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Invited Review Article

The price premium of residential energy performance certificates: A scoping review of the European literature

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A R T I C L E I N F O

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A B S T R A C T

Achieving a reduction in energy demand and a decarbonisation of the energy supply is crucial to reaching overall goals for Net Zero by 2050, underscoring the importance of energy efficiency improvements in the housing sector. While Energy Performance Certificates (EPCs) in the EU are important tools to encourage investment in energy efficiency through market signals, their effectiveness remains in question. This review aims to summarise the European academic literature in English on the price premium of residential EPCs. The objectives are to summarise the scope and scale of the research, the methodological approaches and limitations, and to synthesise the estimated price premium. Adopting a scoping review approach with digital databases and artificial intelligence tools for literature searching, 68 studies and 111 models are included covering studies to May 2024. Findings show that studies are mainly concentrated in those parts of Europe where EPC data are openly available, and that the publication pace increased in recent years. With hedonic models being the dominant approach, major limitations found in this field include property-level data availability and omitted variable bias (OVB), rendering difficulties in isolating the impact of energy efficiency. Results synthesis shows a positive price premium for energy-efficient homes, as well as some variation between submarkets. It suggests future research needs to leverage new forms of data and methods to address the OVB, as well as exploring submarkets and studies on wider housing market impacts. To realise a sustainable transition, policymakers should support property-level data infrastructure, strengthen the implementation and harmonisation of the EPC system, and tailor energy retrofit policies for different submarkets.

1. Introduction

Residential buildings account for around 17 % of CO_2 emissions and 21 % of energy demand globally [1]. To achieve overall goals for Net Zero by 2050, a significant reduction in energy demand and a decarbonisation of the energy supply is crucial [2]. In the residential building sector, improving building energy efficiency could help both processes. It is also vital in reducing residents' vulnerability to energy crises when shortages of energy supply lead to increased prices. Moreover, the poor energy efficiency of dwellings is a major factor for low-income households experiencing fuel poverty, who have to spend a high proportion of income to keep their homes at a comfortable temperature [3]. Overall, the ongoing climate emergency, energy crisis due to geopolitical tensions, and social inequality highlight the urgent need to accelerate the sustainability transition of housing globally.

Mandatory building energy codes play an important role in improving the resilience of the buildings sector, by revealing energy efficiency information for governments, households, and businesses, and encouraging investment in energy efficiency. Currently, 80 countries have adopted building energy codes globally, of which 43 countries have mandatory ones [4]. The EU issued the Energy Performance of Buildings Directive (EBPD) in 2010 [5] which initiated Energy Performance Certificates (EPCs). EPCs are designed to reveal energy efficiency information to consumers and others, eliminating one of the main barriers to energy efficiency investment [6]. Moreover, the Directive has become a significant policy in the housing market as it requires EPCs to be displayed in any sale or rental advertisement. EPCs could therefore play an important role in facilitating the capitalisation of energy efficiency in the housing market and thereby incentivise stakeholders (i.e. homeowners, landlords and tenants, investors, developers, financial institutions).

However, current evidence of the price premium of EPCs is mixed.

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Some studies suggest a price premium for more energy-efficient buildings, others argue that energy efficiency is not appreciated or has no influence in the housing market. While there is a relatively large body of quantitative research evidence, it varies in geographic and temporal coverage, and in the methods applied. A small number of reviews exist already. Two reviews adopt a systematic approach, including [7] and [8]. Cespedes-Lopez et al. [7] applied a *meta*-analysis to review the price premium of properties having an energy certificate globally as well as those of each energy band in Europe, including journal articles, book chapters, reports and theses. Fregonara and Rubino [8] only reviewed the methodologies used to measure the price premium of EPCs in European studies. However, the searching and screening approach taken in these reviews is either relatively limited in scope or the information on the process is incomplete. Two other studies provide a more narrative review. Marmolejo-Duarte et al. [9] only include studies in Spain, and Wilkinson and Sayce [10] merely look at a limited number of studies and case study projects in Europe. Among the three review papers aiming to find the price premium of energy efficiency, the systematic review [7] found there exists an increase in price premium with better energy efficiency – statistical synthesis showed homes with band A have 9.9 % higher sales price compared to band D, while the two narrative reviews suggest either no effective impact [9] or different results across studies [10]. A comprehensive and up-to-date scoping review of existing works is therefore required.

To gain a comprehensive picture of the literature in terms of geography, time coverage and methods as well as results, the aim of this paper is to provide a scoping review [11] of the European academic literature in English on the housing market impact of EPCs. To our knowledge, this is the first scoping review in this field. Despite the global importance of energy codes, this review concentrates on European literature for two reasons. First, it is one of the dominant economic areas contributing largely to building energy efficiency investment. Second, the EPC system is relatively well-developed and consistent across the EU. We focus on peer-reviewed academic sources (i.e. journal articles, book chapters, and PhD theses) only to improve consistency and trustworthiness of the included literature. This review is limited to literature providing quantitative evidence on the sales/rental price premium attached to EPCs in the period subject to the EBPD. Overall, this review summarises peer-reviewed academic sources of European literature in English with coverage to May 2024. To ensure comprehensive coverage of the target literature and the reproducibility of our review, we take a transparent, systematic approach to identifying and screening the literature. This also enables others to build on work by covering other literature including works in other languages or non-academic sources. Our review contributes to the current literature by providing a holistic, scientific, and up-to-date overview of quantitative price-based studies of EPC impacts on the housing market. The detailed research questions are as follows:

(1) What is the scope and scale of the quantitative evidence of the price premium of energy efficiency under the EBPD in terms of geography? How has this literature evolved over time? Which housing sub-markets have been studied more or less, in terms of housing market contexts (i.e., tenure and price type), population (i.e. dwelling type) and intervention (i.e. EPC type)?
(2) How are these studies conducted, i.e. what research designs and analytical models do they employ? What are the variables mostly used in modelling? Is there methodological limitation in the literature?
(3) What price premiums are found in the literature? How do outcomes vary between different countries or regions? Is there evidence of an increasing premium being placed on energy efficiency over time? Are there differences in the price premium between housing sub-markets e.g. houses/apartments, sales/rental market?

The structure of the article is as follows. First, the *EPC Policy and Practice* section highlights the standards of EPCs as a policy intervention, details variations in how they are implemented in different European countries and provides context of relationship between EPC and price premium. The *Methods* section justifies the chosen review approach, as well as the search and screening process, data extraction, and analytical techniques. The *Results* section presents results on research scope, methods, and outcomes. The *Discussion* discusses the results in the wider policy and research context, limitations of this review, and research gaps. Finally, the *Conclusions and Policy Implications* section gives an overall summary and provides recommendations for policy design.

2. EPC policy and practice

2.1. EPC systems and standards

EPCs were initiated in the Energy Performance of Buildings Directive (EPBD) by the European Parliament and the Council of the European Union. The first version of the EPBD was published in 2002 (Directive 2002/91/EC) [12], requiring member states to implement it by 2006. This was recast in 2010 (Directive 2010/31/EU) [5] followed by a revision in 2018 (Directive 2018/844/EU) [13] with stronger EPC assessment standards. These were required to be implemented in 2012 and 2020 respectively. In practice, all member states had implemented the EPC system in national legislation by 2013 [14]. The EPBD as recast made it mandatory for member states to require the EPC to be displayed in any advertisement of housing for sale or rent, stating that buildings should 'be issued an EPC when they are constructed, sold or rented out to a new tenant' (Directive 2010/31/EU, p.11).

To assess building energy performance, the European Commission has established a set of standards called the energy performance of buildings standards or "EPB standards". It allows the EPC ratings to be assessed based on calculated (i.e. "asset rating") or actual metered energy consumption (i.e. "operational rating"). While the former considers the theoretical energy needs of the building based on the building fabric and its services, the latter is based on the energy delivered to the buildings and is influenced by the way the building is maintained and used by occupants.

There are several presentation forms of EPC ratings. First, the Energy Performance Index (EPI) represents the annual energy usage per unit area (in kWh/m2/year), which is a typical starting point of calculating EPCs. The EPI can be mapped and represented in scores or bands. The EPC score typically ranges 0–100 with higher scores indicating better energy efficiency, while bands range from A (most efficient) to G/H (least).

There are two different aspects of the EPCs i.e. different ways of calculating scores/bands: Energy Efficiency Rating (EER) and Environmental Impact Rating (EIR). EER is based on the energy costs associated with energy usage, indicating how much fuel bills are likely to be and reflecting assumptions about the relative costs of different fuels. In comparison, EIR is based on the annual CO_2 emissions associated with energy use, reflecting assumptions about relative carbon emissions of different fuels. Furthermore, the EPCs also provide current and potential ratings in each case. The latter are based on recommendations for potential improvements.

2.2. EPC practices

In practice, there are ongoing discussions and concerns around the EPC systems, mainly including the reliability/quality of EPCs and its variation between countries.

Questions about current EPCs' quality and reliability have been raised across the EU [15]. Researchers suggested that measures may be of low quality, with significant variations between the EPC and actual energy efficiency of buildings [16,17]. This quality is directly related to both methodology and assessment processes. While the inaccuracy of

EPC calculations could arise from using default input values to represent reality [18], there is also variation in the assessment process between individual energy assessors [19]. This could pose a challenge to stakeholders' trust in the system, impeding housing energy efficiency investments. Moreover, there may be a low level of familiarity with EPCs by the public [20] and financial institutions [21], limiting their impact in the housing market.

Additionally, the methodology, implementation, and data availability of EPCs are quite different across EU countries. While the EPB standards offer an internationally-accepted collection of approaches for assessing energy performance, methodologies vary widely across countries to fit with national features [21]. Among the 28 EU countries (pre-Brexit), 12 have implemented a methodology solely reliant on asset ratings, while the rest adopt both asset ratings and operational ratings depending on building type or building age [22]. Individual countries also adopt different mapping criteria between energy consumption and EPC scores/bands [23], and some use a slightly more sophisticated rating schemes e.g. Italy, Ireland [23]. Additionally, in terms of implementing the advertisement requirements into national legislation, countries have different implementation paces [14]. It was not until 2015 that all EU countries required the EPCs to be listed in advertisements [14]. While the UK left the EU in 2020 ("Brexit"), it has maintained the EPC system since then. A more concerning issue is that the public availability of EPC databases varies between countries. While there is open access to EPC data at a national/regional level in some countries, it is restricted to selected organisations or not openly accessible at all in others [14,23]. Table 1 summarises the countries (including pre-Brexit EU countries and Norway) in groups for different EPC methodology and data availability.

2.3. EPC and price premium

"Price premium" is the percentage price difference in a property with a higher energy efficiency compared to the price that would be paid for the same property if it had a lower energy efficiency. Another term widely used in literature is "Willingness to Pay" (WTP), which is same as price premium when represented by the percentage price difference a customer willing to pay. In this review, these two terms are used interchangeably, with the latter used when explaining things from the buyer's perspective.

The price premium of residential energy efficiency becomes more easily measurable after the introduction and mandatory implementation of EPCs. The mandatory reporting of energy efficiency in the housing market could make the higher running costs of inefficient buildings apparent, as well as higher carbon emissions. Additionally, the "green mortgages" provided by the commercial mortgage sector (e.g., low interest rates for buyers/owners of energy efficient properties) could further improve the potential benefits of owning an energy efficient house [24]. Therefore, potential energy savings, environmental benefits, and other financial benefits would result in a price premium from EPC ratings. In the literature, the price premium of energy efficient homes is also called the "green premium", reflecting the expected higher price of more efficient (i.e. "greener") homes. In comparison, "brown discount" refers to the case when buildings with poor energy efficiency suffer from reduced value.

Table 1
EPC Practices across Countries (pre-Brexit EU and Norway).

EPC practices		Countries
EPC methodology[1]	Asset rating	Austria, Bulgaria, Greece, Hungary, Italy, Lithuania, Luxembourg, Netherlands, Portugal, Romania, Slovakia, Spain
	Asset and operational rating[2]	Belgium, Bulgaria, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Ireland, Latvia, Norway, Poland, Slovakia, Slovenia, Sweden, United Kingdom
EPC data availability[3]	Open access	Denmark, Estonia, Spain, Ireland, Italy, Lithuania, Netherlands, Norway, Portugal, Slovakia, Slovenia, Sweden, United Kingdom
	Restricted access	Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Germany, Greece, Finland, France, Hungary, Luxembourg, Latvia, Malta, Poland, Romania

Note: [1]Information retrieved from [22]. [2]Some countries apply operational rating only to specific type of buildings or building age. [3]Information retrieved from [14,23].

3. Methods

3.1. Review approach

Our approach primarily falls into the remit of a scoping review. We aim to map the existing literature in terms of research scope/scale, research methods and results. There is currently no scoping review on this topic, making it a valuable addition to the literature. Beyond the general conduct of a scoping review, we do however move a stage further in attempting some synthesis of the major findings from the studies identified to provide an initial statement on the overall scale of price premium of EPC bands though we stop short of a formal *meta*-analysis.

3.2. Searching and screening

(1) Process and tools

Focussing on the academic literature published in English, we develop a systematic, comprehensive, AI-supported literature searching and quality-controlled screening process (Fig. 1). The whole process includes (1) determining search terms, (2) determining search commands, (3) database searching, (4) database results screening, (5) AI searching, and (6) AI results screening. This could be a cyclic process as we find AI results are helpful for updating the structured search strategy, though we do not implement this here. More details on each stage are explained in the remainder of this section.

We use an AI tool in two stages including initialising search terms and detecting omitted studies. To initialise search terms, we import seed papers to an AI-based literature recommendation tool to collect similar

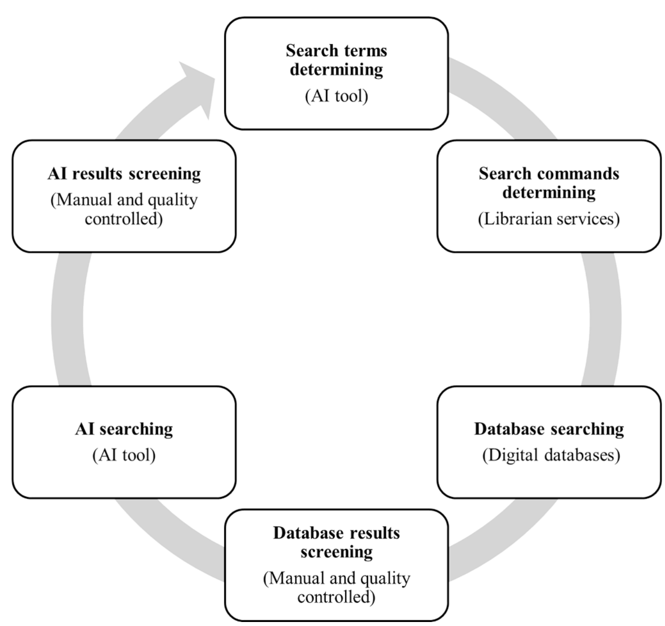

Fig. 1. Searching and Screening Process with Tools/Services Used.

studies, from which we manually identify the search terms and synonyms used. On AI searching, the screened results from the digital databases are imported to the AI tool, which could find similar studies for missing literature detection.

The final choice of digital databases includes Scopus, Web of Science, Business Source Ultimate, Econlit, and International Bibliography of the Social Sciences. The first two are large-scale multidisciplinary databases and others are subject-specific databases relevant to this review, ensuring a comprehensive inclusion of databases. The 'Research Rabbit' (https://www.researchrabbit.ai/) tool is used for AI support. It is an AI-based literature recommendation engine that works based on seed papers and citations, allowing researcher to quickly find studies that are related.

(2) Search terms and commands

To determine the search terms, we identify three seed papers in Google Scholar [25–27] which are agreed to meet the aim of this review and import them into Research Rabbit, where 176 similar studies are identified. We summarise the keywords used in these studies and use these for the title/abstract search (search commands shown in Table 2). Since studies use different logics to describe keywords, we employ two search commands: the first one combines 'house' with 'green premium', and the second combines 'house price' with 'energy efficiency'. Details of search commands for each database is provided in Appendix A.

(3) Inclusion and exclusion criteria

We design the inclusion and exclusion criteria based on population, intervention, outcome, study design, and publication characteristics (Table 3). The research aim is to summarise literature investigating the relationship between EPCs and house prices. First, the literature should target the population of residential buildings, not office/commercial buildings. We exclude studies focusing on office/commercial buildings as they have different EPC regulations compared to the residential market and are affected by different investment decision-making processes. Second, we only include studies exploring the intervention of EPCs implemented in the EU under the EPBD. Additionally, the outcome of any study should include a direct measure of house prices i.e. investigating revealed preferences instead of stated preferences. Also, included literature should adopt quantitative price-based research, while reviews or qualitative research are excluded. Finally, only articles published in peer-review journals, book chapters or theses are included. Noted there existed grey literature on this topic e.g. [28], but this review considers only academic sources to ensure reliability of results. Due to limited time and resources, only studies published in English are considered.

(4) Searching and screening

A summary of the searching and screening process is shown in Fig. 2, including identification and screening of studies from both digital databases and AI tool (Research Rabbit). The digital database searching covering studies until 2nd May 2024. Overall, 68 articles are eligible for final review.

Firstly, digital database searching identified 2277 records (1483 records after deduplication), followed by two stages of screening. In the first stage, titles/abstracts are assessed according to the inclusion and exclusion criteria, through which 1332 (90 %) records are excluded. The reasons include lack of relevance, grey literature, and non-English language. This yielded 151 articles for a further screening. In the second stage, the full text is examined through which 85 articles (56.3 %) are excluded, leaving 66 articles eligible for review. In the full-text screening, there are some studies which are marginal, and where decisions need to be clarified. First, one conference paper [30] and one working paper [31] are included for their contribution to methods which rarely appear in other included studies and meaningful results. We also believe both papers have similar high quality to published articles. The conference paper is subject to stringent peer review and published in distinguished conference proceedings series while the working paper is published in a peer-reviewed journal at the time we write the review. We will refer to the published version of the working paper [32] in the rest of the paper. Second, studies that are unclear and from which it is hard to extract data are also excluded.

Table 2
Finalised Search Command.

Search	Search Command
Search 1	*(hous* OR "domestic propert*" OR "residential propert*" OR dwelling* OR apartment*)* AND ("green value" OR "green premium")
Search 2	*(value OR cost OR price) W/3 (hous* OR "domestic propert*" OR "residential propert*" OR dwelling* OR apartment*)* OR *("housing market" OR "real estate" OR "hous* sales" OR "house prices" OR "housing prices" OR "housing value" OR "domestic property prices" OR "domestic property value" OR "residential property prices" OR "residential property value")* AND ("energy efficiency" OR "energy rating" OR "energy performance certificates" OR "epc")

Table 3
Inclusion and Exclusion Criteria.

Criteria	Inclusion Criteria	Exclusion Criteria
Population	Residential buildings	Office/commercial buildings
Intervention	Energy Performance Certificates (EPC)	
Outcome	Include a direct measure of house price	
Study design	Quantitative price-based research	Qualitative research, reviews
Publication characteristics	Peer-reviewed journal articles or book chapters or PhD theses; Published in the English language	

On screening, we do quality control (i.e. conduct dual review for a random sample of records to estimate if error rates are within acceptable bounds) to reduce the reporting bias. About 10 % random sample of studies (135 articles for first stage and 13 for second stage) are checked by one of the co-authors. The agreement rate is 96 % (113 + 17 out of 135; Table 4) in the first stage and 100 % in the second. It is noted that within all the disagreements, the person suggesting inclusion had doubts, indicating all the five articles are likely to be dropped at the next stage. We agree that error rates are within acceptable bounds for this review.

After the digital database searching, the AI tool is used to detect omitted studies not retrieved through the structured search. By importing the 66 post-screening results from the database searches into Research Rabbit, much similar research is recommended. We choose the top 50 "most relevant" studies returned by Research Rabbit as potential studies for review. To screen these, first we remove duplicated studies (n = 2) and then compared the rest with the studies already identified from digital database, which leads to the removal of 27 studies. The remaining 21 studies are screened according to the inclusion and exclusion criteria, finally detecting just one additional article [33] to be eligible for this review. Most of the other 20 studies were removed because of their focus on commercial/office buildings. Lastly, one more study is added [34] which was mentioned in the literature review of one of our included studies.

On checking, we find that both of the two additional studies were included in our chosen databases but their specific terms do not fit with our structured search commands. This finding provides further insights to update our search commands. However, the fact that there were just two additions at this stage suggests changing search commands would yield very limited benefits. Finally, therefore, we conclude the literature search and screening process with a set of 68 articles.

(5) Summary

In summary, the adopted searching and screening process follows a systematic workflow to ensure the integrity and quality of evidence base at every stage. Based on our experience for this review, digital databases and AI tools are complimentary in literature searching. While database

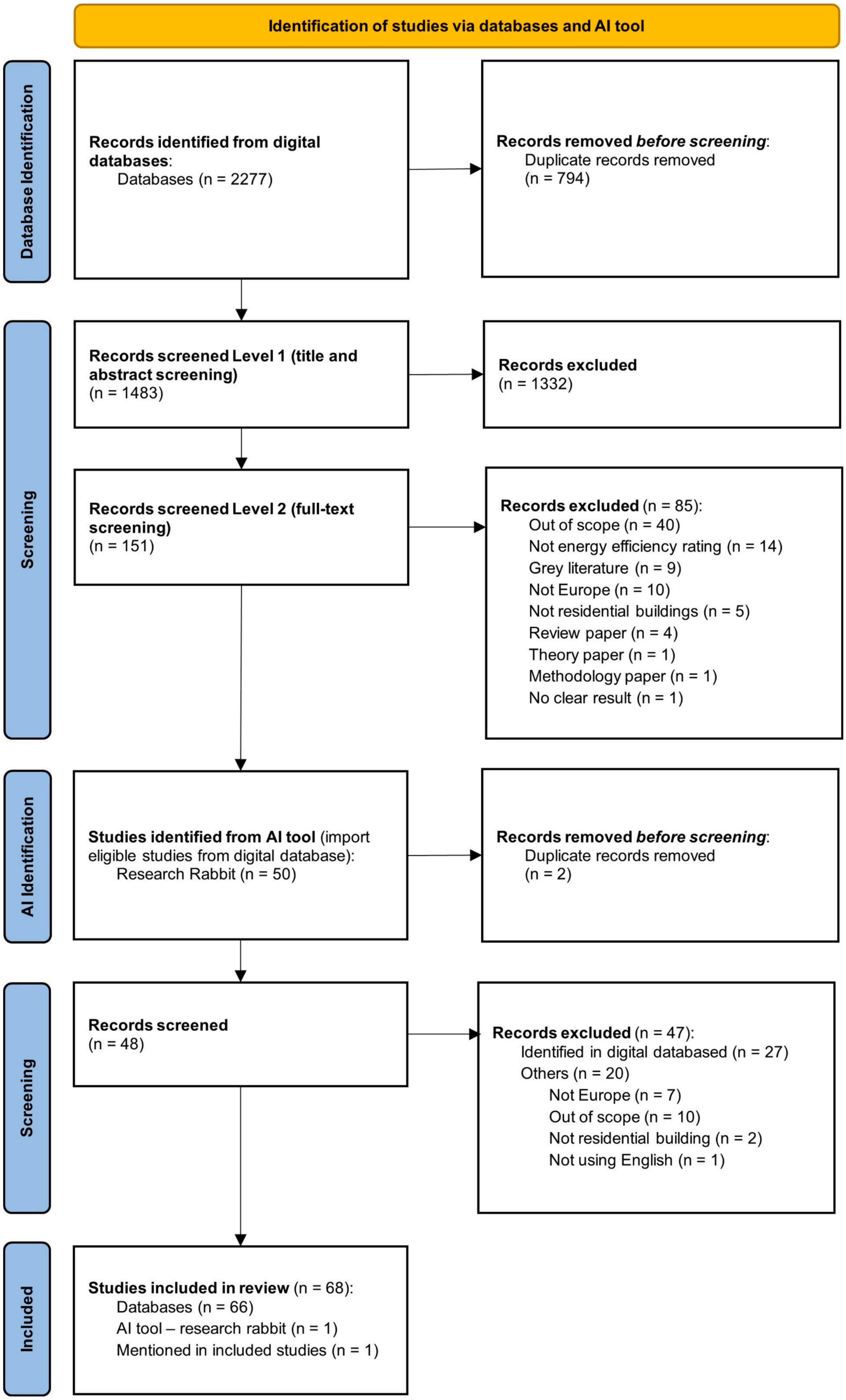

Fig. 2. Flowchart of Searching and Screening Process. *Note: This diagram follows the PRIMA 2020 guideline* [29] *for reporting systematic reviews.*

Table 4
Confusion Matrix of Sample Screening at First Stage of Database Results Screening.

		Author 2		Grand total
		Yes	No	
Author 1	**Yes**	17	1	18
	No	4	113	117
Grand total		21	114	135

searches are transparent and replicable, the retrieved results are limited by the search strategy adopted. In comparison, AI literature recommendation tools do not rely on structured search commands, despite the drawback on reduced transparency. Therefore, compared to traditional literature searching process, we find combining digital database and AI tools could improve the efficiency and accuracy of searching.

3.3. Data extraction

Data extraction captures factors of research scope, methods and outcomes from included studies (Table 5). We initially record data of all categories in the model level and most categories are aggregated to study level when reporting. A few factors need to be explained here. First, the factors in "Time coverage" category are based on the time of data used. Next, there are two factors to extract for research outcome, including "Broad finding" and "Price premium". The former is a qualitative assessment of the overall finding on price premium (e.g. positive or negative) with one result recorded for each study. The latter refers to model coefficients for EPC scores or bands, which are recorded by model. If different models are applied to the same dataset, only the authors' preferred model is recorded. Multiple models are included if they used different data that would result in distinct outcomes. When recording the price premium, if the study used grouped EPC ratings, the coefficients would be recorded as the same for each rating in one group.

Table 5
Data Extraction Form.

Category	Sub-category	Factors	Report level
Research scope and scale	General information	Authors	Study
		Published year	Study
		Journals	Study
	Geography coverage	Research country	Study
		Geographical scale	Study
	Time coverage	Start time	Study
		End time	Study
		Time span	Study
	Research design	Comparative/ Noncomparative	Study
		Cross-sectional/ Longitudinal	Study
	Context	Tenure (sales/rent)	Study
		Price type (transaction/ listing)	Study
	Population	Dwelling type (house/ apartment)	Study
	Sample size	Sample size	Study
	Intervention	EPC aspect (EER/EIR)	Study
		EPC time (current/ potential)	Study
		EPC scale (band/score/ EPI)	Study
Research method	Research model	Research model	Model
	Variables	Variables	Model
		Location fixed effect	Model
		Temporal fixed effect	Model
		Spatial effect	Model
Research outcome	Research outcome	Broad finding	Study
		Price premium	Model

3.4. Analytical techniques

(1) Descriptive analysis and narrative summary

First, we map the results descriptively according to research scope/ scale, methods, and outcome, e.g. present simple frequency counts. A narrative summary [35] of overview/trends is also presented to supplement the frequency tables, figures, etc.

(2) Statistical synthesis

Statistical synthesis of models' coefficients is applied to summarise an overall statement of price premium. Since the models and variables may differ from one another, they need to meet the following conditions to be included for synthesis: (1) use regression methods, (2) use the categorical EER bands as the variable of interest, (3) use log transformed house price as the dependent variable. Studies which group EER bands into a smaller set of categories or transform EER bands to numerical variables are not included. To make model coefficients comparable, the coefficients of each EER band are first subtracted from the coefficient of Band D (i.e. we make Band D the reference point).

There are a few caveats with this approach, including the fact that models use different controls and may have different specifications despite the conditions we impose on selection, and that there are different EPC calculation methodologies in each country, as discussed previously. In addition, and also discussed above, each country uses different cut-points in terms of energy efficiency to produce the bands [23]. Nevertheless, we feel these bands are the most useful basis for comparison since they will have been set to reflect the relative situation of each country's housing stock, i.e. they are appropriate to the national context and housing market in each case. Critically for our review, model coefficients capture the relative value of more or less efficient properties across housing markets with widely-varying underlying housing and energy costs so the absolute energy efficiency rating is not the important factor. As for different step ups between bands across countries (e.g. some countries might have bigger step up from C to B), this could potentially matter but only if consumers pay close attention to the efficiency values of different levels. Based on our knowledge of people's awareness of EPC ratings, most consumers make a broad judgement based on the grades. Therefore, we believe the energy bands used in each country form the best basis for comparing the price premium of energy efficiency across countries.

4. Results

The final literature inventory is made up of 68 studies covering 111 models. We provide the full results of our data extraction in Supplementary material.

4.1. Research scope and scale

(1) Journals, geographic and temporal coverage

Table 6 summarises the timing and geographic coverage of the studies. The earliest publication was 2011 [36]. Studies found in this review range from 2011 to 2024. The number of publications increased over time, with over 67 % of studies published from 2019 to 2024. The literature is dispersed across a wide range of journals with about 40 % of studies published in a journal where it is the only study from that journal meeting our criteria.

The studies spread across Europe geographically from north to south but cover just 12 out of the 29 countries implementing EPCs (including pre-Brexit 28 member states plus Norway) (Fig. 3), while 17 member states having no studies. Despite the focus on publications in English, Italy and Germany are the most popular settings for studies, followed by the United Kingdom, Sweden and Spain. Only two studies have covered more than one country. There are no studies identified for central or eastern Europe (regions defined in [37]), nor for France or Austria. One factor here may certainly be the limiting of our search to studies published in English, but another may be data availability. As mentioned

Table 6
Summary statistics for journals, geography, and temporal coverage.

Characteristics	n	Characteristics	n
Published Year	**68**	**Research country**	**68**
2024 (from Jan to May)	3 (4.4 %)	*Italy*	14 (20.6 %)
2023	8 (11.8 %)	*Germany*	12 (17.6 %)
2022	10 (14.7 %)	*United Kingdom*	9 (13.2 %)
2021	4 (5.9 %)	*Sweden*	8 (11.8 %)
2020	12 (17.6 %)	*Spain*	7 (10.3 %)
2019	9 (13.2 %)	*Norway*	4 (5.9 %)
2018	3 (4.4 %)	*Netherlands*	3 (4.4 %)
2017	4 (5.9 %)	*Portugal*	3 (4.4 %)
2016	7 (10.3 %)	*Belgium*	2 (2.9 %)
2015	2 (2.9 %)	*Ireland*	2 (2.9 %)
2014	2 (2.9 %)	*Finland*	1 (1.5 %)
2013	3 (4.4 %)	*Denmark*	1 (1.5 %)
2012	0 (0.0 %)	*United Kingdom and Netherlands*	1 (1.5 %)
2011	1 (1.5 %)	*Italy and Spain*	1 (1.5 %)
Journals	**68**	**Geographical Scale**	**68**
Energy Policy	*6 (8.8 %)*	*National*	*26 (38.2 %)*
Energy Economics	*6 (8.8 %)*	*Regional*	*12 (17.6 %)*
Energy and Buildings	4 (5.9 %)	*City*	28 (41.2 %)
Journal of European Real Estate Research	4 (5.9 %)	*Neighbourhood*	1 (1.5 %)
Buildings	4 (5.9 %)	*City and neighbourhood*	1 (1.5 %)
Sustainability (Switzerland)	4 (5.9 %)	**Data Time Span**	**68**
International Journal of Housing Markets and Analysis	3 (4.4 %)	*<= 1 year*	10 (14.7 %)
Energy Research and Social Science	3 (4.4 %)	*1–3 years*	13 (19.1 %)
Energies	2 (2.9 %)	*3–5 years*	14 (20.6 %)
Journal of Real Estate Finance and Economics	2 (2.9 %)	*5–10 years*	15 (22.1 %))
Journal of Sustainable Real Estate	2 (2.9 %)	*> 10 years*	7 (10.3 %)
Other (one study each)	28 (41.2 %)	*Not mentioned*	9 (13.2 %)

previously, the EPC data are not publicly accessible in some countries. As shown in Fig. 3, there is a strong relationship between public accessibility of data [14,23] and the volume of published evidence. Specifically, 13 countries have publicly available EPC data (links available in Appendix B) and they account for about 80 % of the identified studies. Among the 18 countries with no publicly available data, there are just 15 studies concentrated in three countries – Germany, Belgium, and Finland. Studies in these countries use EPC data provided indirectly from either website listings or real estate agencies. Overall, we find studies in this field are much more prevalent in countries where EPC data is publicly available. Therefore, we conclude that research evidence in this field is being limited by EPC availability and call for governments to accelerate the process of publishing open EPC data.

Most studies use data at a city or national level, followed by those at regional scales (Table 6). This may be related to EPC data availability, as we find there are no national level studies conducted in Italy/Portugal where EPC data is only publicly accessible in certain regions [14]. While studies at a neighbourhood scale (part of a city) are rare, many studies have suggested differentiating housing market impacts across spatial sub-markets [30,38,39]. As for boundaries to define market areas, most of the included studies applied administrative boundaries, while past studies have suggested that administrative boundaries do not necessarily delineate consistent housing sub-markets [40].

The time coverage of data is shown in Fig. 4. The data of interest include both EPC and house prices data. Though these are matched with each other to study the housing market impact of energy ratings, they may stem from different times. Most papers use data later than 2006 when the EU member states were required to transpose EPC regulations into national laws as stated in first version of EPBD. However, there is a clear time lag between the implementation deadline and time of data used as found here. And all the data adopted are before 2024. The time span of data ranges from less than one year to more than ten (Table 8). Few studies include house price data from periods before EPCs were available. These are mostly comparative or longitudinal studies that include house prices data from an earlier time. Specifically, Fuerst et al. [41,42] include earlier data to do a longitudinal/repeated sales analysis and find the EPCs' impact on price change, while Olaussen et al. [43–45] separate pre/post EPC labelled transactions to investigate if the price premium is related to the energy label itself or other features.

(2) Housing market contexts, population, intervention

Table 7 provides a summary of housing market contexts (i.e., tenure and price type), population (i.e., dwelling type) and intervention (i.e., EPC type). On tenure type, most studies analyse sales market. Nine examine only rental markets with seven more exploring both [41,46–51]. To reflect the revealed preference of homeowners/tenants, transaction price is usually preferred but not always available, in which case a listing price (also known as "asking price") is used as a substitute. It is worth noting that listing price reflects more the sellers' expectations instead of residents' willingness to pay, although no doubt the former is informed by the latter. It is important for researchers to assess any differences between the two before using listing price as a substitute but, for our work, it would only bias results if the differences are affected by energy efficiency in some way and this seems unlikely. Among included models, over 40 % apply transaction prices (n = 29). Meanwhile, slightly more studies (n = 35) adopt listing prices, mostly due to the fact that official transaction information is not available in some countries such as Spain [52] and Italy. Again, it highlights that the availability of data forms a main limitation in this field.

Though most studies include all types of housing, a number focus on submarkets in terms of dwelling type. Several studies suggest that the price premium varies by dwelling type (e.g. [53]). Many studies (n = 20) explore the housing market of only apartments (i.e. multi-family housings) (details in Supplementary material). A smaller number of studies focus merely on houses (i.e. single-family housings, n = 10). Evangelista et al. [54,55] explore a wide range of submarkets in different models, by separating models for existing/new apartments/houses.

As noted in the discussion of EPC systems and standards above, EPCs provide a range of information on energy efficiency which might be thought to influence prices and hence be used in models. First, different aspects of EPC include: the EER reflecting relative energy costs; and the EIR, reflecting relative emissions. Every study but one uses the cost-based measure (EER) rather than the EIR measure of environmental impacts; the exception used both EER and EIR [56]. Secondly, as introduced previously, there are different EPC presentation forms which could potentially affect residents' perceptions. While continuous scores provide more detailed information on energy efficiency, bands offer an aggregated judgement and would produce threshold effect in price premium (more discussion in Section 4.2) [57]. Most use the EPC bands but two models use scores while six report results for both, and 13 use only the EPI. By simply sorting the results according to countries, there is a sign that studies in each country tend to use the same EPC presentation. Specifically, only certain studies in Germany, Sweden, and Netherlands adopt the EPI and only certain studies in the UK use EPC scores, while other studies in these countries and all those in the remaining countries use EPC bands. This further suggests that, among those countries where EPC data is available, there exist obstacles to comparative analysis as the EPC presentation provided in data is different though it may be possible to transform EPC presentation based on given reference e.g. band to score transformation. Thirdly,

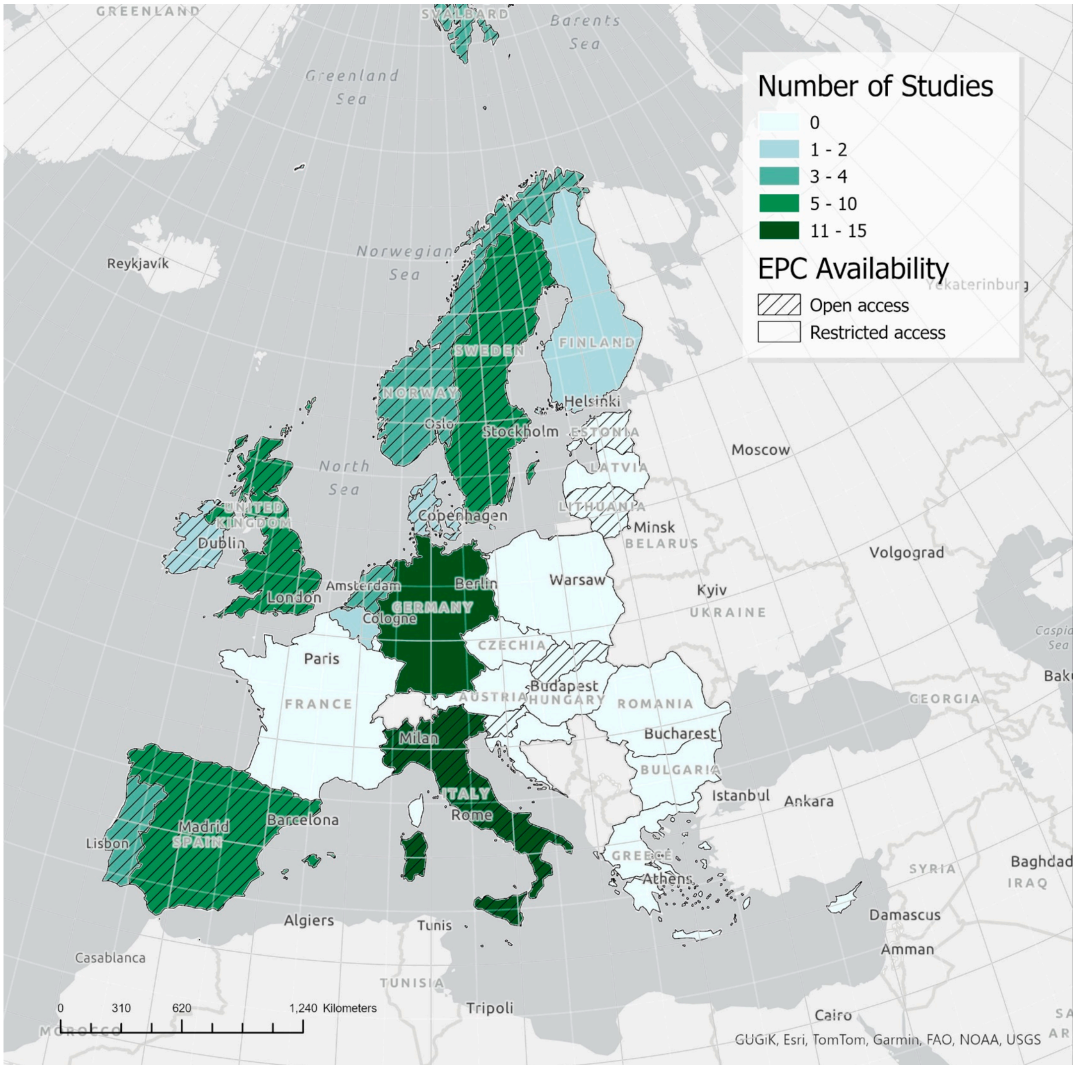

Fig. 3. Geographical Coverage of Studies and EPC Data Availability (pre-Brexit 28 EU member states and Norway).

concerning EPC time, two studies use information on the potential ratings of properties [39,58].

(3) Research design and sample sizes

Table 8 summarises information on study designs and sample sizes. Six studies adopt a comparative perspective, comparing price premiums across different geographical regions within the study area [38,59–63]. While most studies consider the price premium cross-sectionally, eight studies are considered longitudinal studies either for adopting repeated samples or aiming to measure the change of the price premium over time with techniques such as pooled regression. For example, von Platten et al. [64] explore the relationship between energy efficiency improvements and rent increases in Sweden while [41,42] study the impact of energy efficiency ratings on price changes in England/Wales using repeated sales transactions from 1995 to 2012 and 2003 to 2014 respectively. Chegut et al. [59] apply separate regressions on the same appraised rental properties in different years (2012 and 2015 in England; 2010 and 2015 in Netherlands), exploring the change of relationship between energy efficiency rating and appraisal prices over time. Marmolejo-Duarte and Chen [52] include an interaction term between year and EPC rating with spatial pooled regression to assess whether any price premium changed from 2014 to 2016 in Spain. By including sales data before the implementation of EPC, Olaussen et al. [43–45] compare the “post-label” and “pre-label” model to see if the impact of energy efficiency was already priced in before the display of EPCs in Norway, using fixed-effects models on repeated observations. Some studies use repeated samples only for robustness checks alongside the estimate using all observations (e.g. [57]) and are thus not included as longitudinal studies.

While most studies adopt property-level data as the analytical unit, [65] undertake the study at the aggregated level of municipalities in the Portuguese real estate market. This exploration is meaningful for supporting large-scale housing renovations (e.g., municipality level). Though most studies are interested in buyers/tenants’ willingness to pay, a few others utilise appraisal price to explore the attitude of real estate agents on energy efficiency (Table 7) [33,44,59] as this may play an important role in housing market price formation.

Sample sizes vary across a large range from less than one thousand to more than one million. Table 8 shows that most studies have sample size of 10^3-10^4, followed by sample sizes of 10^4-10^5, $<10^3$ and 10^5-10^6. Few studies have a sample over one million, all of which are conducted at a national level in the UK [32], Portugal [54] and Germany [66,67].

4.2. Research methods

(1) Analytical models

In the field of estimating price premiums for housing attributes, hedonic regression [68] is a technique being widely used, where housing price is the dependent variable and attributes influencing buyers’ utility

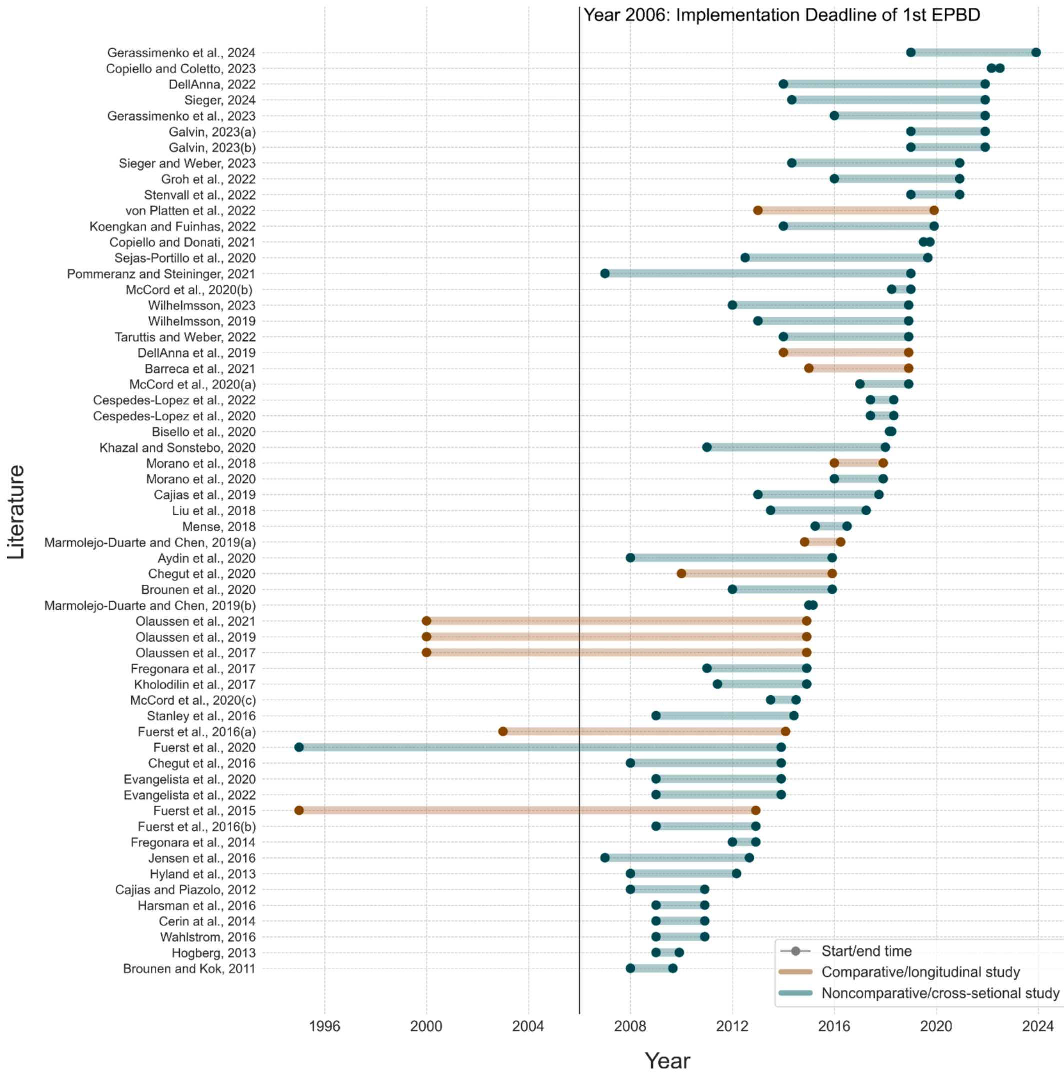

Fig. 4. Time scope and scale of data adopted in literature. *Note: In this figure, the studies can be referred to the 'Reference' field in the data extraction results in Supplementary material. Only one start and end date are used for each study. For studies with different data start times or end times in different models, only the earliest start time and latest end time are chosen to visualise. Six studies are not included in the figure as there is incomplete information on the time span of the data.*

are independent variables. Based on the hedonic framework, specification of the functional form varies, as well as estimation methods (including parametric, semi-parametric and non-parametric estimations) [69,70]. In addition, some scholars use techniques out of hedonic regression to identify the price premium. In this review, we define those models regressing house price on housing attributes as hedonic regression. All analytical models found are summarised in Table 9.

The most common approach (found in 61.3 % of models) is classic linear regression (LR). Most LRs use the semi-log model specification (using log transformed house price) with ordinary least squares (OLS) estimation technique. This parametric approach fits well with the purpose of estimating the price premium by assuming a uniform percentage increase in price associated with the unitary increase of the housing attributes.

We separate those regression models including spatial interactions as spatial regression (SR). Many scholars apply some form of spatial regression to capture the spatial impacts of price premiums, including Spatial Lag Models [25,39,60], Spatial Error Models [38,52,60,61], Geographically Weighted Regression [30,39,71] and Spatial Autoregressive Models [26,72,73]. Several studies recommend taking into account spatial effects [26,72] and temporal heterogeneity [30,72]. Of these, Barreca et al. [38] indicate that local models have better unbiasedness. Copiello and Donati [26] suggest spatial autocorrelation should be considered in models to lessen an overestimation of the price premium.

Various extensions of linear regression are used, most of which are applied to investigate more than a single mean conditional estimate of price premiums. Basic linear regression models adding interaction terms mentioned later could also capture different estimates of the price premium. Firstly, some scholars applied Quantile Regression (QR) to examine the different effects of EPCs across the price spectrum [33,54,65,74,75]. Secondly, two studies adopted a Regression Discontinuity Design (RDD) approach to measure the threshold effect of EPC ratings [32,57]. The main idea behind this method is that houses with EPC scores just below the threshold (i.e. each EPC band) are comparable to those just above the threshold, but there might be a sharp discontinuity at the EPC band to estimate the price premium of energy efficiency. This might occur in the context of discussion about regulatory requirements, minimum energy efficiency standards or green mortgage applications, for example. It might also indicate that consumers focus on bands and not on scores, as noted previously. Thirdly, Multilevel Regression (MLR) have been used to correct model bias when a hierarchical structure is assumed to exist in the observational data. Two studies apply MLR, with Cespedes-Lopez et al. [76] separating housing/district level in the model and Khazal and Sønstebø [77] applying hierarchical geographical areas. Furthermore, the technique of

Table 7
Summary statistics for housing markets.

Characteristics	n	Characteristics	n
Context – tenure type	**68**	**Intervention – EPC aspect**	**68**
Sales	52 (76.5 %)	*EER*	67 (98.5 %)
Rents	9 (13.2 %)	*EER and EIR*	1 (1.5 %)
Sales and rents	7 (10.3 %)	**Intervention – EPC presentation**	**68**
Context – price type	**68**	*Band*	46 (67.6 %)
Transaction price	29 (42.6 %)	*Score*	2 (2.9 %)
Listing price	35 (51.5 %)	*Band and score*	6 (8.8 %)
Appraisal price	3 (4.4 %)	*Energy Performance Index (EPI)*	13 (19.1 %)
Transaction and listing price	1 (1.5 %)	*Band and EPI*	1 (1.5 %)
Population – dwelling type	**68**	**Intervention – EPC time**	**68**
House and apartment	38 (55.9 %)	*Current*	66 (97.1 %)
House	10 (14.7 %)	*Current and potential*	2 (2.9 %)
Apartment	20 (29.4 %)		

Table 8
Summary statistics for research design and sample size.

Characteristics	n	Characteristics	n
Comparative/non-comparative	**68**	**Sample size (number of properties)**	**68**
Non-comparative	62 (91.2 %)	*<= 1,000*	10 (14.7 %)
Comparative	6 (8.8 %)	*1,001—10,000*	25 (36.8 %)
Cross-sectional/ longitudinal	**68**	*10,001—100,000*	17 (25.0 %)
Cross-sectional	60 (88.2 %)	*100,001—1,000,000*	11 (16.2 %)
Longitudinal	8 (11.8 %)	*> 1,000,000*	4 (5.9 %)
		Not applicable	1 (1.5 %)

Note: One study apply data at aggregated municipality-level [65] and record as "Not applicable" in the "Sample Size" category.

Table 9
Summary statistics for analytical models.

Analytical model		n = 111
Linear regression (LR)		*68 (61.3 %)*
Spatial regression (SR)	*Spatial Lag Model (SLM)*	*4 (3.6 %)*
	Spatial Error Model (SEM)	*7 (6.3 %)*
	Geographically Weighted Regression (GWR)	3 (2.7 %)
	Spatial Autoregressive Model (SAR)	*3 (2.7 %)*
Extensions of linear correlation	*Quantile Regression (QR)*	*13 (11.7 %)*
	Regression Discontinuity Design (RDD)	*2 (1.8 %)*
	Multilevel Regression (MLR)	*2 (1.8 %)*
	Evolutionary Polynomial Regression (EPR)	*4 (3.6 %)*
Generalised linear nodel (GLM)	*Generalised Additive Model (GAM)*	*2 (1.8 %)*
	*Ordinal Logistic Regression (OLR)**	*1 (0.9 %)*
	*Analysis of Variance (ANOVA)**	*1 (0.9 %)*
Machine learning	*Random Forest (RF)*	*1 (0.9 %)*

Note: *These approaches do not align with hedonic regression.

Evolutionary Polynomial Regression (EPR), a data mining tool to solve feature engineering problems, is used in three studies [63,78,79] to find the features that could best explain house prices in a concise way. However, this approach uses a genetic algorithm to search for model structures [80] thus not including all commonly-used independent variables. It maintains the hedonic framework by regressing house prices on housing attributes but offers less interpretability compared to the general hedonic approach.

Generalised linear models (GLM) are applied in several studies. Brounen et al. [81] and Groh et al. [82] apply Generalised Additive Models (GAM) to include nonlinear relationships within the model while keeping the hedonic framework. The Analysis of Variance (ANOVA) has been employed in [64], to measure if rent increases with energy performance improvements differ among renovation categories (e.g. no renovation, light renovation, and extensive renovation depending on investment percentage). Other than adopting regression methods with house price as the dependent variable, McCord et al. [53] use an Ordinal Logistic Regression (OLR) approach taking EPC band as the dependent variable and property characteristics/house prices as independent variables, determining the price premium by examining if there is increased probability in higher sales price with a higher EPC rating.

While superior in predictive performance, machine learning (ML) techniques' results are difficult to interpret, making them less adopted in the field of estimation of housing attributes' value [83]. Though not as explicit as coefficient from linear regressions, the interpretability of ML is gaining more attention among scholars to estimate price premium. One study [84] applied a non-parametric machine learning technique of Random Forest (RF), using feature importance coefficients to measure the impact of energy ratings on sales prices.

Overall, it is found that all analytical approaches used are regression models of some form. Most studies follow the hedonic regression approach by estimating attribute-specific effects on house prices. While two exceptional cases include the use of ANOVA and OLR, neither approach could generate an isolated price premium. The prevalence of hedonic regression highlights its theoretical robustness and empirical flexibility. By sorting the studies based on the year they were published, we find that classic LR approaches are predominant in earlier years but are less prevalent in later years. Conversely, increasingly sophisticated models such as spatial regressions and extensions of linear regression are gaining prevalence over time. Regression with advanced machine learning methods first appear in this field in 2023.

(2) Variables

To give a causal interpretation of the parameter estimate, models should control for all variables correlated with energy efficiency and house prices [69] though of course this is never possible in practice. The set of characteristics determining house prices generally fall into three categories: structural, neighbourhood-related, and locational attributes [85]. We summarise the variables found in studies and group them into those three categories plus temporal variables (Table 10). While structural variables control for features of the individual property, neighbourhood-related variables control for those of the neighbourhood context. The remaining two categories typically include dummy variables for geography and time, controlling for which could get rid of variations between properties in terms of geography and time and thus improve the performance of models. Here we only include the fixed geographical attributes (i.e., the sub-area with respect to the whole study area) in the locational category, while some attributes related to location e.g., accessibility are grouped into the neighbourhood-related category. Spatial effects are also included in the locational category, which includes spatial heterogeneity and spatial dependence [86], accounting for which contributes to spatial regression models.

We summarise the inclusion of variables in each model in Table 11, by further separating "Quality variable" from the "Structural variable" category and "Spatial effects" from the "Location" category. The dwelling's structural quality (e.g., "luxury"/ "sophisticated"/ "normal"/ "simple") is also referred to as "property condition", "maintenance

Table 10
Summarised core set of included variables.

Category	Variables
Structural	EPC (variable of interest) Property size Dwelling type Building age Number of rooms, bedrooms, bathrooms Number of floors* Built-in kitchen, basement, garage, terrace/balcony, garden Structural quality (e.g., 'luxury'/'good'/'normal'/'simple') Building services (e.g., parking, lift, air conditioning, etc.) Facilities (e.g., swimming pool, gym, etc.) Heating type (e.g., gas, central heating, etc.)
Neighbourhood-related	Accessibility (e.g., distance to CBD/highway/subway/park/sea, etc.) Socio-economic characteristics (e.g., population density, income level, unemployment rate, etc.)
Locational	Geographical location (e.g., district, postal town, latitude and longitude, etc.) Spatial effects
Temporal	Time-period of transaction (e.g., year, quarter, etc.)

Note: * means the variable is only considered as a feature of an apartment.

Table 11
Summary statistics for included variables per model.

Model characteristics	n	Model characteristics	n
Structural variables	111	**Neighbourhood-related variables**	111
Yes	*110 (99.1 %)*	*Yes*	*50 (45.0 %)*
No	*1 (0.9 %)*	*No*	*61 (55.0 %)*
Location variables	111	**Temporal variables**	111
Yes	87 (78.4 %)	*Yes*	59 (53.2 %)
No	24 (21.6 %)	*No*	52 (46.8 %)
Spatial effects	111	**Quality variables**	111
Yes	17 (15.3 %)	*Yes*	*43 (38.7 %)*
No	94 (84.7 %)	*No*	*68 (61.3 %)*

level", etc. It is considered a significant variable which is likely to correlate with energy efficiency features [26,61,87], as investment in improving energy efficiency is likely to be accompanied by investment in aspects such as fittings and fixtures or decoration. Therefore, it is important to control for this variable to generate an unbiased estimate of price premium for energy efficiency. As shown in Table 11, nearly all models consider structural variables (99.1 %) except for one study applying aggregated-level analysis. In comparison, fewer than half of models include neighbourhood-related variables (45.0 %). Results also show that about 78.4 % of models include location variables while temporal variables are considered in around 53.2 % of models. As introduced previously, 17 out of 111 models apply spatial regressions with spatial effects included. We find that 38.7 % of models consider structural quality to some degree.

Overall, it could be inferred that more than half of the models are at high risk of omitted variable bias (OVB) for limited control of housing attributes. OVB is the bias occurs in estimating parameters in regression, appearing when an independent variable related to the dependent variable and one or more of the included independent variables is omitted. On price premium estimation, omitting variables correlated with energy efficiency and house prices would lead to biased estimates. Specifically, omitting variables positively correlated with energy efficiency (e.g. structural quality) would overestimate the price premium, while omitting those negatively correlated with energy efficiency results in underestimation.

Among all variables, the quality variable is of particular concern for OVB, which is difficult to measure objectively and precisely [85]. Existing studies including quality variables mostly obtained the variables indirectly from online real-estate listings (e.g., [88,89]), real-estate agent association [36,63] or real-estate research centre (e.g., [90]). We further find that these models are highly concentrated in several countries including Italy, Germany, Netherlands, and Spain. Online listings with quality variables are available in Germany (immobilienscout24.de) and Spain (idealista.com), while the agent association in Netherlands (Dutch Association of Realtors) and research centre in Italy (The Real Estate Observatory of the City of Turin) provide relevant data. Traditionally, these variables are mostly measured by real-estate appraisers requiring on-site visits or assigned by sellers [89] which could involve bias. Two studies applied advanced methods (semantic analysis) to extract dwelling quality variable from descriptive text [61,91]. The measurements and sources of these quality variables are summarised in Appendix C.

Generally, the availability of housing-related data forms a main obstacle to tackling OVB. Other than obtaining data directly, there exist several techniques to address endogeneity introduced by OVB. One common approach is using an instrumental variable, a variable correlated with the endogenous independent variable (i.e., driver) while independent of the omitted variables. It could be a substitute variable for the driver as it affects the outcome only through its effect on the driver [92]. One study [56] finds instruments for independent variables in a statistical way (using instruments with higher correlation to the independent variable), choosing EIR band as the instrumental variable for EER band. The logic is that buyers might not consider emissions when buying or renting a property, while environmental impact (EIR) and energy cost savings (EER) of a property are highly correlated. Another study chooses an instrumental variable for energy efficiency (here EPI) theoretically [57]. By assuming the improvement of energy efficiency is the combined result of demand for energy efficient housing and the revision of building codes after the 1973–74 oil crisis, the EPI is instrumented by the logarithm of the oil price two years before the construction of the dwelling. Another way to try to address OVB is adopting longitudinal designs with repeated measures as some quality features remain constant over time (e.g., [41]). However, it is worth noting that some qualities may have changed along with energy efficiency levels.

Other than including individual variables, some researchers add interaction variables to explore whether EPCs have different effects on house prices depending on other independent variables. Examples include: EPC score and several structural variables (e.g., dwelling age) or spatial autocorrelation of property prices (in spatial lag models) [39]; EPC rating and area type [93], climate area [56,87], property type [46], property age [30,87], sales year [52], heating type [87], and environmental awareness/purchasing power [88]. A similar effect would be achieved by estimating different models for different groups e.g., property types [55].

Furthermore, to see if any willingness to pay is general to the public or specific to some groups of buyers rather than others, some studies consider heterogeneity in buyers. Two studies include the household's green attitude in their models [58,88]. In addition, Aydin et al. [57] explore households' characteristics by including number of children and elderly of household in the model. As buyers' willingness to pay for housing energy efficiency is partly driven by green awareness (could be related to households' demographic characteristics [94], socio-economic status), it is meaningful to consider these variables in the model.

4.3. Research outcome

(1) Broad findings

We define three types of broad findings summarising from the conclusions of studies: “positive”, “no impact” and “depends”. No study found that higher energy efficiency leads to lower values. Most studies conclude that energy efficiency has a positive impact on house prices (75.0 %; n = 51) while twelve (17.6 %) find no impact. Five (7.4 %) conclude that the price premium depends on different housing market segments [67,95], the intensity of renovation [64], spatial features [39] or geographical location [47].

Other than the price premium, we take a further step to summarise whether the price premium is growing over time in those longitudinal studies (n = 5). Two studies find the price premium increases over time [52,59] while one suggests no clear growth premium is found [42]. The remaining ones suggest the results are mixed according to intensity of retrofitting [64] and different EPC bands [41].

(2) Price premium

We provide an impression of the scale of the price premium by aggregating results from different models in a form of simple *meta*-analysis. Following the conditions for model filtering mentioned previously, 38 models (within 28 studies) are included for statistical synthesis.

Fig. 5 shows the distribution of estimates for the relative price in each band from these 38 models, summarised as a box plot where the central bar represents the median. The mean is also shown in each case. Overall, there is clear evidence of a positive price premium. Relative to Band D, the median coefficients of EER bands are: A (0.061), B (0.045), C (0.014), E (−0.010), F (−0.026), and G (−0.035). In general, the coefficient increases by 0.01–0.03 for each band increase. As house price is log-transformed[1], the coefficients can be interpreted in terms of house prices percentage change [70]. For example, a coefficient of 0.01 means the dependent variable is higher by about $e^{0.1} = 1.11$ (11 %) relative to a Band D [96]. Therefore, the median price premium of EER bands relative to Band D are: A (6.3 %), B (4.6 %), C (1.4 %), E (−1.0 %), F (−2.6 %), G (−3.4 %). Each additional band worth about 1 %-3 % in price increase. The additional price increase for Band A/B is more substantial than others. This might be caused by OVB where dwelling quality is not included in the model, as homes with Band A/B are likely to be new builds with high quality. It also shows that the estimate of the price premium varies across studies, suggesting the price premium may vary in different housing submarkets (e.g. in terms of geography, time, dwelling types, etc) though there might be sampling variation in studies even given the same population. The varying results could also be caused by different model settings such as the breadth of variables.

While the great majority of models are based on bands, three others (from two studies; both in the UK) [39,97] are based on the EER score (scaled 0–100). On average, these models suggest a price premium of 0.25 % for each unit improvement on the energy efficiency measure (range 0.1 to 0.4 %). In the UK, moving from medium score point of Band D (=61.5) to Band B (=86) would represent an increase of 24.5 points, suggesting a price premium of 6.13 % (= 24.5*0.25 %) which is similar to the previous synthesis.

(3) Outcomes in different housing markets

Apart from an overall summary of research outcomes, we are also interested in the variation of research outcomes by submarkets. To explore the geographical differences among outcomes, we group the studies into two broad areas using the EU’s geographical subregions [37]. We contrast the colder and wetter climates of Northern/Western Europe with the warmer and drier climates of Southern Europe. In addition, to investigate if the price premium is increasing over time given people’s awareness of energy efficiency is expected to improve, we split the research outcomes into two groups, depending on whether the data end time is before 2016 or not. This year is chosen for several reasons. First, as mentioned above, it was not until 2015 that all EU countries mandated the listing of EPCs in commercial media. Second, this dividing line ensures a good balance of data between the two groups. Thirdly, the Paris Agreement on climate change entered into force in 2016, which stated the 1.5 °C temperature increasing threshold and may have drawn people’s attention to climate change since then.

First, broad outcomes are compared in terms of geographical regions and time period. In both northern/western and southern subregions, most studies find positive impacts of energy efficiency with a slightly higher proportion in the northern/western subregions (Table 12). Similarly, most studies found positive effects but a higher proportion of later ones (Table 13). Given relatively small numbers in each case, it is difficult to identify a clear trend here. We further apply the Fisher-Freeman-Halton test [98] which is used to find statistical relationship between categorical variables with small sample size in a 2 × 3 table. The results of test (for geography: $p = 0.15$; for time: $p = 0.14$) do not indicate a significant association between geography/time and broad outcomes.

The coefficients for energy efficiency bands are compared in terms of geographical subregions, time period, dwelling type and tenure (Fig. 6). Generally, the price premiums in northern/western Europe are similar to those in southern Europe. Considering the time period of the data used, the green premium appears slightly higher before 2016, while the brown discount seems greater after 2016. Also, the price premium for energy efficient houses is greater than that for apartments, including the green premium and brown discount. As for tenure type, we find that dwellings with high energy efficiency e.g. Band A/B are more appreciated in the sales market. Noted the data in many studies suffer from the problem of small sample size since there are limited number of buildings with very high/very low energy efficiency e.g. Band A/G, and the small number of models make definitive statements difficult.

5. Discussion

5.1. Discussion of results

In terms of research scope and scale (research question 1), we find a relatively modest literature comprising 68 studies over a 14-year period, almost all providing evidence for a single country, for a region comprising 29 countries (pre-Brexit EU plus Norway). There are signs that the pace of publication is picking up but studies remain geographically concentrated. The lack of evidence from countries in central and eastern Europe is of particular concern. If we are to see the development of a more substantial European evidence base to support the Net Zero target for housing, much more needs to be done at EU level to mandate the provision of open access to property-level EPC data. Researchers will also need access to other linkable property-level data on house prices and property characteristics. Ethical concerns could be one of the main barriers to open access property-level data, which ties to specific properties and may indirectly disclose residents’ information. Open EPC data could potentially reveal residents’ energy usage and socioeconomic status. While restricted access prioritises privacy concerns, open access supports climate goals, market competitiveness, and social equity. Therefore, to promote the open access of EPC and other property-level data, governments should invest in data governance and protection regulations to protect privacy and responsible use of information.

Regarding study designs and methods (research question 2), we find a great deal of variety, although variations on hedonic regression form the core, reflecting its widely accepted theoretical base and high interpretability of models. We find the model sophistication increases over time, with classic linear regression becoming less common while spatial regression and extensions of linear regression become more popular. Having had a period of experimentation with different approaches, however, it would be helpful to have multiple national studies conducted on a consistent basis, providing greater comparability into the

[1] The majority of models (26 out of 38) state that they use the natural log of the house price. The remainder do not explicitly state which base is used but, given standard practice in economics , we assume they follow the same approach as the majority.

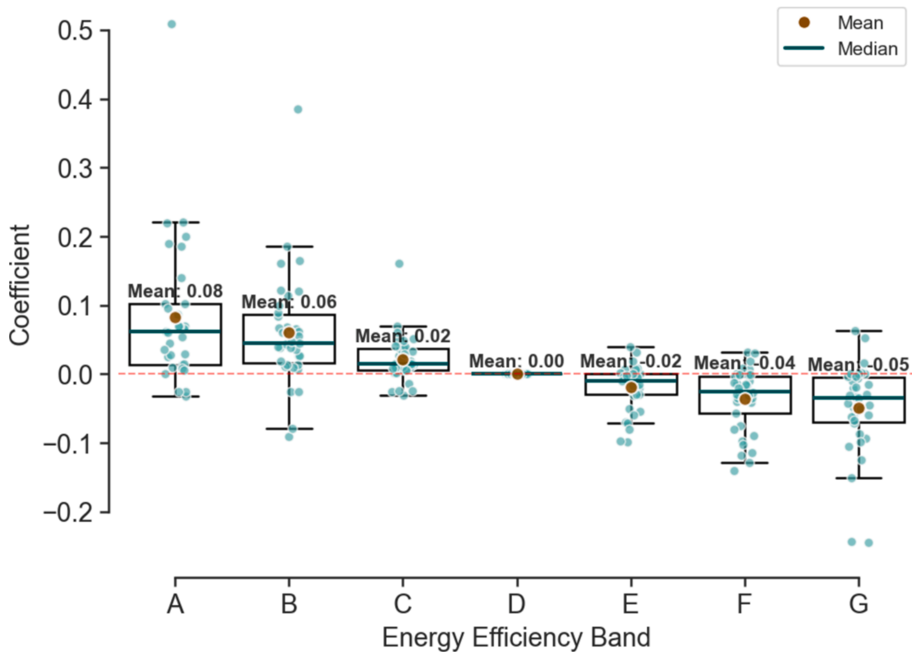

Fig. 5. Distribution of Coefficients of Categorical EER Bands. *Note: models in 28 studies are used to generate this figure. Models with sales and rents are both included as the hedonic approach estimates the relative impact of the variables, which are comparable in terms of coefficients. All the models have results for EPC C/D/E/F/G, but five models have no information on band A and coefficients for band B and band G are missing in two models. And one model has no information on band D which is incomparable with other models and cannot be included in the figure.*

Table 12
Contingency Table for Research Outcome and Geography.

	'Positive'	'No impact'	'Depends'	Total
Northern/western Europe	32	6	5	43
Southern Europe	19	6	0	25
Total	51	12	5	68

Table 13
Contingency Table for Research Outcome and Time.

	'Positive'	'No impact'	'Depends'	Total
After 2016	29	3	3	35
Before 2016	22	9	2	33
Total	51	12	5	68

state of attitudes to energy efficiency in each country.

With most studies using the hedonic model, OVB is a major methodological limitation leading to inaccurate estimate of price premium. Again, this is mainly a result of limited availability of property-level data. Several studies tried to tackle OVB by using longitudinal study designs or instrumental variable approaches. However, the former could incur selection bias as properties that sell more than once may not be representative of the whole housing stock [99]. On both studies including instrumental variable, their choice of variables may not be effective. While the variable of oil price two years before the construction of the dwelling [57] is not necessarily related to housing energy efficiency, the variable of EIR could have a direct impact on house prices. The direct way to address OVB is to include the omitted variable in the model if it is observable and measurable. On estimating the price premium of energy efficiency, potential omitted variables which are possibly correlated with both energy efficiency and house prices include building age, dwelling quality, etc. Dwelling quality is perhaps the critical challenge as it is usually hard to measure but also likely to be correlated with energy efficiency: people making improvements in energy efficiency are likely to make other functional and cosmetic improvements at the same time.

On the third research question, the overwhelming majority report a positive effect overall and, for the group where more direct comparisons were possible, a clear gradient across the bands exists. These suggest a market preference for more energy-efficient homes. Although we noted risks of OVB in some models, we focus on median values on results synthesis to minimise the reporting bias. Comparing to the results of an earlier *meta*-analysis [7], this review finds a smaller effect size for both green premium and brown discount. In terms of applying more systematic searching process and including up to date studies, this review represents an important addition to this field. It is worth noting that although the percentage premium remains the same, in contexts with high house price inflation (e.g., in the UK) the absolute value of the premium would likely be increasing faster than other prices. Presumably this means it is also increasing relative to the cost of improvements. It is also noted that this review mainly focuses on the cost-based EER rating (only one study is found to include EIR rating), where the carbon impact of heating sources is not priced. If the market continues to emphasise the EER rating, unit cost of heating sources would need to be adjusted to reflect their carbon impact to better suit the Net Zero goals.

The geographical coverage of included studies could introduce bias in research findings especially price premium. Included studies are highly concentrated in western, southern, and northern Europe, while missing in central and eastern Europe. As socioeconomic and housing market conditions are significantly different between European countries/regions, the findings of this review could skew towards specific conditions. Additionally, the sample size and time span of data used in each study could affect the robustness of price premium findings. Increasing sample size could increase the precision of effect size estimation [100] and longer time span would improve the robustness and generalisability of results. All these factors should be noted when discussing the price premium findings.

That said, we do not find much variation between northern/western and southern European countries despite very different climates. This could be due to the fact that a good EPC rating is important in both regions for either winter heating or summer cooling. Nor did we find evidence that the gradient is increasing over time. Although our

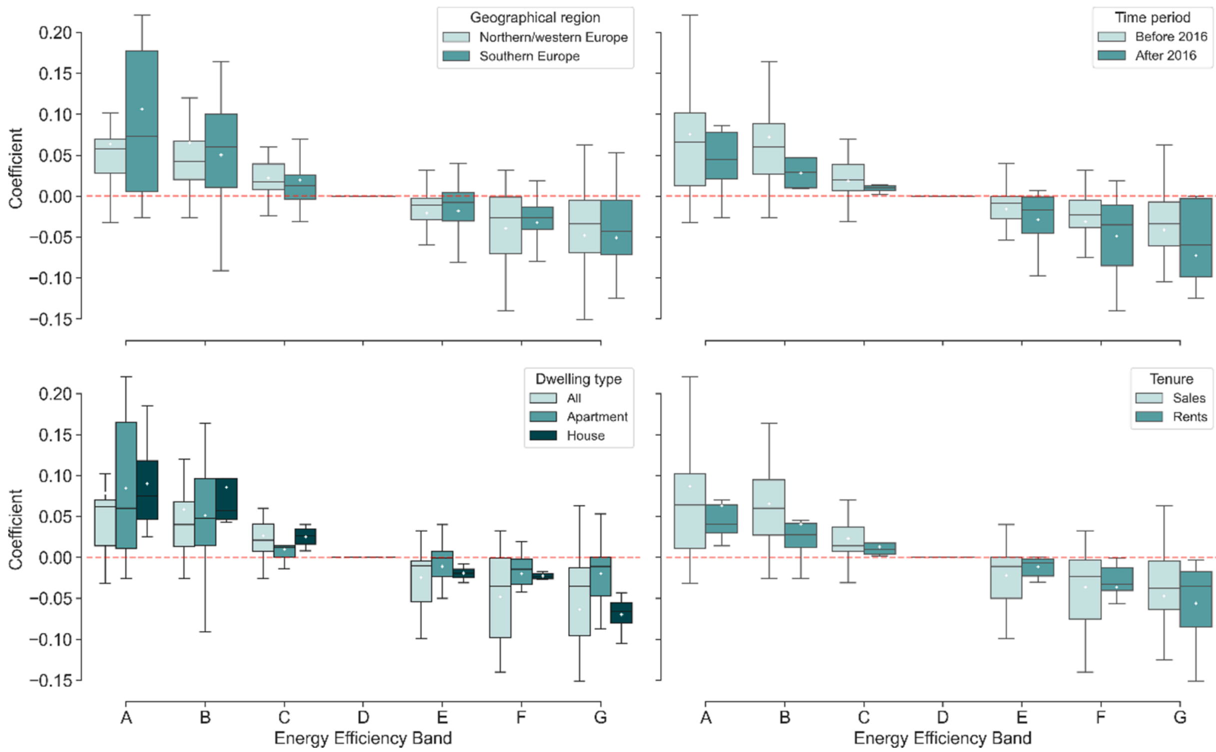

Fig. 6. Distribution of Coefficients of EER Bands in Different Subregions/Time Period/Dwelling Type/Tenure. *Note: Totally 38 models are used to generate these figures. There are 22 models in northern/western Europe and 16 models in southern/eastern Europe. And 26 models only apply data before 2016, while 12 models include data after 2016. Also, 13 models consider only apartments while 4 focus on the houses and 21 ignore dwelling type. Lastly, there are 30 models for sales market and 8 for rental market.*

conclusions here are limited by the small scale of the literature, this last finding is particularly concerning. Despite the increasing awareness of environmental issues and rising energy costs, there is no clear trend of increasing price premium. This indicates that continuing efforts are needed to improve residents' awareness and EPCs' effectiveness. This could also be the result of more government support, lower investment cost due to technology advancements, and that studies are applying more robust data/models, etc. Among the several longitudinal studies investigating whether the price premium changes over time, the results are also mixed. Given these studies are limited in quantity and not up-to-date, future research should make further efforts to explore impact of EPCs on price change.

We do find that the price premium varies between rental/sales markets as well as apartments/houses markets. The finding of a price premium for both sales and rents is important in the context of debates about the 'split incentive' in the rental market. The argument made by some is that landlords do not have the same incentive to carry out energy efficiency improvements since the benefits of lower running costs are enjoyed by the tenant while the landlord carries the investment costs [101]. This review suggests that at least some of the reduction in running costs can be captured in rent while the landlord will presumably also enjoy the same capital gain as others when they come to sell. A recent analysis of energy efficiency levels in the UK found that landlords did not in fact tend to own less efficient properties, once basic property characteristics were taken into account [102].

As mentioned previously, the reliability of EPCs is a concerning issue. In the long term, people's willingness to pay for energy efficiency depends on whether homes with better EPC actually bring energy savings and better living conditions. The overall market incentive would be more effective with better EPC systems. Therefore, it remains fundamental to improve the methodology/quality of EPCs to make it a useful facilitator in housing decarbonisation.

Other than environmental awareness, the mechanism of price premium is influenced by energy cost savings [47,67,103] and the cost of retrofitting [47] as well as other financial benefits. The ongoing energy crisis in Europe could influence consumers' willingness to pay as the potential energy cost savings becomes more attractive. However, the fact that only two studies found in this review cover data after 2022 makes it difficult to draw conclusions here. This calls for future researchers to apply price premium analysis on more recent data and explore changes in willingness to pay. Furthermore, mortgage lenders are increasingly recognising the value of energy-efficient homes, which can lead to better financing options for consumers, thereby raising benefits of purchasing energy-efficient properties.

The finding of a positive price premium could raise broader concerns in terms of the ultimate realisation of housing stock decarbonisation. On the positive side, the premium could encourage homeowners and builders who can afford the investment to prioritise energy efficiency. This could be further supported by policies offering tax incentives [104] and other financial benefits to promote energy-efficient investments. However, there are also disadvantages to consider. Lower-income households and tenants may be pushed towards less efficient homes and might not have the financial means to cover retrofitting costs. In addition, the ongoing housing and cost of living crises in many countries make it challenging to rely solely on market incentives to achieve decarbonisation. Government support such as subsidies should therefore be complementary measures to reach the net zero goals. Furthermore, the price premium should be weighed against the potential carbon savings to ensure that energy-efficient homes contribute effectively to Net Zero goals.

Some other interesting findings from the literature point towards additional future areas of work on the wider housing market impacts of energy efficiency. Bisello et al. [25] suggest the presence of a spillover effect to nearby properties from retrofitting investment. However, no study examined whether there might be more general spillover effects of housing energy efficiency. Also, Copiello and Donati [26] suggest comparing the price premium with the cost of energy efficiency investments, which could aid interpretation of the strength of the market signal which the price premium provides. Researchers are also concerned about the so-called rebound effect of price premium for energy efficiency [105], where households with more energy efficient homes overconsume heating energy while those living in energy inefficient homes use less energy to save money [105].

As data availability and OVB are both found to be major limitations, using new forms of data and methods could make important improvement. New data such as listings text/images would be easily accessible given permission from owner, and include rich information about property quality and features such as location, decoration, facilities, etc. It may be possible to obtain measures of the traditionally hard-to-measure variable of dwelling quality, potentially reducing problems of OVB. While hedonic regression can only include structured data, machine learning (ML) and deep learning (DL) methods are widely used to process unstructured data e.g. text/images. Therefore, price premium modelling could start from using ML/DL to extract attributes from text/images, followed by inclusion of attributes in the hedonic regression. Alternatively, both structured and unstructured data could be put in a ML/DL model to estimate house price in one attempt. However, this approach could not give an estimate of price premium, but only feature importance values e.g. 'SHapley Additive exPlanations' (SHAP) values. This again highlights the importance of the hedonic regression in this field with its high interpretability.

5.2. Limitations

There are several limitations of this review. An important one is stated clearly from the outset: that we only include English-language studies in the review, mainly due to shortage of time and resources. This limitation should be noted when discussing the findings, especially on geographical coverage of studies. Though we conclude that a group of countries has a research gap, there are very likely studies published in other languages missing from this review. Important work also exists in the grey literature which we have not tried to cover for the same reasons. Nonetheless, we develop a comprehensive, systematic, and innovative searching approach as well as quality-control screening approach, to allow reproducibility of results and to minimise bias in findings. In addition to language limitations, access to EPC data [14] appears to be a very significant influence on the geographic coverage of the literature which puts our limitations in context, limiting the applicability of findings across Europe. Further limitations concerns the trustworthiness of research outcomes (especially price premium synthesis) related to the quality of research, which are not controlled for in this review. We try to ensure a minimum standard of studies by limiting the search to articles which have appeared in peer-reviewed journals. Even so, studies may still vary in relation to the scale and quality of data, as well as research design and other features. Frameworks have been proposed for assessing the quality of studies on the basis of these features [106], but these are not applied here, partly because of the relatively small scale of the literature and partly because of the limitations of time.

5.3. Research gaps

In addition to the general comment about the restricted geographical coverage of the current literature, we identify the following knowledge gaps:

(1) Towards new forms of data and methods

To tackle the methodological limitations of OVB and obtain a more accurate estimate of the price premium, prospective research could either extract features from new forms of data (e.g. unstructured images/texts data) to include in the hedonic approach or apply advanced methods (e.g. ML/DL) directly to measure price premium accounting for these features.

(2) Towards sub-market studies

To fit with and inform housing policies on different submarkets (e.g. dwelling types, tenures, geography, years, group of buyers, etc.), it is recommended that future studies look at the impact on submarkets and tailored the research question and method to the specific setting of the submarket.

(3) Towards wider housing market impact of energy efficiency

Upon exploring willingness to pay for housing energy efficiency, it would be valuable to look at wider housing market impacts, for example the comparison of price premium across multiple countries, the spillover effect of energy efficient dwellings, the cost premium of energy efficiency investments, tenants' energy cost savings, etc. This would help policy makers to form a more comprehensive understanding of incentives, obstacles, and impact of housing energy efficiency.

Additionally, we have following comments for future conduct of scoping and systematic review in the same area of interest. To address the limitations of this review, future scoping reviews could improve in: (1) incorporate multilingual searching strategies, (2) include wider types of sources of evidence. Future systematic reviews are needed to provide more robust result synthesis. For quality control on included studies, we recommend systematic reviews to assess the risk of OVB in regression models. We find the primary research in this area is the impact of current EER bands on sales prices considering all dwelling types and using hedonic regression methods, which can be considered as the focus of a systematic review.

6. Conclusions and policy implications

In conclusion, this scoping review provides an overall picture of the European literature studying the price premium of EPCs, from research scope/scale to methods applied and research outcomes. This review is the first to apply a transparent, systematic searching and screening process to the academic literature in English. Drawing upon 68 studies reporting 111 models, this review highlights several major findings among the many. First, the studies are geographically concentrated in a limited number of countries in western, northern, and southern Europe. Additionally, we find hedonic models are predominant in this field with more sophisticated models gaining popularity. Two modelling challenges are identified, including data availability and OVB. Beyond EPC data, there is a lack of comprehensive property-level data, leading to the methodological challenge of OVB, rendering difficulties in isolating the impact of energy efficiency. Finally, this review confirms the presence of a positive price premium associated with higher EPC ratings with each additional EPC band worth about 1 %–3 % in house price increase, suggesting market preference for energy efficient homes. It also finds varying price premium across different sub-markets but no evidence of an increase over time.

For policy makers, the following recommendations need to be considered to support market incentives for housing energy efficiency improvements. First, there is a clear call for the EPBD/governments to accelerate open access to property-level EPC data across EU. It is especially important for EPBD to mandate the open access of EPC data in central and eastern Europe. Harmonisation of the data system would also enable cross-country price premium analyses. It remains crucial for EU regulations to promote other property-level data availability. Second, the market preference for energy efficiency encourages wider implementation of EPBD as well as the promotion of equivalent measures in other dominant economic areas such as the US and China. Furthermore, it is important for governments to acknowledge differences in market incentives between housing submarkets and to adopt submarket-specific policies. Tailoring policies for submarkets would address market-specific barriers and allow wider adoption and greater equity. Specifically, findings from this review suggests flats and rental markets should be given priority in government support.

7. Note

The result of the Fisher-Freeman-Halton test is calculated using https://www.analyticscalculators.com/calculator.aspx?id=58.

CRediT authorship contribution statement

Yunbei Ou: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Nick Bailey:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **David Philip McArthur:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Qunshan Zhao:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

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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. Summary of search strategies and records retrieved

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Database	Interface	Search command	Search date	Records retrieved
SCOPUS	**Elsevier**	(((TITLE (hous* OR "domestic propert*" OR "residential propert*" OR dwelling* OR apartment*) OR ABS (hous* OR "domestic propert*" OR "residential propert*" OR dwelling* OR apartment*))) AND ((TITLE ("green value" OR "green premium") OR ABS ("green value" OR "green premium")))) OR ((((TITLE ((value OR cost OR price) W/3 (hous* OR "domestic propert*" OR "residential propert*" OR dwelling* OR apartment*)) OR ABS ((value OR cost OR price) W/3 (hous* OR "domestic propert*" OR "residential propert*" OR dwelling* OR apartment*)))) OR ((TITLE ("housing market" OR "real estate" OR "hous* sales" OR "house prices" OR "housing prices" OR "housing value" OR "domestic property prices" OR "domestic property value" OR "residential property prices" OR "residential property value") OR ABS ("housing market" OR "real estate" OR "hous* sales" OR "house prices" OR "housing prices" OR "housing value" OR "domestic property prices" OR "domestic property value" OR "residential property prices" OR "residential property value")))) AND ((TITLE ("energy efficiency" OR "energy rating" OR "energy performance certificates" OR "epc") OR ABS ("energy efficiency" OR "energy rating" OR "energy performance certificates" OR "epc"))))	2024/05/02	833
WoS	**Clarivate**	(TS=(house* OR "domestic propert*" OR "residential propert*" OR dwelling* OR apartment*)) AND TS=("green value" OR "green premium") OR (((TS=((value OR cost OR price) NEAR/3 (hous* OR "domestic propert*" OR "residential propert*" OR dwelling* OR apartment*)))) OR TS=("housing market" OR "real estate" OR "hous* sales" OR "house prices" OR "housing prices" OR "housing value" OR "domestic property prices" OR "domestic property value" OR "residential property prices" OR "residential property value")) AND TS=("energy efficiency" OR "energy rating" OR "energy performance certificates" OR "epc")	2024/05/02	797
IBSS	**ProQuest**	(noft(hous* OR "domestic propert*" OR "residential propert*" OR dwelling* OR apartment*) AND noft ("green value" OR "green premium")) OR ((noft((value OR cost OR price) W/3 (hous* OR "domestic propert*" OR "residential propert*" OR dwelling* OR apartment*)) OR noft("housing market" OR "real estate" OR "hous* sales" OR "house prices" OR "housing prices" OR "housing value" OR "domestic property prices" OR "domestic property value" OR "residential property prices" OR "residential property value")) AND noft("energy efficiency" OR "energy rating" OR "energy performance certificates" OR "epc"))	2024/05/02	253
EconLit & Business Source Ultimate	**EBSCOhost**	**S1** TI (hous* OR "domestic propert*" OR "residential propert*" OR dwelling* OR apartment*) OR AB (hous* OR "domestic propert*" OR "residential propert*" OR dwelling* OR apartment*) **S2** TI ("green value" OR "green premium") OR AB ("green value" OR "green premium") **S3** S1 AND S2 **S4** TI ((value OR cost OR price) W3 (hous* OR "domestic propert*" OR "residential propert*" OR dwelling* OR apartment*)) OR AB ((value OR cost OR price) W3 (hous* OR "domestic propert*" OR "residential propert*" OR dwelling* OR apartment*)) OR TI ("housing market" OR "real estate" OR "hous* sales" OR "house prices" OR "housing prices" OR "housing value" OR "domestic property prices" OR "domestic property value" OR "residential property prices" OR "residential property value") OR AB ("housing market" OR "real estate" OR "hous* sales" OR "house prices" OR "housing prices" OR "housing value" OR "domestic property prices" OR "domestic property value" OR "residential property prices" OR "residential property value") **S5** TI ("energy efficiency" OR "energy rating" OR "energy performance certificates" OR "epc") OR AB ("energy	2024/05/02	394

(*continued on next page*)

(*continued*)

Database	Interface	Search command	Search date	Records retrieved
		efficiency" OR "energy rating" OR "energy performance certificates" OR "epc") **S6** S4 AND S5 **S7** S3 OR S6		
Total			2277	

Appendix B. . Links to the openly available national EPC databases of included studies.

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Country/region	Link
England and Wales (UK)	https://epc.opendatacommunities.org/ (accessed 29/09/2024)
Scotland (UK)	https://statistics.gov.scot/data/domestic-energy-performance-certificates (accessed 29/09/2024)
Sweden	https://www.boverket.se/sv/energideklaration/sok-energideklaration/ (accessed 29/09/2024)
Norway	https://www.nve.no/energy-consumption-and-efficiency/energy-labelling-of-housing-and-buildings/ (accessed 29/09/2024)
Netherlands	https://www.ep-online.nl/PublicData (accessed 29/09/2024)
Portugal	https://www.sce.pt/pesquisa-certificados/ (accessed 29/09/2024)
Ireland	https://ndber.seai.ie/BERResearchTool/ber/search.aspx (accessed 29/09/2024)
Denmark	https://old.sparenergi.dk/offentlig/vaerktoejer/find-bygningens-energimaerke (accessed 29/09/2024)

Note: The availability of EPC data in Italy and Spain depends on regions, and thus not included in the table.

Appendix C. . Measurement of housing quality variable from identified sources

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Source type	Source platform	Country/ region	Field	Variables
Online listing	immobilienscout24.de	Germany	'Interior quality' 'Condition'	Categorical: 'luxury', 'good', 'normal', and 'simple' Categorical: 'refurbished','need of renovation','first time use', Etc.
	idealista.com	Spain	'Dwelling state'	Categorical: 'luxury', 'good', etc.
Real-estate agent association	Dutch Association of Realtors	Netherlands	'Interior and exterior maintenance'	Binary
Research centre	The Real Estate Observatory of the City of Turin	Turin (Italy)	'Building quality'	Categorical: 'council housing', 'economical', 'medium-level', 'distinguished' and 'classy'

Appendix D. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2025.115377.

Data availability

The research data in this review contains database searching commands and results, AI searching results, screening results, and data extraction results. All the data and code for producing the results are available on GitHub at: https://github.com/YunbeiOu/ScopingReview_EPC_PricePremium.

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