to the effects of the crisis. Apartments, for instance, illustrate this situation perfectly as the deterioration in prices was very small for the most expensive properties, while the discounts through time were substantial for apartments located at the bottom of the price distribution.

5. Conclusions

This paper provides a comprehensive analysis of the impact of the EPC label on residential property prices in Portugal between 2009 and 2013, a period characterised by the beginning of the legal enforcement of issuing energy efficiency certificates for all dwelling transactions and that largely overlaps with years in which the Portuguese housing market was severely depressed.

The impact of energy efficiency on dwelling transaction prices at the national level was analysed for the first time using the UQR framework in such a way as to allow for their assessment across the price distribution, over time, regions, type of property and according to its new or existing status. This flexible analytical setting yielded very important information not only to those interested in unveiling the complex relationship between energy efficiency and transaction prices in the residential market but also because it provides an illustration of the usefulness of UQR results to tailoring policy measures aimed at increasing energy efficiency levels in Portugal.

The results demonstrate that the impact of the EPC label was not uniform across the price distribution and that it clearly displays differences according to the property type. When analysing the reactions to energy efficiency improvements, we may discern that, while for apartments the impact decreases from the lowest to the highest price quantiles, the opposite pattern emerges for houses with homebuyers targeting the cheapest market segments exhibiting clear price discounts. While the existence of price discounts does not emerge by simply looking at the mean of the price distribution, the use of quantile regression returns these insights and provides a clearer view of the full impact of the EPC label on residential prices. The existence of discounts also emerges for the higher end of the price distribution for apartments at the most energy efficient EPC levels and for the North region of the country when quantile regression analysis is disaggregated by level and region, respectively.

The results returned by the unconditional quantile price index indicate how the housing market crisis did not affect all market segments uniformly with properties pertaining to the highest price quantiles remaining almost unaffected by the strong overall downward price effect experienced throughout this depressed market period.

Analysis of the UQR results throughout time highlights two interesting aspects associated with the implementation of EPC certification in Portugal. Low priced apartments, precisely the segment of the market most affected by the crisis, seem to increasingly reward energy efficiency over the course of time. In fact, in the last two years covered by the dataset (2012 and 2013), these properties register a shift in the entire distribution of partial effects towards better price responsiveness to greater energy efficiency. For houses, an encouraging feature arises with the reduction in the estimated price discount as we move towards 2013.

Moreover, the UQR results illustrate their capacity to provide information important to designing effective policies for this market. In the particular case of Portugal, and based on the analysis undertaken in this paper, we may identify three areas of intervention for which specific tax or financial program incentive schemes might be designed. The high-priced apartment segment, where the UQR results reveal that buyers are not attentive to increases in energy efficiency features, stands out as the first of these areas. Given that tax incentive schemes for high-income earners would be politically sensitive, one possible means of addressing the specific characteristics of this market segment would involve designing programs that could finance dwelling energy efficiency gains in renovation works.[4] Houses, particularly those located at the lower end of the price distribution, emerge as the second possible area for intervention. Given its importance in the Portuguese housing stock,[5] this

[4] Addressing renovations seems to be a good intervention area as according to Zangheri et al. (2021), Portugal accounts for the lowest values for energy savings generated from renovations in the European Union.

[5] The Portuguese housing stock amounts to 5,859,540 classic residential dwellings (Instituto Nacional de Estatística, 2012). Of these, 52% refer to residential single family (detached, semi-detached and row) houses (author's own calculations based on Census data).

is a dwelling category that should receive special attention from policy makers. One feasible example would be the application of a reduced transfer tax scheme linked to the EPC scale coupled with information awareness campaigns on the benefits of higher energy efficiency standards. Finally, the extension of any of the abovementioned policy measures to the lower end of the residential price distribution of all property types in the Lisbon area, the Portuguese region with both the greatest degree of urbanisation and the highest number of transactions, constitutes the third intervention area for implementing more effective energy efficiency schemes.

Inclusion and diversity

One or more of the authors of this paper self-identifies as living with a disability. The author list of this paper includes contributors from the location where the research was conducted who participated in the data collection, design, analysis, and/or interpretation of the work.

CRediT authorship contribution statement

Rui Evangelista: Data curation, Software, Validation, Writing – original draft. **João Andrade e Silva:** Investigation, Methodology, Visualization, Writing – review & editing. **Esmeralda A. Ramalho:** Supervision, Conceptualization, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2022.105955.

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