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Exploring Discrepancies in Energy Performance Certificates: Analyzing Energy Efficiency Premiums for Buildings Based on Theoretical Energy Requirements Versus Actual Energy Consumption

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Abstract

The building sector is lagging its needed decarbonization pathway. This paper examines EPC policy impacts on building economics in the Rhein-Main Region in Germany. Energy efficiency premiums for rents and sales prices and the effects of the EPC type are investigated using data from 01/2015 - 06/2023 (N = 212 167 rent sample; N = 159 573 sales sample) and hedonic price models. Energy efficiency premiums are present and range up to 7.0%, 4.6% and 6.9% for cold and warm rents and sales prices, respectively, when comparing an A+ to a D rated building. Consumption certificates reflect warm rents better but have a limited sales price impact. Results are rent efficiency premiums of up to 7.1% (A+), no rent discounts for energy inefficiency and a general sales price discount of about 3%. Requirement certificates are viewed as objective, yet less consumption-indicative, especially in the sales market. Rent efficiency premiums of up to 8.8% (A+) and no rent discounts for energy inefficiency are estimated for a building with a requirement certificate. Sales price efficiency premiums of up to 7.4% (A+) and sales price inefficiency discounts of up to -10.2% (H) exist. Overall, current German EPC policy does not address imperfect information, and it is recommended to revise its implementation.

Keywords: energy efficiency; energy performance certificate; EPC; hedonic price model; real estate investments; real estate valuation

1. Introduction & overview

The green transformation of the global economy continues to dominate key policy discussion points within national governments and international institutions. At the beginning of 2023, the Intergovernmental Panel on Climate Change (2023, pp. 4-11) presented the alarming current course of climate change and the insufficient actions taken by governments worldwide. Worryingly, the gap between specific sectors and their defined 2050 decarbonization pathways is widening (International Energy Agency and the United Nations Environment Program, 2022, p. 32). One significant driver of emissions is the building sector. The Global Alliance for Buildings and Constructions has indicated that the building sector is responsible for 37% of all energy-related emissions worldwide (International Energy Agency and the United Nations Environment Program, 2022, p. 37). Major industrialized countries, i.e., Germany, have failed and continue to fail to reach their building sector emission targets (Umweltbundesamt, 2023). The EU Commission has made closing the gap between the 2050 pathway and the status quo in the EU one of their key targets (Directorate-General for Climate Action, 2019, p. 6 & p. 9.). The latest policy changes reflect the importance of transforming the building sector. The EU policy, Directive (EU) 2023/1791, requires 3% of the total area of all publicly owned buildings to be renovated each year. National laws such as the Gebäudenergiegesetz (GEG) in Germany define specific types of energy sources and thermal transmittance values for building components when renovating existing buildings. At the same time, the question of climate change is accompanied by the economic demand and social need for appropriate residential real estate for residents in terms of quantity and quality. In Germany, this has

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led to a federal initiative focusing on affordable housing with the goal of building 400 000 new residential buildings per year (Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen, 2022, p. 4). This goal starkly contrasts the reality of only 306 000, 293 000, and 295 000 new buildings built in 2020, 2021, and 2022, respectively (Statistisches Bundesamt, 2023c).

The need for a radical transformation of the building sector and the differences between theoretical demand for and actual supply of living space warrant an in-depth analysis of the current state of residential real estate economics. It seems crucial to understand the regional implications of the energy efficiency policies passed by the EU institutions for the building sector in Germany, the largest EU member state by population and size of the economy (Eurostat, 2023b, 2023c). Evidence is needed to guide the discussions around energy efficiency of buildings on a political level and to understand the incentive structures for all building sector stakeholders (i.e., building owners, tenants, and industry service providers). Both can be achieved by looking at the energy performance certificates (EPCs) of residential buildings. EPCs were first introduced by a key EU policy targeting energy efficiency of buildings, the Energy Performance of Buildings Directive (EPBD) 2002/91/EC. The question arises whether differences in energy efficiency presented in these EPCs impact the rent and sales prices of buildings. This could be caused by the capitalization of energy savings or changes in building specific risk. Past research has provided evidence that differences in energy efficiency of buildings are directly correlated with differences in their rents and sales prices (see Brounen and Kok, 2011; Cajias et al., 2019; Deller, 2022; Högberg, 2013; Hyland et al., 2013). These studies show regional differences across different EU countries for rental and sales price premiums. For the German market, research has shown rental premiums between 0.9% and 5.8% and sales price premiums between and 5.0% and 6.8% when comparing the most efficient buildings to the average building stock (Kholodilin et al., 2017, p. 3231; Cajias et al., 2019, p. 183; Deller, 2022, p. 802). While this research provided first evidence on the topic, distinctive implementation details of the EU policy in Germany have not been considered. This particularly concerns the EPC type used by the building owner. The analysis presented in this paper is one of the first to consider the differences in energy efficiency premiums based on the EPC type used by the building owner. Hedonic price models are specified to analyze a rent data sample and a sales data sample with observations in the Rhein-Main Region in Germany. The results provide evidence for general energy efficiency premiums for the rental and sales market of up to 7.0% and 6.9% respectively. Additionally, evidence is presented that shows significant differences between the used EPC types. While the consumption certificate more accurately encompasses operational costs for buildings in the rental market, the requirement certificate is the one trusted by prospective buyers and crucial in determining sales prices. Controlling for the EPC types increases the premiums of the most efficient buildings with a requirement certificate to 8.8% and 7.4% for the rental and sales market, respectively. The findings of this paper have implications for policy makers and other stakeholders and recommend a revision or at least a re-evaluation of the EPC policy in the German market. Further, it becomes clear that the costs of transforming the building sector must be shared between asset owners, tenants and regulators. While owners might have to accept lower profitability, tenants must support modernizations via increased rents. Regulators need to support the sector transformation with non-financial processual adjustments. Whether financial subsidies by regulators are needed, too, is beyond the scope of this analysis. But evidence for this exists in the literature (Groh et al., 2022, pp. 105-107).

The remainder of this paper is structured as follows: In section 2, the extant literature is reviewed, and the hypotheses of this paper are derived. The review includes normative residential real estate valuation theory, EU and German policy and empirical literature. Next, in section 3, the methodology, the sample statistics, and the model specifications are presented. Section 4 reports the empirical results. They are subsequently discussed in section 5. In the final section 6, a conclusion and outlook on future research opportunities are given.

2. Review of the extant literature

The purpose of this paper is to provide relevant insights based on a rigorous quantitative analysis that can help policymakers and private and institutional investors make informed decisions when it comes to the economic meaning of the energy efficiency of residential real estate. To enable readers from a non-real estate background to better understand the results and implications of the analysis, a short introduction to the characteristics and economics of real estate as an asset class is given. Throughout the paper it will be referred to this normative theory.

2.1. Theoretical background & basic concepts

Real estate belongs to the field of the alternative asset classes. The variety of available investment opportunities within this particular asset class and across other alternative asset classes is vast. Further, the capital invested in real estate is significant. Estimates suggest that fifty percent of global wealth is invested into real estate (Baum & Hartzell, 2021, p. 4). The actual value of real estate as an asset class remains unclear. Overall, the global real estate market is made up of different national and regional markets shaped by their own regulations and characteristics. At the same time, there are characteristics and valuation methodologies regarding real estate as an asset class that remain valid across markets. The core characteristics of real estate are summarized below (Baum & Hartzell, 2021, p. 12–26):

- Depreciation: Properties are real assets that are affected by physical deterioration over time, leading to depreciation of their overall value (Baum & Hartzell, 2021, p. 12).

- Lease and cash flows: The lease agreement of a property is the main determinant of the cash flow generated by the asset over time (Baum & Hartzell, 2021, p. 13).
- Inelasticity of supply: Rise in demand is met by the supply side with a significant time lag that is caused by the long processes of acquiring permits and the subsequent construction of properties (Baum & Hartzell, 2021, p. 13).
- Valuation and investment performance: The appraisal value of a property sets the anchor for any future transactions and results in the issue of valuation smoothing (Baum & Hartzell, 2021, p. 14–15).
- Illiquidity of properties: High transaction costs, long sales processes and large bid-offer spreads are causes for the illiquidity of properties (Baum & Hartzell, 2021, p. 15).
- Asset specific risks: High capital values of properties create specific risks and make reducing risk to the systematic level difficult (Baum & Hartzell, 2021, p. 16–17).
- Leverage: Most investments are accompanied by loans against the property as collateral, resulting in a different risk–return profile (Baum & Hartzell, 2021, p. 18–19).
- Inflation correlation: Evidence in form of strong correlation exists that shows that properties might be an inflation hedge in the long-run (Baum & Hartzell, 2021, p. 19–21).
- Medium risk-return profile: Historical values suggest that while risk appears low, existing illiquidity and income uncertainty of properties result in an overall medium risk-return profile (Baum & Hartzell, 2021, p. 21–22).
- Return impact of real estate cycles: Inelasticity of supply and the caused lag in adaptive behavior leads to cyclical returns of investments (Baum & Hartzell, 2021, p. 22–24).
- Diversification impact of properties: Based on modern portfolio theory, real estate can be used for diversification because it shows low correlation with returns on equities and bonds (Baum & Hartzell, 2021, p. 24–26).

The amount and conditions of leverage used, the potential tax benefits attributed to a property, or the diversifying impact of the property on an investor's portfolio are crucial aspects when determining how much an investor is willing to pay for a property (Baum & Hartzell, 2021, p. 145–156). However, before these factors come into play, an appraisal of a property based on the status quo of market characteristics is calculated. The valuation methodology used for this is explained below. Tax benefits, the impact of leverage or the strategic relevance of an investment are out of scope for the present paper.

Within the German market, the official appraisal process of a property is regulated by the Immobilienwertermittlungsverordnung (ImmoWertV). This act is the basis for an objective valuation of a property and its methodologies are used by surveyors for calculating the valuation of a property for a forced sale. Additional information can be found in the "Muster- Anwendungshinweise zur Immobilienwertermittlungsverordnung," a set of instructions on how to implement the ImmoWertV (Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen, 2023). Each property is an individual case and object-specific characteristics make each appraisal different. This gives some leeway to the individual performing an appraisal.

The appraisal methodologies described in the ImmoWertV are the "Vergleichswertverfahren" (§§ 24-26 ImmoWertV), the "Ertragswertverfahren" (§§ 27-34 ImmoWertV) and the "Sachwertverfahren" (§§ 35-39 ImmoWertV). All methodologies follow the three-step process that is shown in Figure 1 (§ 6 ImmoWertV). First, a methodology is used to provide a preliminary appraisal result. Next, local market characteristics are assessed, and the appraisal is adjusted. This is done regardless of which appraisal methodology was chosen and is the same proceeding for all the methodologies. As a final step, property specific characteristics are valued and included in the appraisal. This can include, for example, rights of special use. The final appraisal value is based on one or several values of the appraisal methodologies.

Internationally, the International Valuation Standards Council (IVSC) is recognized as the leading institution regarding standards in property valuation. This is underlined by the great number of national valuation associations that are members of the IVSC (International Valuation Standards Council, 2023). This includes, for example, the British national valuation association called Royal Institute of Chartered Surveyors. The latest standard on property valuation was published by the IVSC in January 2022 (International Valuation Standards Council, 2022). It describes the same three valuation methods for properties that were presented above: market approach, income approach, cost approach (International Valuation Standards Council, 2022, pp. 33-53). Thus, this general comparability across markets is established. The remainder of the paper focuses on the proceedings described in the ImmoWertV as the regional market of the Rhein-Main Region is under its jurisdiction. The English translation of the methodologies is used to improve the flow of reading. The English terms refer to the implementation in the German ImmoWertV. The market approach refers to the "Vergleichswertverfahren," the income approach refers to the "Ertragswertverfahren" and the cost approach refers to the "Sachwertverfahren."

The market approach is a comparably simple valuation methodology that uses similar transactions in the recent past to value a property (§§ 24-26 ImmoWertV). An overview of the market approach methodology is given in Figure 2.

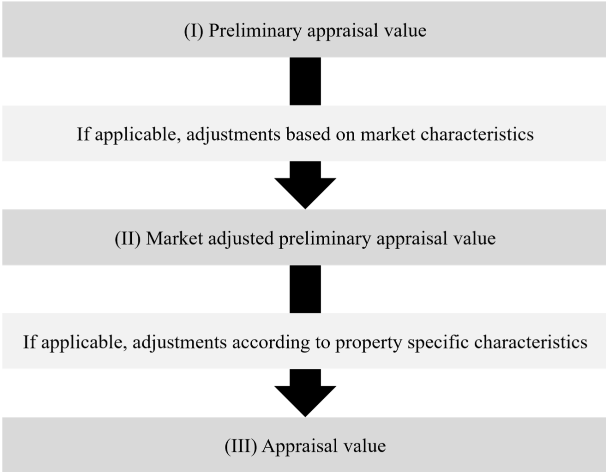

Figure 1: Three-step appraisal process
(source: translated from Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen (2023, p. 14))

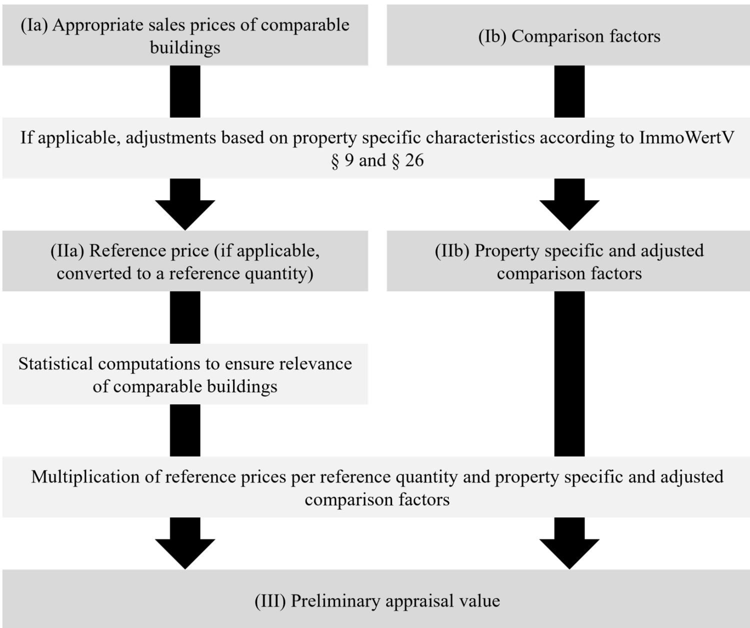

Figure 2: Market approach
(source: translated from Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen (2023, p. 28))

First, a statistically relevant number of transactions are identified. Next, benchmark values for relevant hedonic characteristics are calculated and comparison factors for the property to be valued are defined. These are multiplied and result in a preliminary appraisal value of the property. The preliminary appraisal value is equal to the one mentioned under (I) in Figure 1. It is then adjusted according to the process described above. The market approach is a more qualitative and simplified version of the statistical analysis performed in this paper. In its core, the idea used by the market approach and in this paper remains the same.

The income approach (§§ 27-34 ImmoWertV) is a version of a discounted cash flow (DCF) analysis. The DCF analysis is an internationally used standard valuation methodology for properties and other asset classes. Three different methods are defined for the income approach: a) general income approach b) simplified income approach c) periodic income approach. An overview of those three methods is given in Figure 3.

The preliminary appraisal value of the general income approach is calculated using the following equation (Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen, 2023, p. 30):

$$pAV = (NOI - LV \times cr) \times CF + LV \tag{1}$$

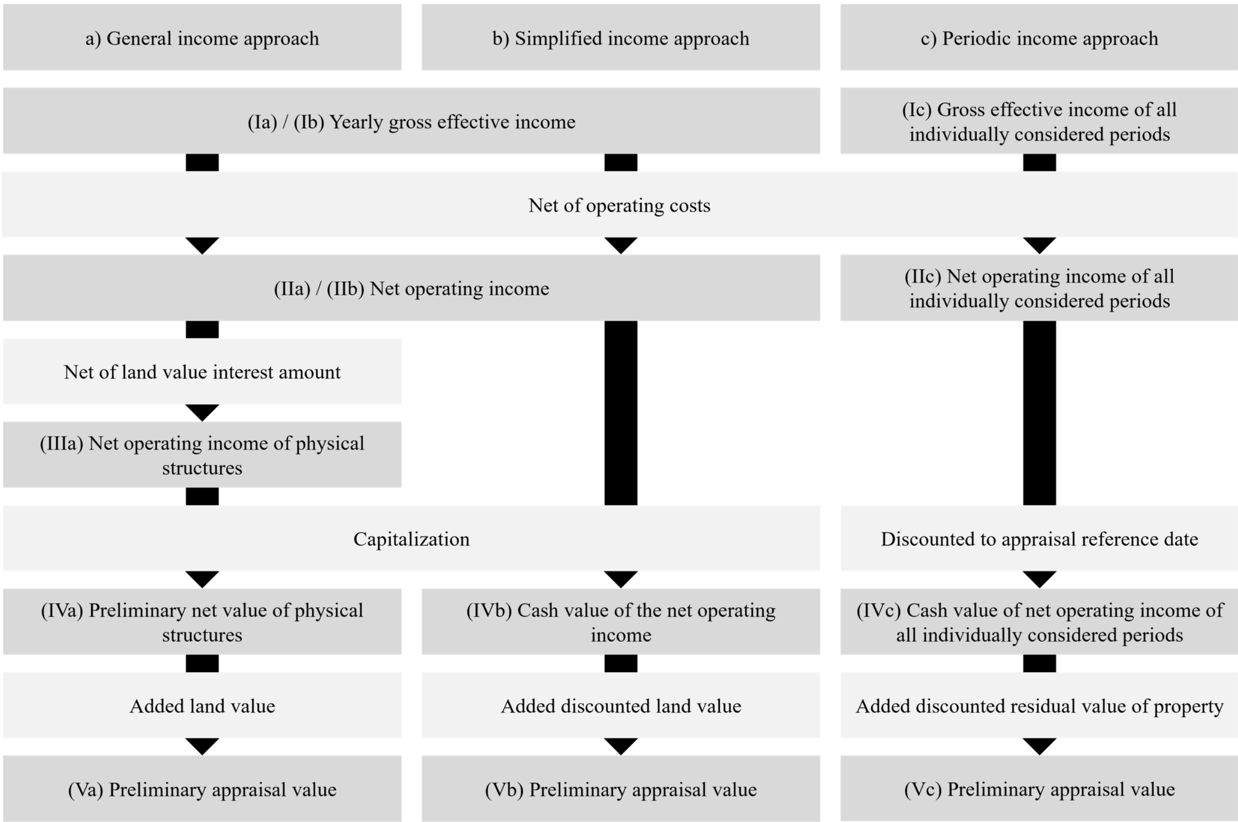

Figure 3: Income approach
(source: translated from Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen (2023, p. 30))

pAV stands for the preliminary appraisal value. NOI is the current yearly net operating income (NOI). *LV* stands for the land value and cr for the capitalization rate (cap rate). CF is the capitalization factor. To calculate the preliminary appraisal value, first, the NOI is calculated. This is done by estimating the yearly gross effective income (GEI) of the property based on current market values or the current lease. Next, operating expenses are deducted. This includes administrative costs, maintenance costs, risk of loss of rental income and running costs. Generally, the running costs are covered by the tenant in Germany following § 556 Bürgerliches Gesetzbuch (BGB). If this is the case, they are not deducted and not included in GEI received by the property owner. The GEI or in Germany the GEI plus the operating costs covered by the tenant is equal to the so-called warm rent. The NOI is equal to the so-called cold rent in Germany. Before multiplying the NOI with the capitalization factor, the land value interest amount is deducted to separate the land value and the income produced by the building. The land value interest amount is the land value multiplied with the cap rate. The land value is calculated based on defined standard land values for the location of the property. The cap rate is calculated iteratively based on past transactions in the local market. Each year, rating committees calculate official cap rates for local markets. One example is the Gutachterausschuss Frankfurt am Main that published the Immobilienmarktbericht 2023 (Debus, 2022). The calculations of the rating committee are based on § 21 ImmoWertV and readers are referred to this regulation for details. Following this, the multiplication with the capitalization factor results in the income value of the building of the considered property. The capitalization factor is calculated using the following equation (Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen, 2023, p. 30):

$$CF = \frac{(1+cr)^n - 1}{(1+cr)^n \times cr} \tag{2}$$

The n in the equation above stands for the number of residual years of usage of the property. This value depends on the construction year, building type and modernizations done to improve the property. As a final step, the land value is added to the value of the property. The resulting preliminary appraisal value is adjusted using the steps of the process described in Figure 1.

The simplified income approach is applied in a similar way. The result is again the preliminary appraisal value that is subsequently adjusted. The meaning of the variables mentioned above stays the same. It is calculated using the following equation (Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen, 2023, p. 31):

$$pAV = NOI \times CF + LV \times DF \tag{3}$$

DF stands for the discount factor applied to the land value. The discount factor is calculated as follows (Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen, 2023, p. 31):

$$DF = (1 + cr)^{-n} \tag{4}$$

Compared to the general income approach, the only differences are that the land value interest amount is not deducted from the NOI and in turn the land value is multiplied with the discount factor when added to the appraisal value. Finally, the periodic income approach is calculated as follows (Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen, 2023, p. 31):

$$\begin{aligned} pAV = {} & NOI_1 \times DF_1 + NOI_2 \times DF_2 \\ & + \ldots NOI_i \times DF_i + RV \times DF_b \end{aligned} \tag{5}$$

RV stands for the residual value of the property. The indexes indicate the specific period of the holding term considered. It starts with the first period and goes up until i, the index of the last period. Index b indicates the overall holding term. This variant of the income approach adds up the discounted future cashflows of the property and allows for changes in rental income and cap rate and thus capitalization factor. The length of the term can differ for each investment and depends on the number of periods considered. If the calculation does not include all periods until the final year of usage of a property, the residual value is added as a final value. The residual value is calculated using the simplified income approach. When considering long term projections, the estimations of these values become more difficult. When considering short term projections, the investment return strongly depends on the residual value of the property.

The final method considered here is the cost approach (§§ 35-39 ImmoWertV). The approach is summarized in Figure 4. The appraisal value is calculated by adding together the production costs of the usable main buildings, additional material assets and the land value. The production costs are equal to the calculated building costs needed in the current market conditions to construct a building that is comparable in kind and size to the property. Usually, these costs are based on industry modelling costs that are then multiplied with the respective reference units of the property. Additional adjustments are done based on the current price index published by the Statistisches Bundesamt in Germany. The average productions costs of the property are subsequently adjusted based on the age and the location of the property. This leads to the preliminary appraisal value mentioned as (I) in Figure 1. Next, this value is adjusted using the respective local market factors as was explained above.

Together, the different methods offer insights into the current appraisal value of the property. The final appraisal value is usually computed by taking the mean value of the different outcomes. In the context of this paper, the question that arises is how an increase or decrease in energy efficiency of a building would affect the outcome of the computation of the appraisal value when applying the presented methodologies. The following paragraphs describe the normative reasoning on why there should be energy efficiency premiums and discounts present in the residential real estate market of Germany. Of note, the market approach is not discussed because, as explained above, it represents a simplified version of the analysis in this paper.

When looking at the variants of the income approach, several variables in the equation could be affected by an increase or decrease in the energy efficiency of a building: gross effective income, net operating income, cap rate and residual years of usage. These variables represent the cashflows generated as well as the discount rate applied to these cash flows. The cash flows are considered first under the aspect of an increase in energy efficiency:

An increase in energy efficiency of a building leads to a decrease of energy usage and thus energy costs. The energy costs are the running costs of the building and are included in the operational expenses. In Germany, the operational expenses are mostly covered by the tenant and not the landlord. Thus, any investment into energy efficiency improvements is paid by the landlord and the decrease in operational expenses benefits the tenant. This is the so-called landlord-tenant dilemma and a key non-technical barrier to improving energy efficiency of real estate (Hirst and Brown, 1990, p. 276; Jaffe and Stavins, 1994, p. 805). Based on this argument alone, no changes to the net operating income of the building would occur. This, however, does not seem plausible in the case of a market environment. The landlord would try to recoup the investments and participate in the energy savings by increasing the cold rent for the tenant. This leads to a capitalization of the investment and an increase in the NOI for the owner. How much of the investment and how fast it can be capitalized remains a discussion topic in current research (see e.g., März et al., 2022, p. 20). It might depend on the kind of investment made and the local policy restrictions on rent increases. Often, energy efficiency improvements are prohibitively expensive compared to the achieved energy savings in monetary terms (März et al., 2022, p. 20). This leads to long recouping periods. Only recouping energy savings in the cold rent seems to make the investments unattractive. One additional option for landlords is to increase the cold rent more than the energy savings achieved by the improvements. This would lead to a disproportionate increase in cold rent and, subsequently, for the tenant to an increase in warm rent compared to the situation before the investment. In conclusion, an increase in energy efficiency would likely lead to an increase in the cold rent and warm rent of a building.

Besides the cash flows, the cap rate is crucial for the appraisal value calculation. As mentioned above, average cap rates for a local market are published each year. The cap rate is an indicative value for the sum of the property market risk premium, a location premium and a mean value for the asset

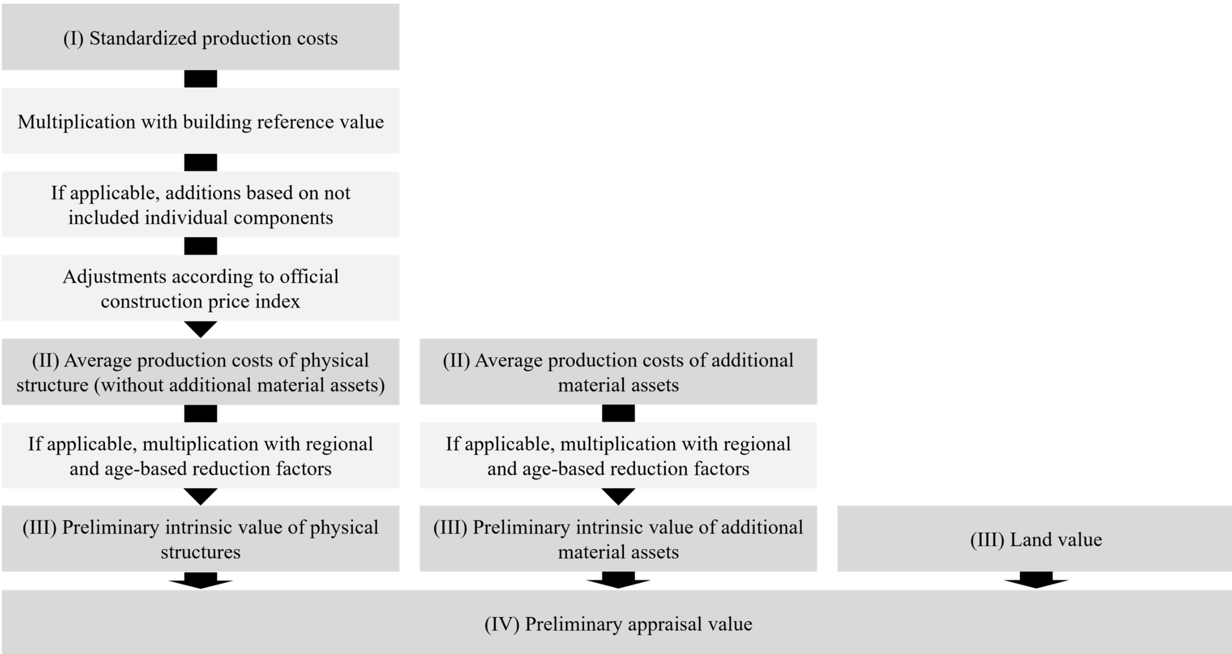

Figure 4: Cost approach
(source: translated from Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen (2023, p. 34))

specific premium (Baum & Hartzell, 2021, p. 153). Which exact cap rate is chosen depends on the decision made by the appraiser and is based on the property specific characteristics (Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen, 2023, p. 33). The question arises how an increase in energy efficiency of a property would affect the risk associated with it. As argued by Deller (2022, p. 806) and underlined by the most recent public discussions regarding energy efficiency policies for buildings (Nieskes, 2023), high energy consumption could be associated with uncertainty and thus higher building specific risk. This leads to a decrease in risk when an increase in energy efficiency can be achieved for a property and thus a lower cap rate. A decrease in the cap rate leads to an increase in the appraisal value.

The last variable that is directly affected is the residual years of usage variable. An increase in energy efficiency can be achieved by modernizing a building. Such a modernization can range from, e.g., improving isolation to changing the heating system or windows. Each of these modernizations improves the energy efficiency of the building and influences the residual years of usage according to Appendix 2 of the ImmoWertV. Appendix 2 of the ImmoWertV provides a list of improvements and a table showing their impact on the residual years of usage. Based on the improvements made, an adjusted value for the residual years of usage is computed. As an example, the following impact could be achieved for an apartment in a multi-family apartment building that is 50 years old with 30 residual years of usage: If modernizations are performed that improve the isolation of the walls and the heating system is replaced, the residual years of usage increase to 37. Recalculating the cap factor of this building now results in 25.97 compared to the cap factor of 22.40 before. A 2% cap rate is applied. The increase in the cap factor results in an increase of 64 260 € in the appraisal value when using a 100 m^2 building and a cold rent of 15 € / m^2. The assumed cold rent is in line with current market prices for the city of Frankfurt a.M., the center of the Rhein-Main Region (Immowelt, 2023).

The other appraisal approach considered here is the cost approach. The appraisal value is based on the production costs of a comparable building in kind and size and adjusted based on age and current market conditions. The question is how an increase or decrease in energy efficiency would affect the appraisal value computed. As a first step, the construction costs are computed. The first preliminary production costs per m^2 to be used can be found in Appendix 4 of the ImmoWertV. They depend on the type and size of the building being constructed. A further differentiating factor is the standard of the building. The standard of the building is defined by the materials and technique used to construct it. A detailed description can be found in Appendix 4 of the ImmoWertV. When looking at specific elements like the outer walls or roof, it becomes clear that a higher level of energy efficiency is associated with a higher level of the standard of the building. The highest standard, level five, requires isolation of the walls and rooftop according to the Passivhaus-Standard for example. This impact of building components associated with energy efficiency on the standard of the building has a direct impact on the construction costs associated with it. For a multi-family home of up to six apartments, a construction cost of 825 € / m^2 is set for the standard level 3. A standard level 5 has a preliminary construction cost of 1190 € /

m^2. For a 100 m^2 apartment, this would change the appraisal value by 36 500 € without including considerations regarding the current construction price index or regional market adjustments. Evidently, it is not only energy efficiency that plays a role when it comes to determining the standard of the building. However, this quick estimation does show its relevance and impact on the appraisal value. Thus, buildings built with a higher level of energy efficiency should have a higher appraisal value when using the cost approach.

Based on the normative analysis above, there is a strong link between the energy efficiency of a building and its appraisal value. The question remains whether this strong link can be found in market prices, too. Further, the magnitude of this link is unclear. Lastly, the appraisal approaches outlined above might not correctly reflect the status quo of methods used by most market participants. For the market to reflect the importance of energy efficiency in market prices, an effective communication of energy efficiency of buildings is necessary. More importantly, differences in energy efficiency between buildings need to be clearly visible. How this communication is implemented is crucial and impacts the level of transparency for market participants. The implementation in the EU market is summarized below.

Depending on the region and type of real estate market, different certificates have been defined to communicate energy efficiency values. They range from certificates with a wide coverage of sustainability characteristics of a property (e.g., LEED, BREEAM) to others focusing primarily on the energy usage of a building (EU EPC) (BRE Group, 2023; Directorate-General for Energy, 2023; U.S. Green Building Council, 2023). When it comes to the residential real estate market in the European Union, the EPC was introduced as a mandatory certificate for communicating the energy efficiency of a building (Directorate-General for Energy, 2023). This purpose of this policy is to address the market failure of imperfect information.

The EPC was first introduced by the EU Energy Performance of Buildings Directive (EPBD) 2002/91/EC in 2002 and has since been replaced or amended multiple times. In 2010, the directive 2010/31/EU was approved, replacing the previous one. It included various changes such as making an EPC a requirement by law when leasing or selling a property and encouraging member states to provide financial incentives for energy efficiency improvements. In 2018 an amendment was approved: EU directive 2018/844/EU. It included improvements regarding the comparability of the calculation methodology used for EPCs and requires member states to formulate long-term renovation strategies. Another objective was to better align the EPBD with other directives such as the Energy Efficiency Directive and the Renewable Energy Directive. In December 2021, the EU Commission proposed a revision of the EPBD. The legislative procedure that can be found under "Procedure 2021/0426/COD" is currently in the stage of the trilogue negotiations (Dulian, 2023). It is likely to lay out compulsory 2030 targets for lowering energy consumption of the building sector overall. It will, however, not change the EPC framework and will not affect the quality, harmonization or accessibility of the EPCs.

As the EPCs on an EU level are regulated by a directive only, each member state has the responsibility to implement them on a national level (Directorate-General for Communication, 2023). The freedom in doing so limits the comparability of EPCs across member states. However, within one member state, the legislation is the same and in the context of this paper this is sufficient. In Germany, the EPC or in German "Energieausweis" is regulated by the Gebäudeenergiegesetz (GEG) in §§ 79-88.

The GEG lays the foundation for the EPC to work as a proxy in this paper. An EPC must be presented to any prospective tenant or buyer and information about the energy efficiency must be included in an online listing (§ 87 GEG). The EPC is valid for ten years if no building modernizations took place during that time (§ 79 GEG). It shows, e.g., the final energy consumption measured in kWh / (m^2 * a), the type of heating system and recommendations for possible energy efficiency improvements (§§ 84-85 GEG). The assessment and issuance of an EPC is only allowed to be performed by people with specific training and professional experience (§ 88 GEG). There are two different EPC types in Germany. One states the final energy consumption in the EPC that is computed using the energy consumption over the last 36 months. This EPC type is called "Verbrauchsausweis" (§ 82 GEG). This is translated to "consumption certificate" and used as such in the remainder of this paper. The second type states the final energy consumption that is computed using the theoretical consumption needs of the building based on material and construction information. It is called "Bedarfsausweis" (§ 81 GEG). This is translated to "requirement certificate" and is used as such in the remainder of this paper. Not every building can be issued either certificate. Certain property characteristics must be fulfilled to be issued a consumption certificate. These characteristics include the construction year, its coherence with energy efficiency laws introduced in 1977 and energy consumption data availability(§ 80 GEG). The different cases are presented in Appendix 1.

The calculations needed for the consumption certificate are easier and thus, this certificate is cheaper to acquire than a requirement certificate (Verbraucherzentrale NRW e.V., 2023b). Critics state that the consumption certificate lacks detailed information on the actual energy efficiency quality of the building and heavily depends on the behavior of the tenants in the past three years (Verbraucherzentrale NRW e.V., 2023b). The difference between theoretical and actual energy consumption has led to the terms of the "prebound" and "rebound" effect (Galvin, 2023, p. 502). The prebound effect describes the phenomenon where the actual energy consumption of an energy inefficient building is on average much lower than its theoretical energy consumption stated in the requirement certificate (Galvin, 2023, p. 502). The rebound effect describes the phenomenon where the actual energy consumption of a highly energy efficient building is on average higher than its theoretical energy consumption stated in the requirement certificate (Galvin, 2023, p. 502).

Independent of the limited comparability across EPC types, reliability and accuracy of the results presented can be assumed across one EPC type because only trained individuals with government issued certifications are allowed to offer certification services and can be held accountable if falsified or incorrect data were used (§ 83 GEG; § 88 GEG). The requirement of including information on the energy efficiency of a building on listings has improved data availability and market transparency. This data has been analyzed by academics since the EU-wide introduction of the EPC to provide evidence for the evaluation of the effectiveness of the policy and its impact on building economics. In the next subsection, the relevant empirical literature in the context of this paper is presented.

2.2. Empirical literature

The field of empirical literature analyzing the connection between sustainability characteristics such as energy efficiency and property valuation is vast. One approach to categorizing the literature is to sort the publications by some of the building sector characteristics that were mentioned above. This leads to the following classification criteria:

I. Year of publication

II. Region of real estate market (i.e., Americas, Europe, Asia, etc.)

III. Type of real estate market (i.e., industrial, commercial, residential)

IV. Type of certificate (i.e., LEED, BREEAM, EPC)

V. Type of transaction (i.e., rent or sale)

VI. Type of property (i.e., apartment, semi-detached, detached)

VII. Methodology applied (i.e., qualitative vs. quantitative)

VIII. Data sample analyzed (i.e., data sources, time span of data)

The first publications in this field of literature regarding residential real estate were performed using data from the USA but were limited by computing power and data availability. Those include for example Dinan and Miranowski (1989), Johnson and Kaserman (1983), and Nevin and Watson (1998). They represent some of the first studies analyzing the impact of sustainability characteristics such as energy efficiency on the valuation of properties. All find evidence that savings on energy costs are capitalized into the value of properties. Since then, data availability and access to computing power have considerably increased, making it possible to analyze different combinations of the above-mentioned classification criteria.

Meta-analyses of literature findings exist but remain limited. One reason why they remain limited could be the notable heterogeneity across markets. Relevant reviews include Ankamah-Yeboah and Rehdanz (2014), Brown and Watkins (2016), Cespedes-Lopez et al. (2019), Dalton and Fuerst (2018), Fizaine et al. (2018), and Kim et al. (2016). Of note, only the reviews by Cespedes-Lopez et al. (2019), Dalton and Fuerst (2018), and Fizaine et al. (2018) were published. The two other reviews are a conference paper and a working paper. Overall, the authors of the literature reviews agree that significant energy efficiency premiums exist in the sales and rental market. However, Dalton and Fuerst state that the values found for the confidence interval of the EPC include zero and thus they cannot state that there exists a significant premium for energy efficiency (Dalton & Fuerst, 2018). They argue that this might be caused by a strong heterogeneity in different EU markets. Further, caution is raised regarding the generalizability of the findings (Cespedes-Lopez et al., 2019, p. 54). The authors argue that findings in literature should only be considered having the respective analyzed market characteristics in mind. The meta-analyses focused on energy efficiency premiums in the sales market. They found average premiums of a magnitude between 3.5% to 7.6% (Fizaine et al., 2018, p. 1017 ; Ankamah-Yeboah and Rehdanz, 2014, p. 20). Dalton and Fuerst (2018, p. 18) also found evidence for the rental market with an overall premium of 8.2%. The lowest value of the sales price premiums was found by Fizaine et al. (2018). They raise the issue of publication bias and argue that considering this bias reduces the magnitude of the energy efficiency premiums on the valuation of buildings from 8% to 3.5-4.5% (Fizaine et al., 2018, p. 1013). Besides evidence for a publication bias, the usability of insights from older studies regarding the current magnitude of premiums or discounts might be limited. The reasons for that are changes in property valuation methods that now explicitly include sustainability characteristics and public and institutional investor green awareness that might influence their willingness to pay. The empirical studies presented help to understand an overarching trend but should not be considered as evidence of causality across markets or outside of the context of their study characteristics (Cespedes-Lopez et al., 2019, p. 54). This includes the analysis presented in this paper that can be categorized using the characteristics from above as follows:

I. Year of publication: not applicable

II. Region of real estate market: Rhein-Main Region, Germany

III. Type of real estate market: residential

IV. Type of certificate: EPC according to GEG in Germany

V. Type of transaction: rent and sale

VI. Type of property: no constraints but included as control variable

VII. Methodology applied: hedonic price model (multivariate regression analysis)

VIII. Data sample analyzed: various online multiple listing sources; 01/2015-06/2023

Keeping the remarks concerning generalizability of results and the specifications of this paper in mind, the remainder of the empirical literature review focuses on similar analyses of the residential real estate market of the EU to increase the comparability and relevance of the findings. An additional constraint for papers to be included is the use of the EPC as a proxy indicator. As mentioned above, it is the widely used certificate for residential buildings across the EU. The earliest study found matching the search criteria was written by Brounen and Kok (2011). The authors analyzed whether an overall energy efficiency premium can be detected in the Dutch market. Over the years, studies have included more complex relationships in their models such as interacting variables that can have a mediating impact on the studied effects. These variables include e.g., signaling effects, purchasing power and environmental awareness (see e.g., Fuerst, Oikarinen, and Harjunen, 2016; Pommeranz and Steininger, 2021). Further, economic theory on scarcity, willingness to pay and other factors has been employed to explain the findings of and understand the mechanisms behind the hedonic price models (Geske, 2022, p. 5-8).

Brounen and Kok (2011) used sales transaction data from the Netherlands and available EPC certifications. They reported an overall premium of 3.7% for a building with an A, B or C label compared to all other labels (Brounen & Kok, 2011, p. 175). Additionally, when analyzing each level individually and comparing it to the D label, they found stepwise premiums ranging from +10.2% for an A rated building to discounts of up to -5.1% for a G rated building (Brounen & Kok, 2011, p. 175). The findings were the first for the EU market and were robust when including more thermal and quality characteristics in the model (Brounen & Kok, 2011, p. 177).

In subsequent years, other analyses were published. The EU Commission initiated their own policy assessment in selected real estate markets that included Austria, Belgium, France and the UK (Bio Intelligence Service et al., 2013). Significant price premiums were found for more energy efficient buildings across all markets except for the regional market of Oxford, UK (Bio Intelligence Service et al., 2013, p. 12). In this market, the sample size and available explanatory variables were insufficient, limiting the explanatory power of this result (Bio Intelligence Service et al., 2013, p. 12). The problem of omitted variables cannot be excluded for the other models either as the age of the building for example was not included in all of them (Bio Intelligence Service et al., 2013, pp. 61-63). Thus, i.e., strong effects of 8% increases in sales prices per one-letter improvement in energy efficiency in Austria should be considered with caution. The study also found evidence of energy efficiency premiums in the rental market ranging from 4.4% in Austria to 1.4% in Ireland per one-letter improvement (Bio Intelligence Service et al., 2013, pp. 12-13). It is pointed out that a difference in magnitude between rural and city areas exists. This can be caused by the relative size of the energy savings compared to the € /m^2 costs of a building. This finding is supported by Hyland et al. (2013, pp. 948-949) who detected stronger effects for rural buildings compared to buildings in bigger cities in Ireland. Besides overall price premiums of 9.3% for sales prices for buildings with an A label compared to a D label and rental premiums of 1.8% for A rated buildings compared to D rated buildings, they identified that when market conditions are worse, the effect of energy efficiency on prices increases (Hyland et al., 2013, pp. 948-949). One reason could be that a broader supply and limited demand allows for more price differentiation in the market. Published in the same year, Högberg (2013, p. 256) showed for the market in Stockholm, Sweden, that a one percent decrease in energy consumption in kWh leads to an increase in sales prices of 0.04%, while the recommendation for specific energy efficiency improvements for a building stated in the EPC reduce sales prices by 2.4%. This shows that the potential need for retrofitting is seen as a hustle and decreases sales prices in the Stockholm market. Other studies across the EU also found significant energy efficiency premiums ranging from 11.3% for A or B rated buildings when compared to D rated buildings in Wales (Fuerst, McAllister, et al., 2016, p. 26) to 9.8% in Spain (de Ayala et al., 2016, pp. 21-22). At the same time, inefficient and G rated buildings are discounted in the market. Fuerst, McAllister, et al. (2016, p. 26) found discounts of -7.17% in Wales and Jensen et al. (2016, pp. 233-234) identified discounts of up to -24.3% in the Danish market.

However, not all evidence found shows positive price premiums in the EU market. Wahlström (2016, p. 197) analyzed single-family buildings in the Swedish residential sector and could not find evidence of price premiums for lower levels of energy consumption. However, Wahlström (2016, p. 204) did find that buyers are willing to pay for specific building characteristics that reduce energy usage. It seems questionable whether a potential multicollinearity problem could exist between these explanatory variables. The author, however, states that this is not the case (Wahlström, 2016, p. 201). Fregonara et al. (2017, p. 165) found no premiums for the Italian market when looking at transaction data in Turin. The sample, however, does not seem sufficiently large and the lack of findings could be caused by missing comparable transactions (Fregonara et al., 2017, pp. 156–158). For the category of A rated buildings, there exists only one observation and for B rated buildings only four (Fregonara et al., 2017, pp. 156–158). Marmolejo-Duarte and Chen (2022, p. 11) found evidence that when including a set of control variables regarding architectural quality, the effect of energy efficiency disappears. The sample used in their study shows a highly skewed distribution of energy efficiency levels with around half of all observations ranked as E (Marmolejo-Duarte & Chen, 2022, p. 9). Overall, the publications questioning the existence of energy efficiency premiums remain limited so far.

When it comes to the German residential real estate market, the first analysis was published by Cajias and Piazolo (2013). They found evidence for an existing positive price premium regarding total return of investments, rents and sales prices for residential buildings after controlling for regional, geographical and building-specific factors using hedonic models and data from 2008-2010 (Cajias & Piazolo, 2013, p. 57). A one percent increase in energy usage decreases on average the total return by -0.015%, the rent by -0.08% and the market value by -0.45% (Cajias & Piazolo, 2013, p. 53). Further, they recommend an asymmetric treatment for analyses of energy efficiency in general (Cajias & Piazolo, 2013, p. 67). When it comes to the generalizability of this paper, some limitations must be mentioned: The data used were collected right after the housing crisis that reached a climax in 2008 and completely dried up funding, strongly changing the financing conditions (Baum & Hartzell, 2021, pp. 60–62). The sample size used for analysis was small with 2630 building observations (Cajias & Piazolo, 2013, p. 57). The energy efficiency categories used were based on the Swiss Norm SIA 2031 and not the German EPC (Cajias & Piazolo, 2013, p. 58). Additionally, the maximum values for the categories have changed and buildings would be categorized differently today. Thus, the paper provided first evidence, but its values should not be generalized to the German market.

In the following years, more papers focusing on the German residential market were published. Kholodilin et al. (2017, p. 3224) analyzed the Berlin market with data from June 2011 to December 2014 that they collected from German multiple listing websites. They found energy efficiency improvements for the sales and rental market. Each additional kWh / (m^2 * a) needed decreases the sales price by -0.05% and the rent by -0.02% (Kholodilin et al., 2017, p. 3231). They further provided evidence on the landlord-tenant dilemma by showing that the energy savings are capitalized well in sales prices but exceed tenants' willingness to pay by a factor of 2.5 (Kholodilin et al., 2017, p. 3232). This seems reasonable because of the strong tenant rights existing in the German real estate market. Overall, the values found seem plausible and are in line with evidence from other markets across Europe.

The capitalization of energy savings in the rental market was further investigated by Cajias et al. (2019, p. 177) using a sample of almost 760 000 observations across all of Germany. They found evidence of energy efficiency premiums in the rental market of 0.9% for A+ rated buildings and discounts of up to -0.5% for H rated buildings when compared to the reference category D (Cajias et al., 2019, pp. 186–187). These premiums differ strongly when comparing secondary markets to the metropolitan regions. In secondary markets green premiums increase to 2.3% for A+ rated buildings and discounts increase to -1.8% for H rated buildings, respectively (Cajias et al., 2019, pp. 186–187). For the top markets, the results were mixed with no clear indications. This might have been caused by the high demand and inelastic supply in these regions (Cajias et al., 2019, p. 186). The reason for these differences remains unclear.

März et al. (2022, pp. 17–18) also provided evidence that energy efficiency premiums for rental apartments exist, but that they differ based on market conditions. This is even the case on a neighborhood level within a city (März et al., 2022, p. 18). Further, they showed that needed investments in energy efficiency improvements are currently not reasonable from a landlord perspective with payback periods of up to 100 years when only considering increases in rent (März et al., 2022, p. 20). However, they measured the effects using a linearly coded explanatory variable for energy efficiency rather than EPC categories (März et al., 2022, p. 14).

The question of whether energy efficiency premiums are big enough to incentivize investments was further analyzed by Groh et al. (2022, p. 95) for the German residential market. The positive energy efficiency premiums that they identified in the German rental market (+3.98% for A+ rated buildings compared to G and H rated buildings) are by far not sufficient to provide enough benefits for investors to accept the investment costs (Groh et al., 2022, pp. 104–107). Even when government subsidies of up to 45% were considered and a potential CO_2 tax split between the landlord and the tenant was included in calculations, the marginal benefits remained below marginal costs for retrofitting the average building (Groh et al., 2022, pp. 104–107). They argue that owner-occupiers have greater benefits and can more easily achieve economically reasonable energy efficiency improvements (Groh et al., 2022, p. 109). The analysis, however, only focused on increases in rent and not increases in building valuation. Such a consideration could change the assessment of the profitability of investments. Increases in building valuation because of higher energy efficiency have been shown by several analyses for the German market (see for example Cajias and Piazolo (2013), Deller (2022), and Kholodilin et al. (2017)). While Cajias and Piazolo (2013) and Kholodilin et al. (2017) used a continuous variable specification, Deller (2022, p. 815) made a categorical comparison. With a study scope similar to the one in this paper, Deller (2022, p. 817) identified premiums of 6.81% for A+ rated buildings and discounts of up to -8.8% for H rated buildings when compared to the reference category of D. The impact of an increase in property valuation on retrofitting profitability has since then been analyzed by Taruttis and Weber (2022). They used data from 2014 – 2018 on single-family homes across all over Germany (Taruttis & Weber, 2022, p. 1). The provided evidence is primarily valid for owner-occupied buildings, for which it seems to be more profitable when it comes to retrofitting (Groh et al., 2022, p. 109). Taruttis and Weber (2022, p. 6) provided evidence of significant energy efficiency premiums with a 100 kWh /(m^2 * a) decrease in energy consumption leading to a 6.9% increase in valuation. They further detected differences between rural and urban areas (Taruttis & Weber, 2022, p. 8). Rural areas experience a higher relative impact, but the absolute impact is comparatively lower when compared to urban buildings (Taruttis & Weber, 2022, p. 11). This is in line with evidence found for other European markets. Further, their study was one of the first to show that the EPC type of a building can have an impact on its valuation (Taruttis & Weber, 2022, pp. 8–9). While the authors considered the effect using subsamples, they did not consider interaction effects. Finally, they looked at investments in energy efficiency. They showed that energy savings are capitalized in building valuations and that the increases in valuation correspond to the capitalization of energy savings but that the investment costs are still higher (Taruttis & Weber, 2022, pp. 12–13). Several limitations regarding the retrofitting computations exist that should be kept in mind: Each analysis focuses on specific mean energy prices, construction costs and in some cases tax incentives and investor interest rates. All these variables are relatively volatile and could change significantly in the coming years, making new computations necessary. Taruttis and Weber (2022, p. 11) state that their computations strongly depend on the assumptions made.

Some studies have addressed the heterogeneity of energy efficiency premiums using more complex hedonic models with interaction effects. Pommeranz and Steininger (2021, p. 220) used German rental apartment data from Q1 2007 until Q1 2019 and identified overall energy efficiency premiums for rents. They analyzed the interaction effect of purchasing power as well as green awareness of inhabitants with these premiums. They found differences of 8.6% in rents when comparing the worst to the best level of energy efficiency. Of note, the threshold value for the EPCs is incorrect in this paper (Pommeranz & Steininger, 2021, p. 228). Since this error affected the descriptive statistics only, it does not impact the main conclusions of the paper: They found evidence that both factors drive the magnitude of energy efficiency premiums (Pommeranz & Steininger, 2021, p. 234). Purchasing power has a stronger effect and outweighs the effect of the green awareness of inhabitants (Pommeranz & Steininger, 2021, p. 234). Pommeranz and Steininger (2021, p. 239) acknowledge the heterogeneity of energy efficiency premiums and suggest further research on this topic to better understand the specific effects.

Galvin (2023) analyzed the topic of the prebound effect in the German residential sales market. Using data from semi-detached houses built before 1980 and sold between 2019 and 2021, the paper provides evidence that purchasers systematically overpay if they base their decision on theoretical energy savings as shown in the requirement certificate compared to actual energy savings (Galvin, 2023, p. 501). Galvin (2023, p. 511) states that the difference between theoretically needed consumption and actual consumption differs based on the energy efficiency level and presents an equation for an adjusted estimation. The results measuring the impact of the consumption certificate are seen as inconclusive as they depend too much on the behavior of the current owners or tenants (Galvin, 2023, p. 511). This seems unlikely as such a conclusion would render the consumption certificate unusable and warrants further analysis (this paper). Galvin (2023, p. 510) only considered the continuous values of energy consumption and did not analyze discrete levels of energy efficiency as shown in the German EPCs. The categorical analysis, however, is recommended to account for a non-linear functional form (Cespedes-Lopez et al., 2019, p. 53). Additionally, only effects on sales prices were analyzed. As is suggested in the paper, data on the rental market and the impact that can be identified in this market should be the subject of future research (Galvin, 2023, p. 505).

In conclusion, the extant empirical literature has demonstrated energy efficiency premiums exist in the German residential rental and sales market. These premiums experience strong heterogeneity associated with characteristics of the inhabitants, market conditions and the EPC type used. The analysis in this paper adds to these findings in three ways: First, by investigating general energy efficiency premiums using data that might reflect the most recent impacts of rises in energy prices and interest rates. Second and third, by addressing the identified gaps in the literature regarding the EPC type analysis for the rental and the sales market. Interaction effects between the EPC type and EPC rent premiums are investigated. The same is done for the EPC sales price premiums. The results show evidence for an important market within Germany while considering heterogeneity aspects that have not been analyzed in detail so far.

2.3. Hypotheses

In the two subsections above, the core concepts of real estate valuation and the current state of the empirical literature were discussed. It was shown that EU and German policy around energy efficiency was adjusted in the last years and that specific aspects regarding the heterogeneity of energy efficiency premiums need to be researched in more detail. These aspects help to define the different hypotheses for this paper. Following the normative approach of real estate valuation theory and evidence found by related literature, significant energy efficiency premiums should exist for the residential real estate market in the Rhein-Main Region of Germany. This leads to the following hypotheses:

> *Hypothesis 1 a): An increase in the energy efficiency of a residential building leads to an increase in its cold rent.*
>
> *Hypothesis 1 b): An increase in the energy efficiency of a residential building leads to an increase in its warm rent.*
>
> *Hypothesis 1 c): An increase in the energy efficiency of a residential building leads to an increase in its sales price.*

Higher energy efficiency results in energy cost savings. The decrease in energy costs is capitalized via increased cold rents. Additionally, signaling effects, prestige factors or the need to recoup investment costs might lead to an increase in warm rent overall. Including the increases in rent in the valuation of a building increases its sales price. Further, a reduction in property-specific risk that affects the cap rate and capitalization factor can lead to an additional value add and increase the sales price even further.

Looking at the heterogeneity of energy efficiency premiums identified by the empirical literature, a gap regarding the impact of the EPC type used by the seller or landlord was identified. First regional evidence regarding the German sales market exists (Galvin, 2023, p. 510), but so far, the rental market has not been analyzed. Further, more evidence for the sales market within the German real estate market needs to be provided. Evidence regarding the effects of the EPC type on the rental and sales markets will present valuable insights. The hypotheses that are to be tested regarding the EPC type used are the following:

Hypothesis 2 a): Based on the EPC type, an increase in the energy efficiency of a residential building leads to an increase in its cold rent.

Hypothesis 2 b): Based on the EPC type, an increase in the energy efficiency of a residential building leads to an increase in its warm rent.

Hypothesis 2 c): Based on the EPC type, an increase in the energy efficiency of a residential building leads to an increase in its sales price.

On average, the requirement certificate and the consumption certificate do not show the same level of energy consumption for the same building (Verbraucherzentrale NRW e.V., 2023a). The impact of this discrepancy on the sales price of a building is currently unclear. The market should be efficient and include the difference in rents and overall building valuation. Market participants are likely to differentiate between the different EPC types and their economic meaning. Analyzing the market will help with understanding the structure of energy efficiency premiums in Germany and the impact of the two different certificates.

3. Methodology & data

In the section above, a normative reasoning for the existence of energy efficiency premiums in the Rhein-Main Region was developed and a gap in the literature was identified. The subsequently formulated hypotheses are tested in the remainder of this paper using a hedonic price model. The first theoretical foundations in the field of hedonic price models were developed by Lancaster (1966) and Rosen (1974). Since then, this methodology has been used in several studies analyzing energy efficiency premiums in real estate markets (see for example, Brounen and Kok, 2011; Deller, 2022; Hyland et al., 2013; Wahlström, 2016). Data used for the analysis in this paper are provided by the Real Estate Pilot AG (www.realestatepilot.com). They were collected from various digital sources. The dates of the observations range from 01/2015 – 06/2023. Next, the used methodology is introduced in more detail and the data generating process, descriptive statistics and model specifications are presented.

3.1. The hedonic price model

Compared to mass-produced products that are nearly identical with regards to function and form, real estate is very heterogeneous. Homogeneous products are traded in an explicit marketplace and their prices can be observed. The price must be paid to access specific characteristics. This observation of prices is not possible when it comes to the characteristics of heterogeneous real estate. They are traded on implicit markets, where the prices of the building-specific characteristics cannot be observed directly. To estimate the implicit prices of individual characteristics, a hedonic price model can be used. In its most basic form, it represents a multiple linear regression of sales prices or rents on real estate characteristics. The regression results, i.e., the coefficients of the independent variables, represent the estimated prices for the individual characteristics. Depending on the functional form, these can be absolute values or price elasticity values. This is the so called "first stage" hedonic model. Its results can be used to define "second stage" hedonic models that identify structural demand and supply parameters when certain assumptions are met. Mathematical theory includes the assumption of perfect elasticity for all characteristics. This is rarely the case in real-life settings and goes beyond the scope of the analysis in this paper. (Malpezzi, 2002, p. 68 - 71)

In today's real estate literature, hedonic price models have become a core research methodology. One could argue that the application today is in line with the first known applications of this methodology to estimate farmland values in Minnesota and Iowa (Haas, 1922; Wallace, 1926). Whether these applications, that took place before the theoretical developments of Lancaster (1966) and Rosen (1974), can be seen as hedonic models has since been discussed in the literature (Colwell & Dilmore, 1999, p. 620). Other early applications can be found in the automobile industry (Court, 1939; Griliches, 1961).

It is undisputed that Lancaster's work on consumer theory and Rosen's publication on hedonic prices and implicit markets paved the way for the theoretical development of this methodology. Lancaster (1966, p. 133) demonstrates how consumers maximize their utility based on product characteristics. He writes that "goods possess, or give rise to, multiple characteristics in fixed proportions and that it is these characteristics, not goods themselves, on which the consumer's preferences are exercised." (Lancaster, 1966, p. 154)

When combining the utility of the characteristics with their implicit prices, a market between buyers and sellers is established. The buyers receive utility from the characteristics of the product that they acquire. They are constrained by their budget. The sellers receive returns from specialized production of goods. The produced goods possess characteristics that are desired by the market. The clearing price for each product characteristic is determined by the distributions of consumer tastes and producer costs. These implicit clearing prices for product characteristics are identified with hedonic price models. (Rosen, 1974, p. 35 -36)

The theoretical foundation as well as empirical application of hedonic price models has since been extended through a variety of publications. An excellent general review of the literature on hedonic price models is given by Malpezzi (2002) and a thorough discussion on theoretical and econometric constraints can be found in Follain and Jimenez (1985) and Sheppard (1999). Further reading includes Bajari and Benkard (2005), Bartik (1987), Blomquist et al. (1988), Edlefsen (1981), Epple (1987), and Roback

(1982). Amemiya (1980), Hocking (1976), and Leamer (1978) comment on the selection process of independent variables.

As stated above, the statistical core of the hedonic price model is a multiple linear regression. In this paper, an ordinary least squares (OLS) estimator is used for estimating the coefficients of the independent variables. The functional form as well as the selection of model parameters are further elaborated on in the remainder of this section. When applying the hedonic price model, certain assumptions must be fulfilled (see Appendix 2). Model assumption tests were performed for all presented models and the results are discussed at the end of section 3.4.

3.2. Review of the data generating process

For quantitively testing the above presented hypotheses by applying a hedonic price model, micro-level data on a building level are required. Ease of data collection depends on the jurisdiction of the analyzed market. In some EU countries, public registries with detailed sales transaction data exist. Other countries offer sales transaction data but cannot provide detailed data on the characteristics of the real estate sold. In the remaining EU countries, there is no publicly available information on market transactions. When it comes to rent data, the challenge of collecting real transaction data is even greater. Within the German market, there is no governmental agency that offers transaction data on a micro-level. The house price index that is published by the Statistische Bundesamt is computed using micro-level sales data provided by the regional committees on real estate (Statistisches Bundesamt, 2018, p. 5-6). However, the raw data are not published. When it comes to rental data in Germany, official rent indices are computed using data from the "Mikrozensus," a yearly survey on working and living conditions in Germany (Statistisches Bundesamt, 2023b). The survey is answered by around 1% of the population in Germany and used for different analyses (Statistisches Bundesamt, 2023b). Because of the difficulty of accessing transaction data in Germany, most empirical literature use listing data collected from digital sources such as multiple listing service providers (see Deller, 2022; Kholodilin et al., 2017; März et al., 2022; Taruttis and Weber, 2022). This use of listing data comes with limitations as discussed by Kholodilin et al. (2017, pp. 3224–3225):

- Duplications of listings across the different digital and analogue listing platforms exist.
- Listings are used for marketing purposes by developers or construction companies.
- Owners / landlords might leave out information on energy efficiency on purpose.
- The final transaction price or rent paid differs from the values stated.

To limit the impact of these issues the raw datasets were prepared prior to analysis (see below).

The data analyzed in this paper are made up of two samples of listing data provided by the Real Estate Pilot AG. The observations for both samples were collected from multiple listing service providers from January 2015 until June 2023. More specifically, for listings to be included in the analysis, the first date of the listing had to be between the 1^{st} of January 2015 and the 30^{th} of June 2023. Data were updated once every day during that period. Of note, the Real Estate Pilot AG filters for and deletes duplicates, addressing one of the issues mentioned by Kholodilin et al. (2017, pp. 3224–3225). Further details regarding the data collection process are published in Deller (2022, p. 811). The cities and counties making up the market of the Rhein-Main Region are defined following theRegionalverband FrankfurtRheinMain (2022). The first sample comprises 917 213 micro-level observations of the rent market in the Rhein-Main Region. The second sample comprises 556 791 micro-level observations of the sales market in the Rhein-Main Region. The data includes information on various hedonic characteristics such as living space, energy consumption in kWh, year of construction, postal code and others.

All the data preparation, cleaning and analysis described in this paper were done using R (www.r-project.org). The R code used is available upon reasonable request. The data preparation was performed before starting with the analysis of the two data samples. This helps address several of the issues mentioned by Kholodilin et al. (2017, pp. 3224–3225). First, the attributes were selected and encoded. The attribute inclusion process was based on a hierarchical method of attribute selection that includes the most relevant explanatory attributes first. Further, the suggestions made by Malpezzi (2002, pp. 78–79) regarding hedonic characteristics were followed as best as possible with the available data sample attributes. To avoid large drops in sample size because of missing values, 19 hedonic characteristics were included in the final selection across both data samples. Appendix 3 shows an overview and a description of the included attributes. The encoding of attributes mainly concerned the binary control attributes that state for example whether a building is refurbished, comes with an elevator or is a landmarked building. Next, the observations with missing data were removed. Observations with complete information are necessary for the hedonic price model. In line with literature, trimming of values and not imputation was performed to manage outliers (see e.g., Taruttis and Weber, 2022, p. 4). This approach also seemed reasonable with regard to the issue of listings being a marketing tool for developers and construction companies. It is likely that they either did not fill out all the information of the 19 attributes or put placeholders in with values that are not plausible and could reliably be identified as erroneous. For example, a value of "9999" entered for energy efficiency is meaningless and must be removed. Trimming the samples helped to filter out such outliers or observations where specific values are placeholders. For the trimming of the data samples, metric independent and dependent attributes were used. Additionally, relative values such as living space per room or the ratio between operating costs to cold rent were computed. When it comes to the sales price sample, the sales price per m^2, the living space in m^2, the living space per room in m^2 and the energy consumption in kWh / (m^2 * a) were considered. The bottom and top half percentile of these absolute and relative metric attributes were computed and any observations exceeding those values were deleted. This is a more conservative approach than others have applied (see e.g., Taruttis and Weber, 2022, p. 4). The same was done with the rent sample. The metric attributes used were the cold rent per m^2, the operating costs in € , the ratio between operating costs to cold rent, the living space in m^2, the living space per room in m^2 and the energy consumption kWh / (m^2 * a). A final plausibility check was performed regarding the construction year of observations following Deller (2022, Appendix 15). To filter out advertisements, all observations with a construction year greater than 2023 were deleted. Observations with a construction year smaller than 1871 were deleted, too, to account for the beginning of the "Gründerzeit" in Germany. The start of the "Gründerzeit" in Germany lead to changes in construction technology. Further, deleting these observations helped to avoid the risk of unobserved refurbishment of the historical building stock as mentioned by Cajias et al. (2019, p. 184).

The two issues of consciously not including specific information and differences between actual transaction and listing values remain to be discussed. Not including specific information in an online listing is a very general limitation of empirical research using online platform data. For buildings, it can be argued that the information not included in the listing itself would have nonetheless been included in the valuation of the building. Thus, while making the usable sample smaller, it should, on average, not bias the results. When it comes to the issue of potential differences between listing and transaction values, two arguments can be made: First, past research has shown that listing prices can be a reasonable representation of transaction prices in a metropolitan region of Germany (Henger & Voigtländer, 2014, p. 15). This is true for time periods of a strong and upward moving real estate market. This was the case for most of the period considered in this paper. Only the past 18 months show the first effects of the rising interest rates and macroeconomic developments such as the energy crisis (Statistisches Bundesamt, 2023a). Second, it can be argued that an above-market listing price increases the time a building remains on the market (Knight, 2002, p. 213). This serves as an incentive for owners and real estate agents to price buildings in line with current market conditions.

The results of the described data generating process and the subsequent data preparation and cleaning were the final data samples used for the remainder of this paper. The rent data sample includes 212 167 observations. The sales data sample includes 159 573 observations. Next, the descriptive sample statistics of both are displayed. This is followed by the specification of the hedonic price models used to test the hypotheses of this paper.

3.3. Descriptive sample statistics

Table 1 gives an overview of the descriptive sample statistics for the rent price sample and Table 2 for the sales price sample. The variables include the dependent variables (i.e., cold rent, warm rent, sales price), the key explanatory variable (i.e., energy efficiency) and additional control variables (e.g., living space, construction year, EPC type). Additional control variables not shown in the tables of the descriptive sample statistics are the nominal variables "type of building," "postal code" and "upload date." The type of building is shortly discussed below, while the definition of postal code and upload date can be found in Appendix 3. All sample statistics of the metric variables are presented without the usage of log values. In the next subsection, log transformation is applied to account for heteroscedasticity of residuals.

The rent price sample is made up of 212 167 observations. The average building for rent in the Rhein-Main Region between the dates 01/2015 – 06/2023 was built in 1979, offers 2.74 rooms stretching across 78.76 m^2 and is equipped with a parking space. Its energy consumption is 119.90 kwh / (m^2 * a), while its cold rent is 855.00 € . Its warm rent amounts to 1 039. 40 € . The energy consumption is equal to the energy efficiency level D. The cold rent is equivalent to 10.86 € / m^2 and the warm rent is equivalent to 13.20 € / m^2. When it comes to the overall sample, 41% are issued a requirement certificate and 59% are issued a consumption certificate, 3% of all buildings are furnished, 28% are refurbished, 13% have not been lived in before, less than 0.5% are landmarked buildings and 26% are equipped with an elevator. The sample statistics show that the dependent variables of cold rent and warm rent and the control variable living space are slightly positively skewed. Their mean is greater than their median. The key explanatory variable energy efficiency is not skewed to a relevant degree.

The distribution of EPC levels of all the observations in the sample is shown in Figure 5. The EPC level with the greatest number of observations is D, which is in line with the mean of the energy consumption of the sample. The number of observations with energy efficiency level B, however, is surprisingly high. One explanation could be the subsidies in the past that were provided by the German federal government for building energy efficient homes or refurbishing existing buildings. Higher construction costs were potentially compensated for and thus the buildings were built with higher levels of energy efficiency. This explanation remains speculative. The distribution should be kept in mind when interpreting the empirical results of the hedonic price models later. One other interesting aspect is the distribution of the EPC type used. The consumption certificate is used more often than the requirement certificate. This is, however, not surprising as it is cheaper to obtain a consumption certificate.

The sales price sample is made up of 159 573 observations. The average building for sale in the Rhein-Main Region between the dates 01/2015 – 06/2023 was built in 1980, offers 4.73 rooms across 134.84 m^2. It is equipped with a parking space and has an energy consumption of 133.07 kWh / (m^2 * a). This is equivalent to an EPC rating of E. The

Table 1: Summary statistics of the rent data sample

Variable	Unit	Mean	P 25	Median	P 75	St. Dev.	Minimum	Maximum
Dependent variables								
Cold rent	Price in Euros (€)	855.00	550.00	740.00	1035.00	451.50	130.00	5700.00
Warm rent	Price in Euros (€)	1039.40	695.90	910.00	1250.00	506.34	198.80	6200.00
Building-specific independent variables								
Energy consumption	kwh / (m * annum)	119.90	76.60	118.00	154.00	56.86	4.40	334.80
Living space	m^2	78.76	56.00	73.07	95.00	33.15	19.53	230.82
Number of rooms	Numeric	2.74	2.00	3.00	3.00	1.09	1.00	12.00
Construction year	Numeric	1979	1963	1982	2003	30.89	1871	2023
EPC type	Binary; reference = requirement	0.59	0.00	1.00	1.00	0.49	0.00	1.00
Furnished	Binary; reference = 0; true = 1	0.03	0.00	0.00	0.00	0.17	0.00	1.00
Refurbished	Binary; reference = 0; true = 1	0.28	0.00	0.00	1.00	0.45	0.00	1.00
First occupancy	Binary; reference = 0; true = 1	0.13	0.00	0.00	0.00	0.33	0.00	1.00
Landmarked building	Binary; reference = 0; true = 1	0.00	0.00	0.00	0.00	0.02	0.00	1.00
Elevator	Binary; reference = 0; true = 1	0.26	0.00	0.00	1.00	0.44	0.00	1.00
Parking space	Binary; reference = 0; true = 1	0.50	0.00	1.00	1.00	0.50	0.00	1.00

Number of observations in the rent data sample: 212167

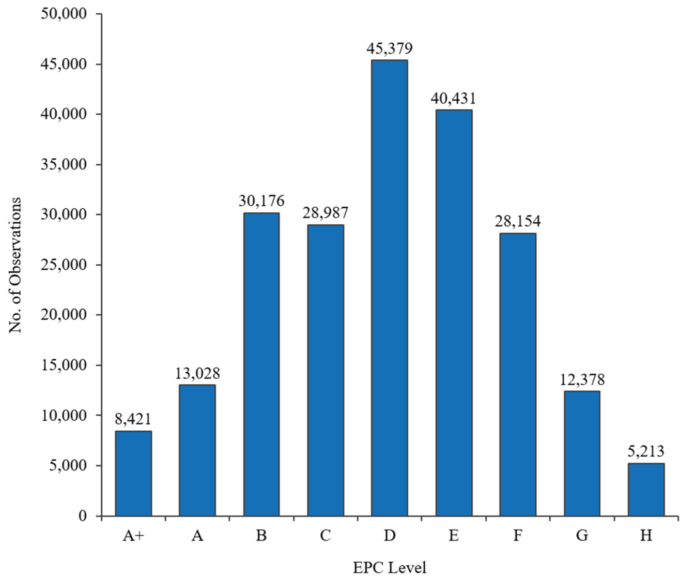

Figure 5: Distribution of EPC levels in the rent sample

sales price of the average building is 419 012.00 € , leading to a price of 3 107.48 € / m^2. Across the overall sample, 46% are issued a requirement certificate and 54% are issued a consumption certificate, 13% of all buildings are refurbished, 11% have not been lived in before, around 1% are landmarked buildings and 18% are equipped with an elevator. Additionally, 12% of all buildings have an active lease and 22% are sold without a commission fee for the buyer. When comparing the mean and median of the variables, the values of the sales price, the energy consumption, the living space and number of rooms point to a positively skewed distribution.

The EPC rating distribution of the key explanatory variable energy consumption is shown in Figure 6. The EPC rating D includes the greatest number of observations, followed by E. This is in line with the mean and median of the variable energy consumption. The mean is at the lower end of the EPC rating E and the median is at the upper end of the EPC rating D. Thus, using different cut off points could have resulted in a histogram that better reflects a normal distribution. The number of observations that have an EPC rating of A+ or H are greater than expected. This might be indicating that owners want to decrease risk of their real estate portfolios by selling very energy inefficient assets and developers that can increase profitability when increasing the energy efficiency of refurbishment or building projects. This again, however, remains speculative and is a topic beyond the scope of the analysis in this paper.

When comparing the rent data sample with the sales data sample, several differences can be noted and should be discussed: A building that is sold is on average bigger in floor size and has more rooms than a building available for rent. It is also less energy efficient and more likely than a building for rent to have a requirement certificate. The higher energy consumption is in line with the significantly lower percentage of buildings that are refurbished in the sales sample compared to the rent sample (13% vs. 28%). A building that is up for sale is also much less likely to have an elevator, but more likely to have a parking space. It is likely that an underlying data sample characteristic is the cause of these differences in distribution. Looking at the data, the most likely one is the building type. Apartments are more likely to be located in the bigger cities and city centers. At these locations, less space is available, making individual properties smaller. At the same time, apartments are part of large multi-family homes that are bigger than the ones in rural areas. This might lead to more buildings that need an elevator and can get a consumption certificate issued. The considerations are supported by the data: the most common building type in the rent data sample is an "apartment" while the most common building type in the sales data sample is a "detached single or dual family home." A more detailed analysis focusing on the impact of energy efficiency based on specific building types would likely result in interesting new insights. This provides an opportunity for research in the future.

Before the specification of the hedonic price models, correlation between the different attributes needs to be assessed within both samples. High correlation between two explanatory variables in a linear model can lead to a decrease in significance for both and should be avoided. Appendix 4 shows the correlation matrix for the rent data sample. The correlation matrix for the sales data sample can be found in Appendix 5. When looking at the correlation of the rent data sample, the attributes "living space" and "number of rooms" show a high value of correlation (0.87). These two attributes show a similarly high value of correlation in the sales data sample (0.91). The question arises whether both attributes should be used as explanatory variables for the hedonic price models. This would be the case if they measured different effects. It can be argued that up to a certain size of a building

Table 2: Summary statistics of the sales data sample

Variable	Unit	Mean	P 25	Median	P 75	St. Dev.	Minimum	Maximum
Dependent variable								
Sales price	Price in Euros (€)	419012.00	219500.00	349000.00	533270.00	300919.80	21000.00	5350000.00
Building-specific independent variables								
Energy consumption	kwh / (m ^{2} annum)	133.07	79.80	123.00	170.00	77.26	0.01	465.39
Living area	m^2	134.84	80.90	119.00	165.00	75.95	26.52	569.00
Number of rooms	Numeric	4.73	3.00	4.00	6.00	2.65	1.00	30.00
Construction year	Numeric	1980	1966	1981	2000	29.22	1871	2023
EPC type	Binary; reference = requirement	0.54	0.00	1.00	1.00	0.50	0.00	1.00
Refurbished	Binary; reference = 0; true = 1	0.13	0.00	0.00	0.00	0.34	0.00	1.00
First occupancy	Binary; reference = 0; true = 1	0.11	0.00	0.00	0.00	0.30	0.00	1.00
Landmarked building	Binary; reference = 0; true = 1	0.01	0.00	0.00	0.00	0.07	0.00	1.00
Elevator	Binary; reference = 0; true = 1	0.18	0.00	0.00	0.00	0.39	0.00	1.00
Parking space	Binary; reference = 0; true = 1	0.66	0.00	1.00	1.00	0.47	0.00	1.00
Active lease	Binary; reference = 0; true = 1	0.12	0.00	0.00	0.00	0.32	0.00	1.00
Contract-specific independent variable								
Commission free	Binary; reference = 0; true = 1	0.22	0.00	0.00	0.00	0.41	0.00	1.00

Number of observations in the sales data sample: 159573

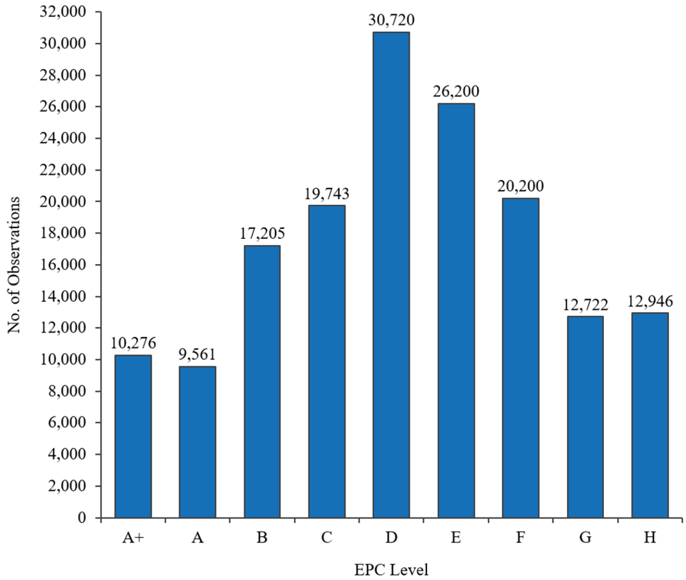

Figure 6: Distribution of EPC levels in the sales sample

an additional room is valued more than having bigger rooms overall. To measure this effect, it is necessary to use both variables for the hedonic price models. This argument alone seems rather weak. However, the interpretation of both attributes is not the purpose of this paper and, thus, it might be beneficial to account for more heterogeneity in the data. Including the attribute as an explanatory variable is also in line with the empirical literature and recommended (Malpezzi, 2002, p. 78). The key explanatory variable energy efficiency is not affected by this potential problem of correlation. The potential problem of multicollinearity is again checked when specifying the hedonic price models. Besides the correlation between these two variables, there is also moderate correlation found between the key explanatory variable of energy efficiency and construction year. This seems plausible as the building standards have increasingly required developers to improve the energy efficiency of newly built buildings. The correlation coefficient for the rent data is -0.53 and therefore smaller than the correlation of -0.63 that can be found in the sales data sample. This is in line with the higher rate of refurbished buildings that was identified above. The potential problem arising from the moderate correlation is checked during the specification of the hedonic price models.

3.4. Specification of the hedonic price models and testing of model assumptions

The two final samples from above are used to estimate the models that measure the impact of energy efficiency on the cold and warm rent and on the sales prices of residential real estate. Different models are specified for each of the dependent variables *"cold_rent,"* *"warm_rent,"* and *"sales_price."* The cold rent models are used to test hypotheses 1 a) and 2 a). The warm rent models are used to test hypotheses 1 b) and 2 b). The sales price models are used to test hypotheses 1 c) and 2 c). The first model specified for all dependent variables is a basic hedonic price model that includes the key explanatory variable energy efficiency and the most relevant control variables. Next, a full categorical model that includes all control variables is specified. The term "categorical" refers to the way the key explanatory variable energy consumption is coded. In this model and the basic model, it is specified using the EPC rating of the observation. Robustness of those models is tested by exchanging the EPC rating with the continuous value of the energy consumption of the buildings. This model is the full continuous model. The fourth and final model includes all variables from the full categorical model, the EPC type used and an interaction term between the EPC type and the EPC rating. This is the full interaction model. All independent variables are either building, location, time or contract specific characteristics. As stated, a hierarchical method of variable selection is applied. The definitions and the indexes remain the same across all models. An overview of all definitions can be found in Appendix 6. The results of all models are presented in the next section. In total, twelve models are specified. All of the full categorical models are based on Deller (2022, pp. 815–816). The cold rent models are defined first. This is followed by the warm rent models. The section concludes by presenting the sales price models. The basic cold rent model is specified in the following way:

$$\begin{aligned}\ln(cold\_rent_{ilt}) = \alpha + \beta_1 epc\_level_i + \beta_2 living\_space_i \\ + \beta_3 \ln(living\_space_i) + \beta_4 construction\_year_i \\ + \gamma_l + \varepsilon_{ilt}\end{aligned} \quad (6)$$

A log-linear functional form is chosen to account for heteroscedasticity (Malpezzi, 2002, p. 80). This is done by transforming the dependent variable *"cold_rent"* using the natural logarithm. The indexes *"i," "l"* and *"t"* stand for the observation *"i,"* the location *"l"* and the time *"t."* The basic cold rent model includes the intercept "α", the independent variables and the error term "ε." The first independent variable is the *"epc_level."* It is coded as a categorical variable ranging from A+ to H. These categories are based on the definition of the EPC ratings in Appendix 10 of the GEG. Including the energy efficiency of a building as a categorical variable and not a continuous variable is done to account for potential non-linearity. It is also recommended in the literature (Cespedes-Lopez et al., 2019, p. 53). Additionally, the categories ranging from A+ to H are well known and often used to communicate the energy efficiency of a building. The impact of the letter grade rating might be more significant for the valuation of the energy efficiency of a building than the value of energy consumption measured as kWh / (m^2 * a). Nevertheless, the impact of the continuous variable is investigated in the third cold rent model as a robustness check. The reference value of *"epc_level"* is defined as the EPC rating D. This includes the general EPC rating and does not consider whether the EPC type used is a consumption certificate or a requirement certificate. Choosing the EPC level D as the reference value serves two goals: It helps to make a comparison with the average building in the data sample more intuitive and is in line with the recommendations made in literature (Cespedes-Lopez et al., 2019, p. 53). Next, the *"living_space"* of the building is included. This metric variable measures living space in m^2. The living space is included as a continuous variable that is not transformed and in a second variable that is transformed using the natural logarithm. Including both terms was done to account for non-linearity in the data and increase compliance with this assumption of the hedonic price model. This decision, however, increases multicollinearity between the two independent variables. As living space is not the key explanatory variable that is to be interpreted in this analysis, this is accepted. When interpreting the results, this must be kept in mind and thus the coefficients of the two variables that include the living space can only be interpreted with caution. The *"construction_year"* variable is added as a categorical variable that controls for the year a building was constructed using 10-year intervals. This follows literature such as Cajias et al. (2019, p. 184). The age of a building has a significant impact on its value and cold rent. It is the key reference point when accounting for the depreciation of a real estate asset. The final control variable included in the basic model is the categorical variable "γ" that controls for the location of the building on a postal code level. Location, too, is a key characteristic of a building and has a significant impact on its rent and sales price. Limitations exist regarding the location control using postal codes as they can stretch across micro-locations. However, using postal codes is the most appropriate measure as usage of streets as control variables would lead to a significant decrease in sample size.

In the remainder of this sub-section, only the additional or changed explanatory variables are elaborated on when presenting the specifications of the hedonic price models. All other variable definitions and indexes remain the same. The full categorical cold rent model that includes all control variables is specified in the following way:

$$\begin{aligned}\ln(cold\_rent_{ilt}) &= \alpha + \beta_1 epc\_level_i \\ &+ \beta_2 living\_space_i + \beta_3 \ln(living\_space_i) \\ &+ \beta_4 no\_rooms_i + \beta_5 furnished_i \\ &+ \beta_6 refurbished_i + \beta_7 first\_occupancy_i \\ &+ \beta_8 landmarked\_building_i + \beta_9 elevator_i \\ &+ \beta_{10} parking\_space_i + \beta_{11} building\_type_i \\ &+ \beta_{12} construction\_year_i + \gamma_l + \delta_t + \varepsilon_{ilt}\end{aligned} \tag{7}$$

Additional control variables that are added are *"no_rooms," "furnished," "refurbished," "first_occupancy," "landmarked_building," "elevator," "parking_space," "building_type"* and *"δ"*. The *"no_rooms"* variable is a categorical variable that indicates the number of rooms of the property. It ranges from one to twelve rooms (see also section 3.3) and its reference value is set to one. It is included as a categorical variable and not a continuous variable to allow for a more flexible functional form following Malpezzi (2002, p. 81). The variable *"building_type"* is controlling for the building type. It is coded as a categorical variable and controls for differences in valuation between e.g., an apartment and a detached single-family building. The *"δ"* variable stands for the quarter and the year an observation was first seen online. It controls for differences in valuation that are caused by the real estate market cycle. The models were also tested with monthly control variables, leading to no relevant changes of the coefficients regarding magnitude or significance. The remaining variables are binary control variables that either indicate that a building has a certain characteristic or does not have a certain characteristic. The property is either furnished, has been refurbished in the past, has not been occupied before, falls under the "Denkmalschutz" in Germany, is equipped with an elevator, comes with a parking space or the respective opposite. As a robustness check, a full continuous cold rent model using the explanatory variable *"energy_consumption"* is also specified:

$$\begin{aligned}\ln(cold\_rent_{ilt}) &= \alpha + \beta_1 energy\_consumption_i \\ &+ \beta_2 living\_space_i + \beta_3 \ln(living\_space_i) \\ &+ \beta_4 no\_rooms_i + \beta_5 furnished_i \\ &+ \beta_6 refurbished_i + \beta_7 first\_occupancy_i \\ &+ \beta_8 landmarked\_building_i + \beta_9 elevator_i \\ &+ \beta_{10} parking\_space_i + \beta_{11} building\_type_i \\ &+ \beta_{12} construction\_year_i + \gamma_l + \delta_t + \varepsilon_{ilt}\end{aligned} \tag{8}$$

The only difference between this model and the previous model is the key explanatory variable of *"energy_consumption"* that is now included. The variable *"epc_level"* is not included in this model. The variable *"energy_consumption"* is a metric variable indicating the energy consumption of a building in kWh / (m^2 * a). The final model for estimating the impact of energy efficiency on the cold rent of a building includes the EPC type used to communicate the energy efficiency of the building and an interaction term between the EPC type used and the EPC rating. The full interaction cold rent model is defined in the following way:

$$\begin{aligned}\ln(cold\_rent_{ilt}) = \alpha + \beta_1 epc\_level_i \\ + \beta_2 epc\_type_i + \beta_3 epc\_type_i * epc\_level_i \\ + \beta_4 living\_space_i + \beta_5 \ln(living\_space_i) \\ + \beta_6 no\_rooms_i + \beta_7 furnished_i \\ + \beta_8 refurbished_i + \beta_9 first\_occupancy_i \\ + \beta_{10} landmarked\_building_i + \beta_{11} elevator_i \\ + \beta_{12} parking\_space_i + \beta_{13} building\_type_i \\ + \beta_{14} construction\_year_i + \gamma_l + \delta_t + \varepsilon_{ilt}\end{aligned} \tag{9}$$

The *"epc_type"* variable is a binary control variable that indicates whether the building is issued a requirement certificate or a consumption certificate. The coefficient of this binary variable measures the magnitude of the difference between the two EPC types when a building has the *"epc_level"* that is equal to D. The reference value is set to requirement certificate. The term *"epc_type * epc_level"* is the interaction term between the EPC type issued and the EPC rating. If the building is issued a requirement certificate, the variable *"epc_type"* is equal to zero because this is the reference value of the binary control variable. In this case, the whole term *"epc_type * epc_level"* is equal to zero. If the building is issued a consumption certificate, the control variable *"epc_type"* is equal to one. Then, the coefficient of the interaction term is added to the coefficient of the *"epc_type"* variable. Together, the terms measure the premiums or discounts for a respective EPC level when a consumption certificate is used compared to the reference value of a building with an EPC level of D and a requirement certificate.

Next, the warm rent models are specified. They help to test the hypotheses 1 b) and 2 b). While the specification of the warm rent models remains similar to the cold rent models, their interpretation is more complex. The reason for this is the added layer of costs that can vary significantly between around 6% and 60% of the cold rent in the data sample. The basic warm rent model is defined in the following way:

$$\begin{aligned}\ln(warm\_rent_{ilt}) = \alpha + \beta_1 epc\_level_i \\ + \beta_2 living\_space_i + \beta_3 \ln(living\_space_i) \\ + \beta_4 construction\_year_i + \gamma_l + \varepsilon_{ilt}\end{aligned} \tag{10}$$

Compared to the basic cold rent model, only the dependent variable is changed. The dependent variable is now equal to the warm rent of the building. Again, this variable is transformed using the natural logarithm to account for potential heteroscedasticity. All other explanatory variables remain the same as in the basic cold rent model. This is also the case for the full categorical warm rent model, the full continuous warm rent model and the full interaction warm rent model. Thus, these three models are specified in the following way:

$$\begin{aligned}\ln(warm\_rent_{ilt}) = \alpha + \beta_1 epc\_level_i \\ + \beta_2 living\_space_i + \beta_3 \ln(living\_space_i) \\ + \beta_4 no\_rooms_i + \beta_5 furnished_i \\ + \beta_6 refurbished_i + \beta_7 first\_occupancy_i \\ + \beta_8 landmarked\_building_i + \beta_9 elevator_i \\ + \beta_{10} parking\_space_i + \beta_{11} building\_type_i \\ + \beta_{12} construction\_year_i + \gamma_l + \delta_t + \varepsilon_{ilt}\end{aligned} \tag{11}$$

$$\begin{aligned}\ln(warm\_rent_{ilt}) = \alpha + \beta_1 energy\_consumption_i \\ + \beta_2 living\_space_i + \beta_3 \ln(living\_space_i) \\ + \beta_4 no\_rooms_i + \beta_5 furnished_i \\ + \beta_6 refurbished_i + \beta_7 first\_occupancy_i \\ + \beta_8 landmarked\_building_i + \beta_9 elevator_i \\ + \beta_{10} parking\_space_i + \beta_{11} building\_type_i \\ + \beta_{12} construction\_year_i + \gamma_l + \delta_t + \varepsilon_{ilt}\end{aligned} \tag{12}$$

$$\begin{aligned}\ln(warm\_rent_{ilt}) = \alpha + \beta_1 epc\_level_i \\ + \beta_2 epc\_type_i + \beta_3 epc\_type_i * epc\_level_i \\ + \beta_4 living\_space_i + \beta_5 \ln(living\_space_i) \\ + \beta_6 no\_rooms_i + \beta_7 furnished_i \\ + \beta_8 refurbished_i + \beta_9 first\_occupancy_i \\ + \beta_{10} landmarked\_building_i + \beta_{11} elevator_i \\ + \beta_{12} parking\_space_i + \beta_{13} building\_type_i \\ + \beta_{14} construction\_year_i + \gamma_l + \delta_t + \varepsilon_{ilt}\end{aligned} \tag{13}$$

The six different models specified above all concern the rental market and use the same data sample to estimate the coefficients. For analyzing the effect of energy efficiency on the sales prices of a building, a different data sample is used. While the underlying data is different, the models themselves are only partially adjusted. The variable *"furnished"* is dropped as an explanatory variable. On the other hand, additional relevant explanatory variables are added to control for heterogeneity in the data. These include the *"active_lease"* and *"commission_free"* variables. Starting again with the basic model, it is specified in the following way:

$$\begin{aligned}\ln(sales\_price_{ilt}) = \alpha + \beta_1 epc\_level_i + \\ + \beta_2 \ln(living\_space_i) + \beta_3 construction\_year_i \\ + \gamma_l + \varepsilon_{ilt}\end{aligned} \tag{14}$$

The dependent variable *"sales_price"* is equal to the listing sales price of the observation. The dependent variable is transformed using the natural logarithm to account for potential heteroscedasticity. Compared to the basic cold rent model, the linear non-transformed term of the *"living_space"* variable is not included in the model. The residual plot of the model was considered, and no relevant non-linearity was found that would require an additional term. The key explanatory variable *"epc_level"* and the other control variables remain the same as in the basic cold rent model and basic warm rent model. The full categorical sales price model is specified in the following way:

$$\begin{aligned}\ln(sales\_price_{ilt}) &= \alpha + \beta_1 epc\_level_i \\ &+ \beta_2 \ln(living\_space_i) + \beta_3 no\_rooms_i \\ &+ \beta_4 active\_lease_i + \beta_5 refurbished_i \\ &+ \beta_6 first\_occupancy_i + \beta_7 landmarked\_building_i \\ &+ \beta_8 elevator_i + \beta_9 parking\_space_i \\ &+ \beta_{10} building\_type_i + \beta_{11} construction\_year_i \\ &+ \beta_{12} commission\_free_i + \gamma_l + \delta_t + \epsilon_{ilt}\end{aligned} \quad (15)$$

The added variables are *"no_rooms," "active_lease," "refurbished," "first_occupancy," "landmarked_building," "elevator," "parking_space," "building_type," "commission_free"* and *"δ."* The variable *"furnished"* is not added to the model as it is generally not relevant for properties that are for sale. Like the cold rent model, the *"no_rooms"* variable is a categorical variable indicating the number of rooms of the building. For the sales price data sample, it ranges from 1 to 30 rooms. All the other explanatory variables that were included in the rent models have the same meaning. This includes the *"δ"* variable controlling for the upload date of the building. Two variables, however, were not included before: *"active_lease"* and *"commission_free."* The *"active_lease"* variable indicates whether the building for sale has an active lease. This limits the buyer's possibilities of leasing the property or occupying the building. One implication can be the limitation of the agreed upon rent between the previous owner and the tenant. If it is below current rents in the market, the income generated by the property is smaller than the potential one of a comparable property without an active lease. The variable *"commission_free"* indicates whether the buyer must pay a commission to a real estate agent managing the sale or not. If no commission must be paid, this reduces the additional transaction costs that a buyer needs to pay for when becoming the new owner of a property. The third model, the full continuous sales price model, is specified in the following way:

$$\begin{aligned}\ln(sales\_price_{ilt}) &= \alpha + \beta_1 energy\_consumption_i \\ &+ \beta_2 ln(living_space_i) + \beta_3 no\_rooms_i \\ &+ \beta_4 active\_lease_i + \beta_5 refurbished_i \\ &+ \beta_6 first\_occupancy_i + \beta_7 landmarked\_building_i \\ &+ \beta_8 elevator_i + \beta_9 parking\_space_i \\ &+ \beta_{10} building\_type_i + \beta_{11} construction\_year_i \\ &+ \beta_{12} commission\_free_i + \gamma_l + \delta_t + \varepsilon_{ilt}\end{aligned} \quad (16)$$

As explained above for the rent models, the only difference between this model and the full categorical sales price model is the key explanatory variable of *"energy_consumption"* that is now included. The variable *"epc_level"* is not included in this model. The variable *"energy_consumption"* is a metric variable indicating the energy consumption of a building in kWh / (m^2 * a). The final model for estimating the impact of energy efficiency on the sales price of a building includes the EPC type and an interaction term between the EPC type used and the EPC rating. The full interaction sales price model is defined in the following way:

$$\begin{aligned}\ln(sales\_price_{ilt}) &= \alpha + \beta_1 epc\_level_i + \beta_2 epc\_type_i \\ &+ \beta_3 epc\_type_i * epc\_level_i + \beta_4 \ln(living\_space_i) \\ &+ \beta_5 no\_rooms_i + \beta_6 active\_lease_i \\ &+ \beta_7 refurbished_i + \beta_8 first\_occupancy_i \\ &+ \beta_9 landmarked\_building_i + \beta_{10} elevator_i \\ &+ \beta_{11} parking\_space_i + \beta_{12} building\_type_i \\ &+ \beta_{13} construction\_year_i + \beta_{14} commission\_free_i \\ &+ \gamma_l + \delta_t + \varepsilon_{ilt}\end{aligned} \quad (17)$$

The variable *"epc_type"* and the interaction term *"epc_type * epc_level"* are both added to the full categorical sales price model. The interpretation of both is the same as for the full cold rent interaction model and the full warm rent interaction model with the difference that the impact on the sales price is measured.

Finally, the specified models are run, and their explanatory power is assessed by validating the model assumptions mentioned in section 3.1. The assumptions, their definitions and the respective tests that are run can be found in Appendix 2. The results of these assumptions tests are shortly summarized now before presenting the empirical results in the next section.

Linearity assumption: Graphical plots showing the fitted values on the x-axis and the magnitude of their residuals on the y-axis are used to assess this assumption. Overall, no relevant deviation from linearity can be detected. While there is some non-linearity present for the basic models, the full categorical, continuous and interaction models show almost perfect linearity of residuals. This supports the conclusion that the full models have a greater explanatory power and should be the ones interpreted rather than the basic models.

No multicollinearity assumption: Strong multicollinearity impacts the significance of the correlated variables. First indicative values for correlation in the data were presented with the correlation matrixes and discussed in section 3.3. To assess multicollinearity of explanatory variables, the variance inflation factor (VIF) is calculated. As the models include multiple categorical explanatory variables with more than one degree of freedom, the values of the variables are likely to be artificially inflated. Thus, the generalized variance inflation factor (GVIF) is calculated following Fox and Monette (1992, p. 140). Overall, no problematic multicollinearity is found for the models. It should be mentioned that there exist high values for the explanatory variables that are based on the amount of living space. However, this was expected and considered when the models were specified. The moderate correlation found in the data in section 3.3 for energy efficiency and construction year does not result in problematic multicollinearity. The same is true for the use of the number of rooms as categorically coded variable. The values of the GVIF for all variables except the ones based on living space models range between 1.0 and 1.4. The terms based on living space show high values of up to 5.9, potentially impacting their significance values.

Homoscedasticity assumption: Heteroscedasticity impacts the significance of coefficients. To address this problem, the dependent variable is log-transformed, a graphical plot of residuals is used for diagnosis and robust standard errors , also known as White standard errors, that account for heteroscedasticity are calculated (see White, 1980). In the plots, there is only a slight deviation from the perfect value of one for the square root of the absolute values of the standardized residuals present. Such a deviation is common for multiple linear regression applications and the reason why additionally White standard errors are computed. They are presented as part of the empirical results in the next section. Thus, the homoscedasticity assumption can be seen as sufficiently fulfilled.

No autocorrelation assumption: The Durbin-Watson statistic is used to test the assumption of no autocorrelation. The test can result in values that are between zero and four. No autocorrelation is present when the test result is equal to two. A rather conservative approach is to say that values below 1 and above 3 are of concern and problematic (Field et al., 2012, p. 917). The values found for the cold rent, warm rent and sales price models range between 1.72 and 1.96. This indicates weak autocorrelation for some models and almost none for others. However, all values are within the unproblematic area of 1 - 3, resulting in the no autocorrelation assumption being sufficiently fulfilled.

Exogeneity assumption: The exogeneity assumption requires the expected value of the residual vector to be zero. This is always technically fulfilled for the data sample used to estimate the models and caused by the mathematical process of minimizing the squared residuals of the model. However, no statement can be made regarding the overall population. Further, the potential problem of omitted variable bias is not addressed. These are general limitations of any empirical study that employs hedonic price models.

4. Presentation of the empirical results

The economic analysis in this paper consists of two parts. The first part addresses hypotheses 1 a) – 1 c) regarding the general impact of energy efficiency on cold rent, warm rent and sales prices. The second part addresses hypotheses 2 a) – 2 c) regarding the impact of energy efficiency based on the EPC type used on the cold rent, warm rent and sales prices. Thus, the empirical results of the models that do not include the interaction term are presented first. This is followed by the presentation of the empirical results of the models that include the interaction term. The results in the tables are rounded to five decimal places. Significance computations were done using the non-rounded values. All coefficients presented in the tables show the impact on the log-transformed dependent variable. A one unit increase in a non-log transformed explanatory variable increases the log value of the dependent variable by the magnitude of the coefficient. To make the understanding of these values and their economic meaning more intuitive, they are converted into percentage values in the text. All standard errors presented are robust White standard errors. They can be found below the coefficient values in the tables. The focus is on the key explanatory variable of energy efficiency. The other explanatory variables are shortly presented at the end of the section.

Table 3 shows the empirical results of the basic, full categorical and full continuous cold rent model. The basic cold rent model shows a strong overall statistical significance. Its F-statistic is equal to 2 936 (p-value: < 2.2e-16) with 499 and 211 667 degrees of freedom for the regression and error, respectively. The R-squared is equal to 0.8737 and the adjusted R-squared is equal to 0.8734. These values indicate that a significant proportion of the variance can be explained by this model while the high R squared value is not caused by a high number of explanatory variables. For the rest of the models, the R-squared and adjusted R-squared values are presented, too. Their meaning remains the same if no large difference in magnitude exists. All explanatory variables are highly significant at the 0.1% level. Significant cold rent premiums are present for an above average energy efficient building. The discounts for a very inefficient building are also significant but comparatively smaller. The magnitude of the coefficients of the EPC levels ranges from 9.9% for an A+ rated building to -1.9% and -1.1% for a G and H rated building when compared to a D rated building. Looking at the magnitude of these values, no continuous linear decrease in cold rent is present.

When looking at the empirical results of the full categorical cold rent model, this non-linearity becomes more evident: The full categorical cold rent model shows a strong overall statistical significance, too. Its F-statistic is equal to 3 505 (p-value: < 2.2e-16) with 581 and 211 585 degrees of freedom for the regression and error, respectively. The R squared is equal to 0.9059 and the adjusted R squared is equal to 0.9056. When looking at the coefficients of the different EPC levels, highly significant premiums for a building that is rated higher than D are estimated. An A+ rated building is estimated to have a cold rent 7.0% higher than a D rated building. An A, B, and C rated building is estimated to have 3.5%, 3.2% and 1.0% higher cold rent, respectively. The estimates for the EPC level E, F, G, and H do not show the same significance level as before. Their coefficients are equal to -0.1%, 0.2%, -0.8% and -0.4% respectively, but only the coefficient of the EPC level G is still significant at the 5% level. Thus, it cannot be stated that the impact of the EPC levels E, F and H on cold rent is different from zero. Similarly, to the basic cold rent model, there are strong premiums present for a very energy efficient building and only limited or no discounts present for an energy inefficient building.

Table 3: Cold rent hedonic regression results

Independent variables	(1) Basic model	(2) Full categorical model	(3) Full continuous model	(4) Full interaction model
EPC - A+ (Ref: D)	0.09489 **** 0.00239	0.06783 *** 0.00210	-	0.08458 *** 0.00264
EPC - A (Ref: D)	0.04815 *** 0.00207	0.03395 *** 0.00182	-	0.04962 *** 0.00250
EPC - B (Ref: D)	0.04488 *** 0.00160	0.03194 *** 0.00141	-	0.05191 *** 0.00222
EPC - C (Ref: D)	0.01766 *** 0.00130	0.00994 *** 0.00113	-	0.02902 *** 0.00232
EPC - E (Ref: D)	-0.00707 *** 0.00117	-0.00053 0.00100	-	0.00269 0.00231
EPC - F (Ref: D)	-0.00798 *** 0.00133	0.00199 0.00114	-	0.00315 0.00242
EPC - G (Ref: D)	-0.01925 *** 0.00186	-0.00758 *** 0.00162	-	-0.01478 ** 0.00277
EPC - H (Ref: D)	-0.01136 *** 0.00276	-0.00402 0.00234	-	-0.00412 0.00323
EPC type (consumption)	-	-	-	0.01094 *** 0.00179
EPC - A+ Int.	-	-	-	-0.02727 *** 0.00586
EPC - A Int.	-	-	-	-0.01818 *** 0.00377
EPC - B Int.	-	-	-	-0.03527 *** 0.00263
EPC - C Int.	-	-	-	-0.02579 *** 0.00262
EPC - E Int.	-	-	-	-0.00411 0.00254
EPC - F Int.	-	-	-	-0.00049 0.00272
EPC - G Int.	-	-	-	0.01872 *** 0.00339
EPC - H Int.	-	-	-	0.01146 * 0.00489
Energy consumption	-	-	-0.00017 *** 0.00001	-
Living space	0.00401 *** 0.00005	0.00288 *** 0.00006	0.00291 *** 0.00006	0.00286 *** 0.00006
Ln (living space)	0.57596 *** 0.00350	0.61415 *** 0.00513	0.61204 *** 0.00514	0.61602 *** 0.00513
Refurbished	-	0.04216 *** 0.00077	0.04167 *** 0.00078	0.04246 *** 0.00077
First occupancy	-	0.06711 *** 0.00109	0.06900 *** 0.00109	0.06664 *** 0.00109
Landmarked building	-	0.05402 *** 0.01213	0.05387 *** 0.01223	0.05241 *** 0.01198
Elevator	-	0.01906 *** 0.00089	0.01969 *** 0.00089	0.01866 *** 0.00089
Parking space	-	0.03820 *** 0.00075	0.03811 *** 0.00075	0.03796 *** 0.00075
Furnished	-	0.17042 *** 0.00259	0.17062 *** 0.00259	0.17074 *** 0.00259
Intercept	3.40426 *** 0.03643	3.13110 *** 0.03349	3.16666 *** 0.03304	3.11788 *** 0.03322
Categorical control variables				
No. of rooms	No	Yes	Yes	Yes
Building type	No	Yes	Yes	Yes
Construction year	Yes	Yes	Yes	Yes
Location	Yes	Yes	Yes	Yes
Upload date	No	Yes	Yes	Yes
Model statistics				
R squared	0.8737	0.9059	0.9055	0.9061
Adjusted R squared	0.8734	0.9056	0.9052	0.9058
No. of observations	212 167	212 167	212 167	212 167

Significance Levels: (*) $p < 0.05$; (**) $p < 0.01$; (***) $p < 0.001$ Of note: The coefficients show the impact of the log-transformed dependent variable. In the text, the converted valves in percent are used. Thus there might exist differences between the valves.

When looking at the full continuous model, the overall significance of the model does not change much compared to the other two models. Its F-statistic is equal to 3 532 (p-value: < 2.2e-16) with 574 and 211 585 degrees of freedom for the regression and error, respectively. The R squared is equal to 0.9055 and the adjusted R squared is equal to 0.9052. When looking at the value of the coefficient of the explanatory variable *"energy_consumption,"* the estimate is highly significant at the 0.1% level. The magnitude of the coefficient is small with -0.02%. This means that each additional kWh / (m^2 * a) decreases the cold rent by 0.02%. The direction of the coefficient is in line with the full categorical model, but its magnitude is much smaller.

Table 4 displays the empirical results of the basic, full categorical and full continuous warm rent model. The basic warm rent model shows a strong overall statistical significance. Its F-statistic is equal to 2 925 (p-value: < 2.2e-16) with 499 and 211 667 degrees of freedom for the regression and error, respectively. The R squared is equal to 0.8733 and the adjusted R squared is equal to 0.8730. Again, these values indicate that a significant proportion of the variance can be explained by this model while the high R squared value is not caused by a high number of explanatory variables. Most explanatory variables are highly significant at a 0.1% level. Significant at the 1% level is the EPC level H. Not significant are the EPC levels E and F. Similarly, to the basic cold rent model, significant warm rent premiums are present for an above average energy efficient building. The discounts for a very inefficient building are less significant and comparatively smaller. The magnitude of the coefficients of the EPC levels ranges from 7.4% for an A+ rated building to -1.1% and -0.7% for a G and H rated building when compared to a D rated building. Looking at the magnitude of the values, they are showing a non-linear decrease and premiums for an energy efficient building are much greater than the discounts for an energy inefficient building.

The full categorical warm rent model shows a strong overall statistical significance, too. Its F-statistic is equal to 3 521 (p-value: <2.2e-16) with 581 and 211 585 degrees of freedom for the regression and error, respectively. The R squared is equal to 0.9063 and the adjusted R squared is equal to 0.9060. When looking at the coefficients of the different EPC levels, highly significant premiums for a building that is rated higher than D are estimated. The EPC levels above D are all significant at the 0.1% level. The magnitude of the coefficients is smaller than the ones found in the basic warm rent model and smaller than the ones found for the full categorical cold rent model. An A+ rated building is estimated to have a warm rent 4.6% higher than a D rated building. An A, B, and C rated building is estimated to have 2.0%, 2.1% and 0.4% higher warm rents, respectively. The estimates for the EPC level E and F are significant at the 0.1% level with estimates indicating warm rents that are 0.6% and 1.1% higher, respectively. EPC level G and H show lower significance levels at 5%. Their coefficients are equal to 0.3% and 0.4% respectively. Similarly, to the basic and full categorical cold rent models, there are strong premiums present for a very energy efficient building. No discounts are present for an energy inefficient building. The premiums for an energy efficient building above the D level are smaller compared to the cold rent model. There are small premiums for an energy inefficient building below the D level when compared to the cold rent model.

When looking at the full continuous model, the overall significance of the model does not change much compared to the other two models. Its F-statistic is equal to 3 553 (p-value: <2.2e-16) with 574 and 211 592 degrees of freedom for the regression and error, respectively. The R squared is equal to 0.9060 and the adjusted R squared is equal to 0.9057. When looking at the value of the coefficient of the explanatory variable *"energy_consumption,"* the estimate is highly significant at the 0.1% level. The magnitude of the coefficient is small with -0.004%. This means that each additional kWh / (m^2 * a) decreases the warm rent by 0.004%. The direction of the coefficient is the same as the above D rated buildings in the full categorical warm rent model and in the full categorical cold rent model, but its magnitude is much smaller.

Table 5 displays the empirical results of the basic, full categorical and full continuous sales price model. The basic sales price model shows a strong overall statistical significance. Its F-statistic is equal to 1 001 (p-value: < 2.2e-16) with 508 and 159 064 degrees of freedom for the regression and error, respectively. The R squared is equal to 0.7617 and the adjusted R squared is equal to 0.7609. Most explanatory variables are highly significant at the 0.1% level. Significant at the 1% level is the EPC level H. Significant at the 5% level is the EPC level G. Not significant is the EPC level F. Significant sales price premiums are present for an above average energy efficient building. The discounts for an inefficient building are less significant and smaller. The magnitude of the coefficients of the EPC levels ranges from 16.4% for an A+ rated building to -1.1% for an H rated building when compared to a D rated building. Looking at the form of the values, it is comparable with the one found for the basic cold rent model and basic warm rent model. It is also non-linear, but premiums for an energy efficient building are much greater. At the same time, the discounts are not as large and oscillating around zero.

The full categorical sales price model shows a clearer picture regarding the premiums for an energy efficient building and the discounts for an energy inefficient building. Overall, the model shows a strong statistical significance. Its F-statistic is equal to 1 761 (p-value: < 2.2e-16) with 609 and 158 963 degrees of freedom for the regression and error, respectively. The R squared is equal to 0.8709 and the adjusted R squared is equal to 0.8704. When looking at the coefficients of the different EPC levels, highly significant premiums for a building that is rated higher than D are estimated. The EPC levels A+, A and B are all significant at the 0.1% level. The EPC level C is significant at the 1% level. The magnitude of the coefficients is lower than the ones found in the basic sales price model. An A+ rated building is estimated to have a sales price 6.9% higher than a D rated building. An A, B, and C rated building is estimated to have a 2.6%, 3.1% and

Table 4: Warm rent hedonic regression results

Independent variables	**(1) Basic model**	**(2) Full categorical model**	**(3) Full continuous model**	**(4) Full interaction model**
EPC - A+ (Ref: D)	0.07131 *** 0.00226	0.04496 *** 0.00195	-	0.06521 *** 0.00246
EPC - A (Ref: D)	0.03419 *** 0.00196	0.02005 *** 0.00170	-	0.03947 *** 0.00233
EPC - B (Ref: D)	0.03434 *** 0.00151	0.02047 *** 0.00132	-	0.04319 *** 0.00208
EPC - C (Ref: D)	0.01233 *** 0.00122	0.00392 *** 0.00105	-	0.02243 *** 0.00219
EPC - E (Ref: D)	-0.00141 0.00109	0.00557 *** 0.00094	-	0.00561 *** 0.00218
EPC - F (Ref: D)	0.00015 0.00124	0.01142 *** 0.00107	-	0.00991 ** 0.00230
EPC - G (Ref: D)	-0.01062 *** 0.00172	0.00295 * 0.00150	-	-0.00372 0.00258
EPC - H (Ref: D)	-0.00671 ** 0.00256	0.00426 * 0.00221	-	0.00614 * 0.00306
EPC type (consumption)	-	-	-	0.01863 *** 0.00168
EPC - A+ Int.	-	-	-	-0.03552 *** 0.00538
EPC - A Int.	-	-	-	-0.02639 *** 0.00357
EPC - B Int.	-	-	-	-0.03782 *** 0.00247
EPC - C Int.	-	-	-	-0.02417 *** 0.00246
EPC - E Int.	-	-	-	0.00006 0.00240
EPC - F Int.	-	-	-	0.00383 0.00257
EPC - G Int.	-	-	-	0.02047 *** 0.00315
EPC - H Int.	-	-	-	0.01262 ** 0.00458
Energy consumption	-	-	-0.00004 *** 0.00001	-
Living space	0.00320 *** 0.00004	0.00282 *** 0.00006	0.00284 *** 0.00006	0.00280 *** 0.00006
Ln (living space)	0.59321 *** 0.00327	0.58261 *** 0.00476	0.58098 *** 0.00477	0.58516 *** 0.00476
Refurbished	-	0.03619 *** 0.00072	0.03577 *** 0.00072	0.03640 *** 0.00072
First occupancy	-	0.05764 *** 0.00101	0.05910 *** 0.00101	0.05739 *** 0.00101
Landmarked building	-	0.06186 *** 0.01257	0.06235 *** 0.01263	0.05980 *** 0.01247
Elevator	-	0.03560 *** 0.00082	0.03591 *** 0.00082	0.03533 *** 0.00082
Parking space	-	0.03725 *** 0.00069	0.03720 *** 0.00069	0.03673 *** 0.00069
Furnished	-	0.16025 *** 0.00241	0.16035 *** 0.00241	0.16058 *** 0.00241
Intercept	3.66727 *** 0.03246	3.54800 *** 0.02907	3.56467 *** 0.02885	3.52455 *** 0.02866
Categorical control variables				
No. of rooms	No	Yes	Yes	Yes
Building type	No	Yes	Yes	Yes
Construction year	Yes	Yes	Yes	Yes
Location	Yes	Yes	Yes	Yes
Upload date	No	Yes	Yes	Yes
Model statistics				
R squared	0.8733	0.9063	0.9060	0.9067
Adjusted R squared	0.8730	0.9060	0.9057	0.9064
No. of observations	212 167	212 167	212 167	212 167

Significance Levels: (*) $p < 0.05$; (**) $p < 0.01$; (***) $p < 0.001$ Of note: The coefficients show the impact of the log-transformed dependent variable. In the text, the converted valves in percent are used. Thus there might exist differences between the valves.

0.6% higher sales price, respectively. The estimates for the EPC level E and F are not significant. The coefficients are estimated at 0.6% and 1.1%, respectively. However, it cannot be excluded that these EPC levels have no impact on the sales price. EPC level G and H are highly significant again at the 0.1% level. Their coefficients are equal to -1.7% and -7.5% respectively. Overall, there are significant and large premiums present for energy efficient buildings and significant and large discounts present for energy inefficient buildings.

When looking at the full continuous model, the overall significance of the model does not change much compared to the other two sales price models. Its F-statistic is equal to 1 779 (p-value: < 2.2e-16) with 602 and 158 970 degrees of freedom for the regression and error, respectively. The R squared is equal to 0.8707 and the adjusted R squared is equal to 0.8702. When looking at the coefficient of the explanatory variable *"energy_consumption,"* the estimate is highly significant at the 0.1% level. The magnitude of the coefficient is small with -0.04%. This means that each additional kWh / (m^2 * a) decreases the cold rent by 0.04%. Compared to the rent models, the estimate found is larger in magnitude and comes closer to the coefficients of the full categorical sales price model.

Based on the findings above, it is assessed in section 5 whether hypotheses 1 a) – 1 c) are supported by market data. To assess hypotheses 2 a) – 2 c), the more complex full interaction hedonic price models are used. The interaction term *"epc_type * epc_level"* and the binary explanatory variable *"epc_type"* are included in the models to capture the difference in valuation between a building that uses a requirement certificate compared to a consumption certificate. The findings for the interaction models can be found in the last column of Tables 3, 4 and 5. To increase the intuitive understanding of the values, they are converted into percentage values. Further, they are added together to show the overall and direct comparison between the two EPC types. The reference building is a building that is issued a requirement certificate and has an EPC rating D. Any comparison is made to this reference building. Table 6 displays the computed percentage values of the premiums and discounts of buildings with a requirement certificate and a consumption certificate based on the full interaction cold rent, warm rent and sales price model. Figures 7, 8 and 9 visualize the findings.

The full interaction cold rent model shows a strong overall statistical significance. Its F-statistic is equal to 2 936 (p-value: <2.2e-16) with 590 and 211 576 degrees of freedom for the regression and error, respectively. The R squared is equal to 0.9061 and the adjusted R squared is equal to 0.9058. As before, these values indicate that a significant proportion of the variance can be explained by this model while the high R squared value is not caused by a high number of explanatory variables. When looking at the coefficients of the different EPC levels, highly significant premiums for a building that is rated higher than D are estimated for both EPC types. The EPC levels A+, A, B and C are all significant at the 0.1% level. An A+ rated building with a requirement certificate is estimated to have a cold rent 8.82% higher than a D rated building. An A, B, and C rated building is estimated to have 5.09%, 5.33% and 2.94% higher cold rent, respectively. The coefficients of a building with a consumption certificate are lower. An A+ rated building is estimated to have a 7.08% higher cold rent while an A, B and C rated building is estimated to have a 4.34%, 2.82% and 1.50% higher cold rent, respectively. A D rated building with a consumption certificate has a 1.1% higher cold rent than a building with a requirement certificate. The estimates for the EPC level E and F are not significant for either EPC type. The coefficients are estimated with 0.26% and 0.31% for the requirement certificate and 0.95% and 1.41% for the consumption certificate, respectively. However, it cannot be excluded that these EPC levels have no impact on the cold rent. EPC level G is highly significant again at the 0.1% level. The coefficients are equal to -1.39% for the requirement certificate and 1.57% for the consumption certificate. While the EPC level H is not significant for the requirement certificate (with a coefficient of -0.40%), it is significant at the 5% level for the consumption certificate with a coefficient value of 1.85%. Overall, there are significant and large premiums present for a very energy efficient building. They are larger for the requirement certificate. For a very energy inefficient building there are no large discounts visible. There are even higher cold rents estimated for an inefficient building with a consumption certificate.

The full interaction warm rent model shows a strong overall statistical significance. Its F-statistic is equal to 3 483 (p-value: <2.2e-16) with 590 and 211 576 degrees of freedom for the regression and error, respectively. The R squared is equal to 0.9067 and the adjusted R squared is equal to 0.9064. When looking at the coefficients of the different EPC levels, highly significant premiums for a building that is rated higher than D are estimated for both EPC types. The EPC levels A+, A, B and C are all significant at the 0.1% level. An A+ rated building with a requirement certificate issued is estimated to have a warm rent 6.74% higher than a D rated building. An A, B, and C rated building is estimated to have 4.02%, 4.40% and 2.27% higher warm rent, respectively. The coefficients of a building with a consumption certificate are a bit lower: An A+ rated building is estimated to have a 5.00% higher warm rent while an A, B and C rated building are estimated to have 3.25%, 2.5% and 1.71% higher warm rent, respectively. A D rated building with a consumption certificate has a 1.88% higher warm rent than a building with a requirement certificate. The estimates for a building with a requirement certificate and an EPC level E (0.56%) are significant at the 1% level and significant at the 0.1% level for an EPC level F (0.99%). EPC level G (-0.30%) is not significant while the EPC level H (0.61%) is significant at the 5% level. When it comes to a building with a consumption certificate, the EPC levels E (2.45%) and F (3.28%) are not significant while the EPC level G (3.67%) is significant at the 0.1% level and the EPC level H (3.80%) is significant at the 1% level. Overall, there are still significant and large premiums present for a very energy efficient building. They are larger for the requirement certificate. A very energy inefficient building shows a higher warm rent compared to a D

Table 5: Sales price hedonic regression results

Independent variables	**(1) Basic model**	**(2) Full categorical model**	**(3) Full continuous model**	**(4) Full interaction model**
EPC - A+ (Ref: D)	0.15196 *** 0.00478	0.06730 *** 0.00374	-	0.07137 *** 0.00498
EPC - A (Ref: D)	0.05853 *** 0.00458	0.02614 *** 0.00357	-	0.04167 *** 0.00509
EPC - B (Ref: D)	0.04600 *** 0.00358	0.03024 *** 0.00272	-	0.04557 *** 0.00474
EPC - C (Ref: D)	0.01832 *** 0.00290	0.00602 ** 0.00208	-	0.01705 *** 0.00465
EPC - E (Ref: D)	-0.00929 *** 0.00274	-0.00319 0.00193	-	-0.01666 *** 0.00412
EPC - F (Ref: D)	-0.00050 0.00311	-0.00370 0.00227	-	-0.01880 *** 0.00414
EPC - G (Ref: D)	0.00852 * 0.00393	-0.01745 *** 0.00295	-	-0.04447 *** 0.00437
EPC - H (Ref: D)	-0.01105 ** 0.00426	-0.07799 *** 0.00334	-	-0.10711 *** 0.00439
EPC type (consumption)	-	-	-	-0.02981 *** 0.00333
EPC - A+ Int.	-	-	-	0.01070 0.00821
EPC - A Int.	-	-	-	-0.02983 *** 0.00636
EPC - B Int.	-	-	-	-0.02201 *** 0.00508
EPC - C Int.	-	-	-	-0.01297 * 0.00513
EPC - E Int.	-	-	-	0.01617 *** 0.00465
EPC - F Int.	-	-	-	0.01588 ** 0.00492
EPC - G Int.	-	-	-	0.04499 *** 0.00629
EPC - H Int.	-	-	-	0.08648 *** 0.00884
Energy consumption	-	-	-0.00038 *** 0.00001	-
Ln (living space)	1.00805 *** 0.00179	0.90813 *** 0.00368	0.90783 *** 0.00368	0.90461 *** 0.00368
Refurbished	-	0.04945 *** 0.00192	0.04885 *** 0.00192	0.04884 *** 0.00191
First occupancy	-	0.05171 *** 0.00281	0.05197 *** 0.00282	0.04724 *** 0.00280
Landmarked building	-	0.01774 0.01200	0.01795 0.01198	0.01632 0.01192
Elevator	-	-0.03396 *** 0.00182	-0.03511 *** 0.00181	-0.03478 *** 0.00181
Parking space	-	0.01745 *** 0.00137	0.01692 *** 0.00137	0.01815 *** 0.00137
Existing lease	-	-0.05869 *** 0.00185	-0.05858 *** 0.00185	-0.05827 *** 0.00185
Commission free	-	0.02027 *** 0.00157	0.02047 *** 0.00157	0.01836 *** 0.00157
Intercept	7.24672 *** 0.11175	7.21082 *** 0.08352	7.26770 *** 0.08368	7.24219 *** 0.08315
Categorical control variables				
No. of rooms	No	Yes	Yes	Yes
Building type	No	Yes	Yes	Yes
Construction year	Yes	Yes	Yes	Yes
Location	Yes	Yes	Yes	Yes
Upload date	No	Yes	Yes	Yes
Model statistics				
R squared	0.7617	0.8709	0.8707	0.8713
Adjusted R squared	0.7609	0.8704	0.8702	0.8708
No. of observations	159 573	159 573	159 573	159 573

Significance Levels: (*) $p < 0.05$; (**) $p < 0.01$; (***) $p < 0.001$ Of note: The coefficients show the impact of the log-transformed dependent variable. In the text, the converted valves in percent are used. Thus there might exist differences between the valves.

Table 6: Full interaction model results in percentage values

EPC level	Cold rent interaction effects: Requirement certificate	Cold rent interaction effects: Consumption certificate	Warm rent interaction effects: Requirement certificate	Warm rent interaction effects: Consumption certificate	Sales price interaction effects: Requirement certificate	Sales price interaction effects: Consumption certificate
A+	8.82%	7.08%	6.74%	5.00%	7.40%	5.36%
A	5.09%	4.34%	4.02%	3.25%	4.26%	-1.78%
B	5.33%	2.82%	4.40%	2.50%	4.66%	-0.62%
C	2.94%	1.50%	2.27%	1.71%	1.72%	-2.54%
D	0.00%	1.10%	0.00%	1.88%	0.00%	-2.94%
E	0.26%	0.95%	0.56%	2.45%	-1.65%	-2.98%
F	0.31%	1.41%	0.99%	3.28%	-1.86%	-3.22%
G	-1.39%	1.57%	-0.30%	3.67%	-4.35%	-2.89%
H	-0.40%	1.85%	0.61%	3.80%	-10.16%	-4.92%

Of note: The grey font color is used for non-significant values.

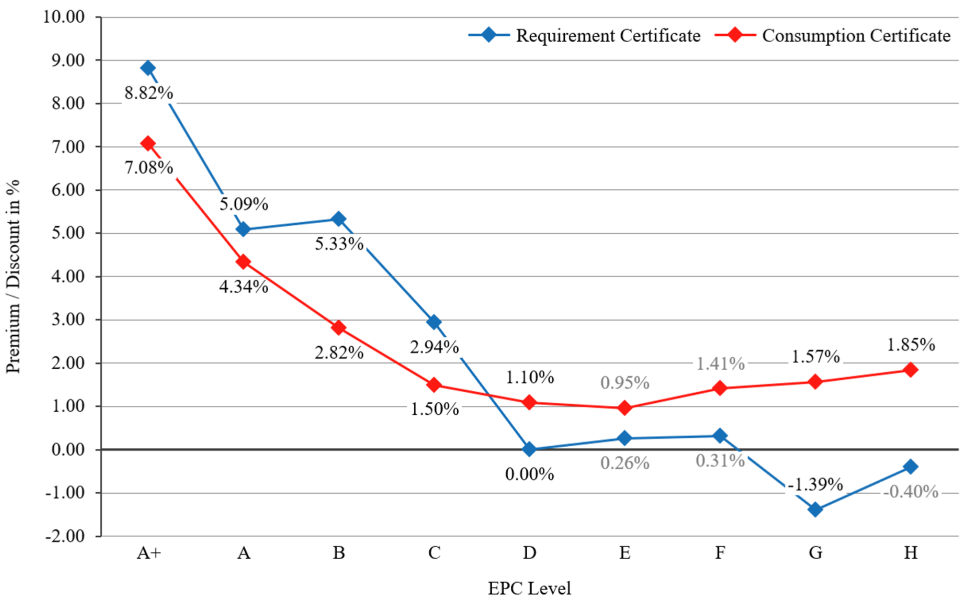

Figure 7: Full interaction cold rent effects (font color grey for non-significant values)

rated building, mainly when it is issued a consumption certificate.

The sales price interaction model shows a strong overall statistical significance. Its F-statistic is equal to 1 742 (p-value: <2.2e-16) with 618 and 158 954 degrees of freedom for the regression and error, respectively. The R squared is equal to 0.8713 and the adjusted R squared is equal to 0.8708. When looking at the coefficients of the different EPC levels, all are highly significant at the 0.1% level for a building that is issued a requirement certificate. For a building issued with a consumption certificate, EPC levels A, B, D, E, G and H are significant at the 0.1% level, EPC level F is significant at the 1% level and EPC level C is significant at the 5% level. Only EPC level A+ is not significant. The coefficients for a building with a requirement certificate are estimated at 7.4% for EPC level A+, 4.26% for A, 4.66% for B, 1.72% for C, -1.65% for E, -1.86% for F, -4.35% for G and -10.16% for H. These values are higher compared to the ones found for the full categorical sales price model. The coefficients for a building with a consumption certificate do not show premiums for above-average energy efficient buildings. Only the non-significant EPC level A+ has a premium of 5.36%. The other EPC levels show discounts. An A rated building with a consumption certificate is estimated to have a discount of -1.78%, a B rated building -0.62%, a C rated building -2.54%, a D rated building -2.94%, an E rated building -2.98%, a F rated building -3.22%, a G rated building -2.89% and an H rated building -4.92%. Overall, there are significant and large premiums and discounts present for a building with a requirement certificate. Buildings with a consumption certificate are estimated to have significantly lower sales price compared to buildings with a requirement certificate across all EPC levels except for G and H.

In the full categorical, continuous and interaction model, various control variables are included. The estimates for their coefficients differ between the cold rent, warm rent and sales

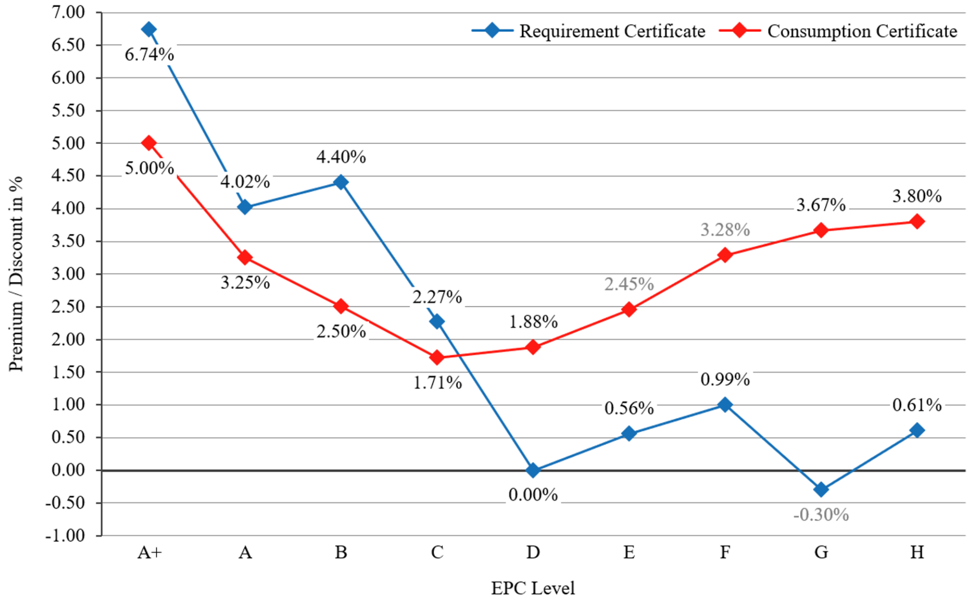

Figure 8: Full interaction warm rent effects (font color grey for non-significant values)

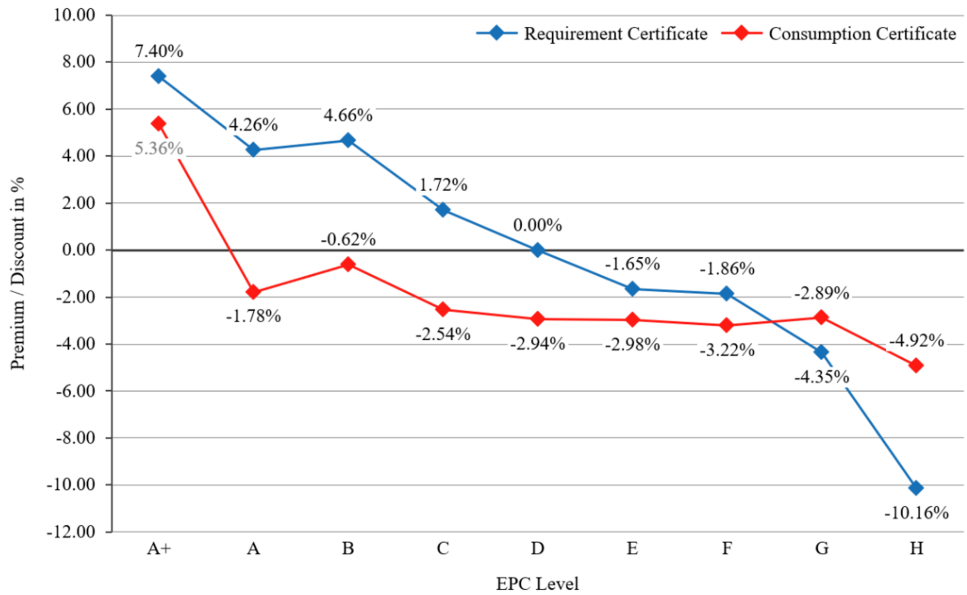

Figure 9: Full interaction sales price effects (font color grey for non-significant values)

price models. When considering the different models for only one of the dependent variables, the significance and magnitude of the coefficients of the control variables do not change much. The values presented below are taken from the full categorical models found in Tables 3, 4 and 5. The control variables of the cold rent model are all significant at the 0.1% level. An increase in living space increases the cold rent by 0.3% for every additional m^2. It also increases relatively by 84.8% for every 100% increase in living space. A furnished building has an 18.6% higher cold rent, the cold rent for a newly built building increases by 6.9% and for a refurbished building by 4.3%. A landmarked building has a 5.5% higher cold rent. Equipping a building with an elevator increases the cold rent by 1.9% and an existing parking space by 3.9%. The coefficients for the warm rent model are similar. They are overall a bit smaller, except for the elevator. This seems logical as the operating costs are not directly affected by most, except for the elevator, and thus their impact is proportionally smaller. Each additional m^2 of space increases the warm rent by 0.3% and the relative increase is 79.1% for every 100% increase in living space. Furnishing an apartment leads to a 17.4% increase in warm rent. A newly built building can achieve a 5.9% higher warm rent and a refurbished building a 3.7% higher warm rent. A landmarked building has a 6.4%

higher warm rent. Adding an elevator to a building increases the warm rent by 3.6%, while a parking space increases the warm rent by 3.8%. Most of the hedonic characteristics of the full categorical sales price model are also highly significant. Except for the control variable *"landmarked_building,"* which is not significant, all are significant at the 0.1% level. A 100% increase in living space increases the sales price by 147.9%. A newly built building is valued at 5.3% more and a refurbished building is estimated at a 5.1% higher sales price. Selling a building without a commission increases the price by 2.0%, while a parking space increases the building price by 1.8%. An elevator decreases the sales price by -3.3% and an existing lease decreases the sales price by -5.6%.

5. Discussion

This study aims to analyze how the energy efficiency of a building impacts its cold rent, warm rent and sales price in the residential real estate market in the Rhein-Main Region in Germany. Based on the normative approach of real estate valuation theory and evidence found in the extant literature, significant energy efficiency premiums should exist. For the rental market it was hypothesized that the energy efficiency of a building influences both its cold rent and warm rent (hypotheses 1a, 1b) and that these effects depend on the EPC type of the building (hypotheses 2a, 2b). For the sales market it was hypothesized that an increase in the energy efficiency of a building increases its sales price (hypothesis 1c), and that the EPC type modifies this effect (hypothesis 2c). These hypotheses were tested using real world data and hedonic price models. Next, the results of these estimations are discussed, and it is assessed whether they corroborate the hypotheses. Finally, possibilities for future research are outlined.

The impact of the energy efficiency of a building on its cold and warm rent

Hypothesis 1 a) states that an increase in the energy efficiency of a residential building leads to an increase in its cold rent. To test this hypothesis, the different cold rent models ranging from the basic cold rent model to the full continuous cold rent model were specified. Following the normative logic that led to the formulation of this hypothesis, there should be a clear linear trend from A+ to H. The reason for this is that energy savings or additional energy costs are reflected in the cold rent of residential real estate in a market environment. All market participants should be price takers in perfect market conditions. When looking at the results of the full categorical cold rent model, this is only partially supported. Above-average energy efficient buildings achieve significant cold rent premiums of up to 7.0% (A+ rating) when compared to a D-rated building. Even though C rated buildings can achieve a 1.0% higher cold rent, the trend towards decreasing cold rents does not continue for buildings with higher energy consumption. Significance is low and there is no clear indication of large discounts. This shows a non-linear impact of energy efficiency on the cold rent of residential buildings. The existence of this non-linear impact demonstrates that while the full continuous model serves its purpose as a robustness check, its coefficients should be interpreted with caution. A reason for this non-linear impact could be market conditions. For example, in a market in which housing is scarce, the negotiation power of prospective tenants is not strong enough to achieve discounts for energy inefficient buildings compared to the average. At the same time, owners can ask for premiums for buildings that are better than the average building stock. While this might be beneficial for owners of highly energy inefficient buildings, this inhibits the renovation of the current building stock. The incentive of improving the energy efficiency of a G rated building for example is limited because it must at least be increased to an energy efficiency level of C. Achieving an EPC level of A or B would be better as it seems unlikely that a 1.0% increase in cold rent achieved with EPC level C would be enough to recoup the investment costs in a reasonable way. This is in line with literature that argues that refurbishment of the building stock is currently not profitable for building owners (März, Stelk, & Stelzer 2022, p. 20). In conclusion, the hypothesis 1 a) is supported for above-average energy efficient buildings only.

An additional layer of complexity is considered with the full interaction cold rent model. It is used to test hypothesis 2 a), which states that based on the EPC type, an increase in the energy efficiency of a residential building leads to an increase in its cold rent. It seems plausible that the requirement certificate is trusted more by prospective tenants than the consumption certificate. The reason for this is that it is based on the building characteristics and thus more objective than the consumption values that are dependent on the behavior of past and current tenants. This leads to the assumption that the requirement certificate should result in clear premiums and discounts. The discounts could now be present with this variable included in the model that addresses a crucial source of heterogeneity in the data. Whether premiums and discounts are present for the consumption certificate is difficult to predict because it depends on the perception of this EPC type by prospective tenants. When looking at buildings with a requirement certificate, significant premiums for energy efficient buildings exist and range up to 8.8% (A+ rating). The premiums found are greater than the ones for the full categorical model for all levels above D. However, there are still no continuous discounts found for energy inefficient buildings. When looking at the buildings with a consumption certificate, significant premiums for above-average energy efficient buildings exist, too. This means that prospective tenants do find some value in the information communicated via the consumption certificate. The magnitude of some coefficients is smaller than for the requirement certificate. Further, a continuously decreasing trend is visible until the D rated building. Then, counterintuitively, the cold rent shows an increase again for a building with a consumption certificate. The findings for the buildings with a requirement certificate of the full interaction model can be explained in the same way as for the full categorical model: differences in negotiation power and a minimum cold rent as a floor value that can be achieved in a competitive market environment. However, this cannot explain the findings for the buildings with a consumption certificate. Here, EPC levels G and H are significant and show positive cold rent premiums of 1.6% and 1.9%. Two explanations come to mind: First, there might be an unobserved variable that is impacting the model results (e.g., an architectural design premium predominantly found in G and H rated buildings that have a consumption certificate). However, no indication for this exists and this explanation remains speculative. Secondly, prospective tenants might be more sensitive to the operational costs that must be paid rather than a small premium on the cold rent of a building. Thus, an owner could choose to decrease the operational costs allocated to the tenant while increasing the cold rent of the building. This could be part of a sales strategy that utilizes the price sensitivity of prospective tenants. While the higher cold rent might be achieved, it is conceivable that such a building will remain on the market for a longer time. Evidence for this exists for the German market (Cajias et al., 2019, p. 177). However, this is speculative and remains unclear with the data used in this analysis. Whether the assumption regarding the sales strategy holds any merit is discussed again when looking at the full interaction warm rent model results. It presents an interesting opportunity for future research. In conclusion, hypothesis 2 a) is partially supported as differences between EPC types exist. Evidence for this is the existence of significant premiums for above-average energy efficient buildings. The premiums exist for both EPC types but are larger for a building with a requirement certificate. No continuous discounts exist for energy inefficient buildings. Highly inefficient buildings (G and H rated) with a consumption certificate might even be priced higher to compete in a market with tenants that have become increasingly more green-aware and sensitive to operational costs.

Hypothesis 1 b) states that an increase in the energy efficiency of a residential building leads to an increase in its warm rent. To test this hypothesis, the different warm rent models ranging from the basic warm rent model to the full continuous warm rent model were specified. Following the normative logic that led to the formulation of this hypothesis, there should be no premiums or discounts present if only the energy savings or additional expenditures are capitalized into cold rents. If only the energy savings and additional expenditures are capitalized, then adding the respective operating costs to the cold rent would result in the same warm rent. If, additionally, investment costs are recouped to make the construction or the modernization of the building viable, there might still be premiums present for the above-energy efficient buildings. Signaling and prestige effects might be present that affect above-average and below-average energy efficient buildings. When looking at the results of the full categorical warm rent model, this is only partially supported. All EPC level coefficients are significant. For above-average energy efficient buildings, premiums exist that go up to 4.6%. This indicates that while a more energy efficient building has lower energy costs, its cold rent is increased by more than the savings achieved with the better energy efficiency. Two explanations appear plausible: First, highly energy efficient buildings might be able to utilize their image to generate prestige premiums. This might be caused by a subgroup of prospective tenants that value energy efficiency more than others, leading to scarcity and higher cold rents on the market. This is in line with literature that has found an energy efficiency premium connected to green awareness (Pommeranz & Steininger, 2021, p. 234). Secondly, the effect might be caused by the mentioned need of investors to recoup their investments more quickly. When building modernizations have taken place, it is allowed to raise rents to achieve this (§ 555 BGB). While this explains the results for the above-average energy efficient buildings, it does not explain the findings for the below-average energy efficient buildings. Here, small premiums are found, too. Based on the normative reasoning, they should not be present. This needs to be interpreted in the context of the full categorical cold rent model. There, the normative reasoning was not supported either. No continuous discounts were found. Thus, it seems logical that when no cold rent discounts for energy inefficient buildings are found that the warm rent is comparably higher because of an increase in energy costs. This increase should be linear, though, which is not found here. It levels off for the G and H rated buildings. Further interpretation requires the additional control for heterogeneity by the full interaction warm rent model. Before going into detail regarding this, it can be said in conclusion that hypothesis 1 b) is only partially supported. While significant warm rent premiums exist, there are no continuous discounts present. Counterintuitively, there are small premiums present for energy inefficient buildings.

The hypothesis 2b) states that based on the EPC type, an increase in the energy efficiency of a residential building leads to an increase in its warm rent. As already explained for hypothesis 2 a), there should be a difference visible between the requirement certificate and the consumption certificate caused by the difference in objectivity and perception of the calculated values. This is combined with the normative reasoning for the warm rent presented above. The resulting prediction is that there are warm rent premiums present for buildings with a requirement certificate, while it remains difficult to predict the results for a building with a consumption certificate. Looking at the model results, this is partially supported. Significant premiums greater in magnitude than in the full categorical model are found for a building with a requirement certificate and a building with a consumption certificate. They range up to 6.7% (A+ rating) for a requirement certificate and up to 5.0% (A+ rating) for a consumption certificate. The results for below-average energy efficient buildings are less clear. They are similar to the findings for the cold rent models. Significant premiums that remain small in magnitude are found for the requirement certificate for buildings rated E, F or H. This is the case even though there were no discounts for the cold rent. Based on the cold rent findings, there should be a linear increase in warm rents present for a building with a requirement certificate that shows the rising energy costs. However, this is not the case. The rents are a bit higher than the cold rents, but the findings seem inconclusive regarding this aspect. Three explanations exist: First, this might be additional evidence for the existence of the prebound effect that was mentioned in section 2.1 (Galvin, 2023, p. 502). Even though the objective energy requirements of a building are high, the actual consumption is much lower, not leading to higher energy costs and thus not leading to a higher warm rent. Second, the owner might financially offset some of the heating costs by not allocating all the other types of operating costs to the tenant to stay competitive in the market. Third: There is a systematic bias in the data because owners enter operating costs in the listings that do not include heating costs. The last one is a possible but rather speculative explanation. The most likely explanation is the first, as evidence for this effect has already been presented in literature. However, this explanation of the prebound effect does not hold true for a building with a consumption certificate. This is the case because the energy efficiency is calculated based on past consumption values that already include the occupant behavior that can cause the prebound effect. A linear increase in warm rent should be visible. Further, the premiums already present for energy inefficient buildings in the cold rent model should increase the magnitude of the warm rent premiums further. Thus, G and H rated buildings should see a disproportionate increase in warm rent. While there is an increase present, this increase flattens significantly for the G and H rated buildings. These values are significant, while the ones for E and F rated buildings are not significant. The findings are difficult to explain at first. However, the flattening of the values for G or H rated buildings is in line with the speculative explanation given for the cold rent results: The owner might be waiving specific operating costs while increasing the cold rent of the building to make up for the additional costs. These operating costs cannot be heating costs, as they are paid for by the tenant, but must be other operating costs. Whether this is true and whether the sensitivity of prospective tenants regarding cold rents is lower than for operating costs should be considered in future research. This would improve the understanding of pricing decisions made by market participants. In conclusion, hypothesis 2 b) is supported by the evidence as significant differences exist between the EPC types. This is shown by the difference in magnitude for above-average and below-average energy efficient buildings.

The impact of the energy efficiency of a building on its sales price

The final dependent variable that is considered is the sales price. Hypothesis 1 c) states that an increase in the energy efficiency of a residential building leads to an increase in its sales price. Following the reasoning from section 2.1, this is caused by an increase in cash flow and a decrease in the cap rate because of lower building-specific risk. When looking at the results of the full categorical sales price model, this is almost fully supported by the findings. Above-average energy efficient buildings show significant and large premiums of up to 7.0% (A+ rating). Further, inefficient buildings show significant discounts of up to -7.5% (H rating). Only EPC levels E and F are not significant, and the impact could be equal to zero. This indicates that an average level of energy efficiency (i.e., buildings rated D-F) does not significantly influence the sales price. Other hedonic characteristics seem to be more important for the buying decision. However, when a building is highly inefficient, prospective buyers realize that additional investments might be necessary shortly after purchasing the building, requiring discounts to account for this. In conclusion, hypothesis 1 c) is mainly supported by the evidence, but exceptions exist for the average of the current building stock where other hedonic characteristics might outweigh the impact of energy efficiency regarding purchasing decisions.

The final hypothesis to be evaluated is hypothesis 2 c) that states that based on the EPC type, an increase in the energy efficiency of a residential building leads to an increase in its sales price. The prediction of the hypothesis focuses on the perception of the different EPC types and the extent to which the values presented in them are trusted. It seems plausible that the requirement certificate is trusted more and thus shows a stronger relationship between sales price and energy efficiency while the consumption certificate is seen as not reliable because its values are influenced too much by previous occupants. Looking at the results of the full interaction sales price model, this hypothesis is supported by the evidence. The coefficients of all the EPC levels of the requirement certificate are highly significant. This is also the case for the ones that were not significant in the full categorical model. Further, the values show larger premiums for energy efficient buildings and larger discounts for energy inefficient buildings. Looking at the graph in Figure 8, the sales price of a building continuously decreases with the EPC categories that indicate lower energy efficiency. This shows that prospective buyers rationally account for differences in energy consumption and energy costs. Disproportionally large premiums and discounts are present for the A+ and H rated buildings. The additional premiums existing for A+ rated buildings might be caused by scarcity of such buildings on the market or by disproportionately high construction costs for such buildings. They thus achieve higher sales prices. The additional discounts for H rated buildings show that the building specific risk increases with higher energy consumption. This indicates that the risk of these buildings becoming a stranded asset might be relevant to the formation of their sales prices. Finally, the values found for the consumption certificate are considered. All coefficients, except the one for the A+ rating, are significant. Their magnitude is different from the ones found for a building with a requirement certificate. While it might be possible to detect a linear relationship when excluding the EPC level A+, the slope of this linear relationship is very small. The results indicate three things: First, buildings with a consumption certificate are generally valued lower than buildings with a requirement certificate. This is the case for all except for highly energy inefficient buildings, which show smaller discounts. One explanation could be as follows: Compared to a rental contract, the obligations agreed upon in a sales contract are several factors greater. Additionally, the buyers might become the occupiers of the building. Combining both aspects makes uncertainty become an important factor. It seems plausible that prospective buyers see greater uncertainty in a consumption certificate than in a requirement certificate. Thus, the values are not trusted and the impact on sales prices limited. The general uncertainty is compensated for by a discount when compared to the average D rated building with a requirement certificate. Second, the values presented in a consumption certificate are generally seen as less objective and more dependent on occupant behavior. This is also relevant when comparing two buildings that both have a consumption certificate. They are both priced similarly in the middle of the scale (C-G). Prospective buyers are probably of the opinion that any shift in this area might be caused by behavior. This leads to the situation that potential differences in energy consumption and energy cost are not included in the sales price. Third, the top and bottom end of the energy efficiency scale show disproportionally large premiums and discounts that were already found for buildings with a requirement certificate. The explanation behind these values remains the same: scarcity on the one hand and building specific risk on the other. Even though these extreme values are measured using a consumption certificate, they seem to be indicative for the energy efficiency of the building. Thus, some informational value is provided by the consumption certificate when extreme energy consumption values are displayed. Extreme values could indicate building characteristics beyond the impact of the occupant's behavior. In conclusion, the hypothesis 2 c) is supported by the results of the analysis. Significant differences exist between the impact of energy efficiency on the sales price of a building with a requirement certificate compared to a building with a consumption certificate. There are large and significant premiums and discounts present for buildings with a requirement certificate. Uncertainty and impacts of occupant behavior make buildings with a consumption certificate difficult to value, leading to moderate discounts for most buildings and limited impacts at the upper and lower end of the scale. While there is a clear linear relationship with extreme values at both ends of the scale for a building with a requirement certificate, there is a much weaker relationship found for a building with a consumption certificate.

Limitations of the present study

When it comes to the generalizability of the results found in this paper, there are several limitations that need to be considered: First, the data used for the analysis only consists of observations from the Rhein-Main Region. This means that the validity of results is greatest for the Rhein-Main Region. For other regions in Germany, the results can be seen as a benchmark value to consider but should not be used as is for quantitative assessments such as profitability computations. The same is true for the usage or comparison of these values on an international level: Within the EU, the implementation of the EPC is different. Beyond the EU, there are other proxies used to measure energy efficiency. Thus, as explained in the literature review, the findings do not establish causality, but are guidance regarding the development of the industry. Second, the limitation of using listings and not actual transaction data should be mentioned again. This was discussed in section 3.2. Third, the data sample is limited by the time period considered. Data were collected starting from 01/2015. Thus, a long time period is considered. Using data only from the first or last years might lead to different estimates. An analysis focusing on the development of the impact of energy efficiency on residential buildings over the years is an interesting topic for future research. Fourth, a further data sample limitation is the information on control variables. This includes the level of detail for control variables (i.e., operating costs) and the problem of missing information resulting in a reduction of the sample size. Finally, the EPC type allocation might not be truly random. This could be caused by the relevant characteristics for allocation according to § 80 GEG. Identifying a subsample with a truly random allocation and no selection bias is another opportunity for future research.

Comparison of the residential markets of the Rhein-Main Region, Germany and the EU

Keeping the limitations above in mind, the results of this paper are now considered in the wider context of empirical literature. First, the results are compared to publications focusing on the German residential market. Next, they are compared to findings in different EU markets. The first evidence that was provided for the German market by Cajias and Piazolo (2013, p. 58) is barely comparable because of their elasticity measurement in percent and usage of other norms. If the values are transferred to a comparison between a D (115 kWh / (m^2 * a)) and an A+ (15 kWh / (m^2 * a)) rated building, no meaningful results are computed (Cajias & Piazolo, 2013, p. 53). Kholodilin et al. (2017) presented the first comparable evidence. The authors measured the linear impact of an increase in kWh / (m^2 * a). Cold rent decreases by -0.02% and the sales price by -0.05% for each additional kWh / (m^2 * a) of energy consumption (Kholodilin et al., 2017, p. 3231) . This is close to the findings of the continuous models in this paper. Each additional kWh / (m^2 * a) is estimated to decrease cold rent by -0.017% and the sales price by -0.038%. This is also in line with the decrease in rent of -0.017% per kWh / (m^2 * a) found by März et al. (2022, pp. 17–18). However, as already discussed, the continuous measurement understates the impact of energy efficiency because of its mainly non-linear impact on rents and sales prices. Cajias et al. (2019) analyzed the impact of energy efficiency using the EPC rating as a categorical variable. Their analysis using a large sample for all of Germany found much lower premiums for the rental market than the ones in this paper. The 0.9% found by Cajias et al. (2019, pp. 186-187) are much lower than the cold rent premiums of 8.8% and 7.1% found by this paper when controlling for the EPC type. This may be explained by the different time periods investigated and the competitive residential market of the Rhein-Main region. However, more recent literature for the rental market presented by Groh et al. (2022, pp. 104–107) also found lower values with premiums of 3.98% for an A+ building compared to a G or H rated building. Sales price values found by Taruttis and Weber (2022) are closer to the ones in this paper. They estimated a premium of 6.9% for a decrease of 100 kWh / (m^2 * a) in energy usage (Taruttis & Weber, 2022, p. 6). The 6.9% are close to the sales price premiums of 5.4% and 7.4% found in this paper when comparing an A+ rated building to a D rated building and controlling for the EPC type. The remaining papers regarding the German residential real estate market focus on integrating additional factors in their models. Pommeranz and Steininger (2021) analyzed interaction effects with data on purchasing power and green awareness of inhabitants. They found a difference of 8.6% for the rental market between an A+ and H rated building (Pommeranz & Steininger, 2021, p. 235). Galvin (2023, p. 501) introduced the differences between EPC types in a more elaborate way than before by considering the prebound effect and comparing the theoretical savings to actual savings. However, here, the continuous encoding of the energy efficiency variable was used in the model (Galvin, 2023, p. 510). The variable was log-transformed, and the results are similar to the ones found for the full continuous model in this paper. When transforming the absolute values found by Galvin (2023) to percentage values using his descriptive statistics of the average building, a decrease of -0.035% is found for each additional kWh / (m^2 * a) while the estimate of the continuous model in this paper is -0.038%. Finally, the results in this paper are compared to Deller (2022, p. 802), a study that analyzed energy efficiency premiums within the same region. However, only general energy efficiency premiums were presented, and the data samples used were much smaller than the ones in this paper (Deller, 2022, p. 802). When looking at the findings, they are comparable to the ones found for the full categorical models in this paper. While the functional form of the coefficients is similar, the magnitude of the premiums for an A+ rated building is greater in this paper for the cold rent model (7.0% compared to 5.8%) and warm rent model (4.6% compared to 3.9%) (Deller, 2022, p. 802). While almost identical premiums for an A+ rated building in the sales market exist (6.9% compared to 6.8%), larger premiums for a B rated building are found in the present study (B: 3.1% compared to 1.5%) (Deller, 2022, p. 802). Additionally, the findings in this paper show greater significance, which is likely caused by the increase in the data sample sizes (Deller, 2022, p. 818). In sum, the results of the present analysis extend and confirm the earlier results of Deller (2022).

Overall, the comparison with literature for the German market indicates that the values found for the continuous models are similar, while the ones found for the full categorical models and the full interaction models are comparably high. Especially the full interaction model shows larger premiums and discounts in comparison. This might point to the aspect that controlling for heterogeneity in the data is crucial. Further, future research should use the categorical variable of the EPC rating to capture the non-linear form of the impact of energy efficiency on the dependent variables. It should follow the literature by setting the reference category to D.

While the estimates found in this paper are comparatively large for the German market, this is not the case when compared to other EU countries. Higher sales price premiums have been found for the most energy efficient buildings when compared to D rated buildings in the Netherlands (Brounen & Kok, 2011, p. 175), Ireland (Hyland et al., 2013, p. 948 – 949) and Wales (Fuerst, McAllister, et al., 2016, p. 26). Evidence of large sales price discounts for highly inefficient buildings was also found in Wales (Fuerst, McAllister, et al., 2016, p. 26). Still, the discounts found using the full interaction sales price model in this paper are even larger for the worst buildings with a requirement certificate (H rating: -10.2%). When comparing the full continuous sales price model with findings on the EU level, they are quite similar. Högberg (2013, p. 256), for example, found a decrease of -0.04% for each additional kWh / (m^2 * a) in Stockholm, Sweden.

It becomes evident that differences between EU countries might exist. Several reasons make this seem plausible: First, the EPC is implemented in a different way in each country. Technical differences in computation methods or cut-off points for the EPC ratings could lead to differing results. Sweden, for example, does not have the EPC rating A+ and starts with A (Boverket, 2023). Second, energy costs are significantly different in the EU countries (Eurostat, 2023a). This would, based on the normative reasoning of capitalizing energy savings, lead to different impacts of the energy efficiency level on the valuation of a residential property. Third, average house prices are significantly different (Deloitte, 2023, p. 32). This is especially true for metropolitan regions such as Paris for example (Deloitte, 2023, p. 19-20). As the impact is mostly measured in percentage values, this leads to different outcomes. Fourth, refurbishment costs are not the same in different EU countries (CBRE, 2021, p. 24). The need to invest into energy efficiency improvements can decrease the value of a property (Högberg, 2013, p. 256). Thus, if these improvements are relatively more or less expensive, this leads to differences in discounts. This might also be an explanation for the large discounts found in the German market compared to other markets. In conclusion, major differences between EU markets exist that might be caused by the implementation details of the EPC or differing local market conditions.

6. Conclusion & outlook

The analysis in this paper sets out to present new evidence that can help answer two overarching questions: How does energy efficiency impact residential real estate economics? What role does the EPC type of a building play? These two questions are considered within the regional scope of the

Rhein-Main Region in Germany. Six different hypotheses are defined and tested. These six hypotheses focus on the impact of energy efficiency of buildings on the three dependent variables cold rent, warm rent and sales price. They are analyzed using two different data samples. The first data sample contains 212 167 observations and is used to test the impact on the cold rent and warm rent, while the second data sample contains 159 573 observations and explores the impact on the sales price. Hedonic price models are defined using various building characteristics ranging from energy efficiency in kWh / (m^2 * a) to building size and availability of elevators. The results of the models show that above-average energy efficient buildings can achieve premiums for cold rents (EPC rating A+ compared to D: 7.0%), warm rents (EPC rating A+ compared to D: 4.6%) and sales prices (EPC rating A+ compared to D: 6.9%). When taking the EPC type into account, these effects become even stronger (EPC rating A+ compared to D: 8.8%, 6.7%, 7.4%, respectively). This does not hold true for a building with a consumption certificate that is for sale. Compared to an average building with a requirement certificate, such a building shows a significant discount. Considering a building that is below-average in energy efficiency, further differences exist. Below-average energy efficient buildings show no continuous discounts for cold rents leading to comparatively higher warm rents. This effect is even stronger for buildings with a consumption certificate. Sales prices for below average buildings with a requirement certificate show large discounts (EPC rating H compared to D: -10.2%). Buildings with a consumption certificate only show limited sales price discounts (EPC rating H compared to D: -4.9%).

The contribution of this paper to the literature is threefold: First, new evidence regarding the existence of energy efficiency premiums in the rent and sales market is presented. The evidence is based on data samples stretching across a time period of 8.5 years. This supports the conclusion that these energy efficiency premiums exist across longer time periods. Secondly, it presents the first detailed evidence of energy efficiency premiums based on EPC types for the German rental market. It shows the importance of occupant behavior regarding operating costs and warm rents. Third, it provides evidence on the difference in perception of EPC types in the sales market. It is shown that requirement certificates are seen as objective while consumption certificates bring only limited value to prospective buyers. Additionally, interesting new research opportunities are identified. Their exploration will help to better understand the heterogeneity of energy efficiency premiums in the future.

The question that remains is how the new evidence fits in with the challenges of the current status quo in the building sector. Two core challenges currently are i) the provision of enough suitable living space via new buildings or refurbishments and ii) getting the overall building stock in line with industry emission targets. While no holistic answer to these questions can be given, implications for different building sector stakeholders can be derived. These include current and prospective owners and tenants, service providers in the building sector and policy makers. The implications are as follows:

- Owners can achieve a higher cash flow by increasing the level of energy efficiency of a building (C or better) while a floor price for cold rents protects them from a potential cash-flow downside for an energy inefficient building (D-H).
- Owners can in general increase the sales price of a building by improving its energy efficiency. The energy efficiency level should be shown with a requirement certificate.
- Owners of highly inefficient buildings issued with a requirement certificate should consider improving their energy efficiency to protect them from large sales price discounts and future downside risk.
- Prospective tenants looking for the most economical choice should primarily consider a building with a requirement certificate that is rated D-G. They should be aware that their consumption behavior is relevant when renting a building with a requirement certificate. This is less the case for a building with a consumption certificate.
- Policy makers should rethink the way the EPC types in Germany are implemented. One suggestion would be to retire the consumption certificate while at the same time adding additional information on the requirement certificate that is indicative of actual consumption (i.e., including a 95% corridor based on average real-world values).
- Service providers in the real estate industry should focus on solutions that can create the most value at scale with the least investment. One suggestion would be to consider G and H rated properties with a requirement certificate and increase their efficiency to a C or D rating. This could present a substantial market opportunity.

The presented implications are formulated based on the evidence found in this paper. It should be noted that the evidence in itself is no proof of causality. The implications represent an academic perspective on real estate valuation but cannot give a general answer regarding the viability of business models or development projects. Thus, as a next step, the evidence should be used by the mentioned stakeholders to develop an overarching building sector transformation strategy. One approach could be along the following lines: First, the profitability analyses of new building projects and refurbishment initiatives should be adjusted by integrating the found values. Next, an indicative ranking should be drafted that shows which of the initiatives is most effective and cost efficient when it comes to increasing energy efficiency across the overall building stock. Finally, the mentioned stakeholders should focus on enabling these initiatives top-down together.

The importance of this transformation being led by a coalition of stakeholders seems to be difficult to overstate. Once the key levers are identified from a physical and construction perspective and their cost efficiency has been determined, it will be necessary to streamline administrative and approval processes and provide funding at a reasonable cost. Additionally, it will be crucial to communicate the importance of these initiatives effectively to the public as they will be directly affected as tenants or owner-occupants.

Together, the described implications and the next steps might support the progress needed to face the monumental challenge of creating energy efficient living space at socially acceptable costs. It seems plausible that energy efficiency will become an even more important aspect of residential real estate valuation in the future. The magnitude of this effect in the long term will be determined by the decisions of the stakeholders made in the next few years. The differentiation is likely to increase should factors such as scarcity of newly built energy efficient buildings and high costs of refurbishments last. Once these factors are improved or the levels of energy costs decrease, differentiation between buildings with different levels of energy efficiency will likely decrease. Further research on how this is achievable within the existing time frame defined by the building sector decarbonization pathway is urgently needed.

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