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The Economic Upside of Green Real Estate Investments: Analyzing the Impact of Energy Efficiency on Building Valuation in the Residential Sector

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Abstract

The rising sustainability awareness will affect the carbon-intensive European real estate industry and will force it to adapt to meet climate targets. The purpose of this thesis is to examine whether the energy efficiency of buildings plays a role in the valuation of buildings in the residential sector in the Rhein-Main Region in Germany. This is done by looking at the impact of energy performance certificates of buildings on their rent and sales prices. Data from publicly available real estate advertisements for the years 2019-2020 are analyzed using hedonic regression models. The rent market analysis (N = 44 442) finds significant cold rent premiums of 5.82%, 2.04%, 3.06% for A+, A and B rated buildings compared to the reference level of D. Significant warm rent premiums of 3.86% and 1.98% are found for A+ and B rated buildings. No significant discounts are found for buildings rated below D for cold and warm rents. The sales market analysis (N = 31 426) shows significant premiums of 6.81%, 3.14% and 1.52% for A+, A and B rated buildings, a range of indifference with no premiums or discounts for C to F rated buildings and discounts of -1.73% and -8.80% for G and H rated buildings. The results show that high energy efficiency of buildings creates significant value for investors.

Keywords: Real estate investments; real estate valuation; green buildings; energy efficiency; sustainability.

1. Introduction: Why sustainability matters for the real estate industry

During the last couple of years, climate action has been at the top of the agenda in society, politics and in the economy. Different industries are being shaped by this trend. For example, consumer brands such as Adidas are now selling shoes made out of plastic waste collected from the ocean,[1] the search engine Ecosia supports reforestation around the globe[2] and corporations such as Apple Inc. have published their own targets regarding carbon emissions.[3]

In the field of finance, sustainability aspects have been gaining attention as well. The new field that has emerged is broadly called sustainable finance and comprises all market participant behavior taking sustainability issues into account when making decisions.[4] Further distinctions can be made depending on the objectives of the actors involved. Green Finance, for example, "(...) can be understood as financing of investments that provide environmental benefits in the broader context of environmentally sustainable development."[5] The assets under management in responsible investment funds have increased significantly in the past years in Europe.[6] This reflects the overall increase in demand regarding sustainable assets.

Additional to the increase in demand of sustainable assets, in September 2020 the European Commission announced the plan to adjust the EU climate action target for 2030. The aim to reduce greenhouse emissions will be increased from 40% to 55% compared to the levels of 1990.[7] The climate action targets in general and this additional increase in greenhouse gas reductions by 37,5% are likely to shape future policies and regulations and therefore all industries. The magnitude of the impact this has on different industries depends on their emissions. One very emission in-

[1] Cf. Morgan (2020).
[2] Cf. Eschment (2020).
[3] Cf. Kelion (2020).
[4] Cf. Federal Ministry of Finance (2020).
[5] Ma, Sheren, and Zadek (2016, p. 3).
[6] Cf. KPMG Luxembourg (2019, p. 9).
[7] Cf. European Commission (2020b, p. 1).

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tensive industry is real estate. According to the 2018 Global Status Report of the Global Alliance for Buildings and Constructions, the real estate industry is responsible for 40% of all energy-related carbon dioxide emissions worldwide.[8] To reduce emissions caused by this sector in Europe, the European Commission has published its Renovation Wave Strategy in October 2020. The aim is to double the current rate of renovation in Europe and increase energy efficiency of buildings.[9] For regulators and industry participants it is crucial to understand the implications of such policy changes. Thus, the current market situation and its response to regulations should be examined. When combining the continuous policy changes with an increased demand for responsible investments, the question arises whether and how energy efficiency changes the valuation of a building. Further, it is relevant to determine whether theoretical adjustments to building valuation can be supported by empirical evidence from real estate market data. Answering the first question lays the theoretical groundwork of this research, while the second question is answered by its empirical findings. The empirical analysis is focused on the regional residential real estate market of the Rhein-Main Region in Germany.[10]

This thesis paper is structured as follows: In section 2, the theoretical approach is discussed: Relevant valuation methods of buildings are introduced, the impact energy efficiency can have on building valuation is shown and a measure for energy efficiency is defined. Section 3 focuses on past research and points to areas where further analysis is needed. Section 4 explains the fundamentals of hedonic price models. In section 5, the data generating process and descriptive statistics are presented. This is followed by the specification of the hedonic models in section 6 and the presentation of the empirical results in section 7. The empirical results are discussed in section 8. The paper concludes with a summary of the main findings and an outlook on future market development and needed research in section 9.

2. Development of the theoretical approach & derivation of hypotheses

2.1. Definition of the thesis perspective, aim, scope and limitations

A sound theoretical approach and study design lay the groundwork for empirical research. Thus, in a first step, the perspective, the aims and the scope and limitations of the study are defined. The perspective analyzed in this paper is that of a real estate investor using equity to invest. Debt financing of real estate as well as mixed financing or other forms of financing are not considered. Financing decisions are assumed to be based on the risk approach of the investor. The factors influencing such decisions are outside the scope of this paper. Further, the research focus lies on single residential building valuation and not portfolio optimization. Additional factors, e.g. diversification aspects to reduce the uncertainty of an investment, come into play when realizing a portfolio of assets.[11] When applying portfolio optimization to real estate, the weight and importance of building characteristics might change. Thus, considering real estate portfolios instead of single buildings in the analysis would skew the measurement of the impact of energy efficiency on the valuation of a single building.

Real estate as an asset is bound to a certain location. Its valuation depends on the local market characteristics.[12] Therefore, the valuation of buildings needs to be a relative comparison between similar assets in the same location. Comparing absolute values between different locations does not appear to be meaningful. The same holds true when talking about premiums or discounts regarding the energy efficiency of buildings or describing other characteristics that are impacting the valuation of the building significantly. Thus, this paper focuses on the local market of the Rhein-Main Region in Germany, which is one of the metropolitan regions in Germany.[13] It is further assumed to be of considerable interest for real estate investors as this region is the financial hub of Germany. This position has been strengthened by the decision and subsequent process of the United Kingdom leaving the EU common market.[14]

Real estate transaction decisions of investors may also depend on taxes. As the focus of this paper is the actual valuation of the building, taxes are a not a part of the analysis. Further, tax laws can change at any given time. Using current tax regulation would make the analysis meaningful only until the next adjustments take place. Including other tax advantages that stem from e.g. the corporate structure used by an investor are beyond the scope of this analysis.

Summary of the scope of this thesis:

- real estate investor perspective with equity only
- single residential building valuation, no portfolio
- findings only applicable for local market in the Rhein-Main Region
- analysis does not consider tax laws

2.2. Summary of the fundamentals of real estate valuation

One of the first researchers to formulate a general theory on how to calculate the value of an investment was John Burr Williams. In his book “The Theory Of Investment Value” he states: “The purchase of a stock or bond, like other transactions which give rise to the phenomenon of interest, represents the exchange of present goods for future goods – dividends, or coupons and principal, in this case being the claim

[8] Cf. International Energy Agency and the United Nations Environment Programme (2018, p. 9).
[9] Cf. European Commission (2020a, p. 1).
[10] Cf. Statista Research Department (2021). The counties and urban districts listed here define this region for the whole thesis.
[11] Cf. Markowitz (1991, p. 470).
[12] Cf. Belke and Keil (2017, p. 17).
[13] Cf. Gesetz über die Metropolregion Frankfurt/Rhein-Main (MetropolG).
[14] Cf. Schleidt (2020).

on future goods. To appraise the investment value, then, it is necessary to estimate the future payments. The annuity of payments, adjusted for changes in the value of money itself, may then be discounted at the pure interest rate demanded by the investor."[15] In other words: the value of the investment today is equal to all future discounted cash flows produced by the asset. Williams applies this to stocks and bonds. The general underlying method of discounting future cashflows can also be applied to other cashflow producing assets such as real estate. How to apply the discounted cash flow (DCF) method to the asset class of real estate is described in detail by Baum and Hartzell (2021).[16] Based on this more recent publication, the relevant elements of this valuation method regarding real estate are summarized in this subsection. Next, it is discussed how energy efficiency can influence them. The theory and methods in this subsection are taken from Baum and Hartzell (2021)[17] if no other source is given. The price of an asset today based on the DCF method is defined by the following equation:

$$Price_0 = \sum_{t=1}^{T} E(CF_t)/(1+r)^t \quad (1)$$

The price in period zero is equal to the appropriate value of the asset. The value of t indicates the time period. This value ranges from t = 1 to T and defines the number of summands. The expected cash flow (CF) of a certain period is defined by E (CF_t). This value is then discounted by 1 plus the discount rate of the investor to the power of the time period to reflect the present value of the future cash flow. Based on this equation, two elements can be determined that are essential for determining the value of the asset for the investor:

- future cash flows
- personal discount rate

The future cash flow depends on two different inputs: income and capital.[18] Based on a combination of current data and forecast data, the aim of an investor is to make the most accurate estimation of both inputs that is possible. To conduct the calculation of the future cash flows in detail, the investment intentions need to be defined. This includes the holding period of the asset. Holding periods of buildings are theoretically unrestricted. What is important to note is that a shorter holding period results in a higher dependency of the return of investment on the sales estimate of the asset. Since the sales estimate is less predictable than rent revenue, risk may be increased with a shorter holding period.[19] After defining the investment intentions, the estimates regarding income and capital inputs are calculated. Factors such as the depreciation of the asset and the occurring expenses[20] need to be considered. The income input is defined by the lease rent. The capital input is the estimation of the resale price.

Relevant for the income input for the DCF calculation is the net operating income (NOI). Figure 1 shows how the NOI is calculated. The lease rent is the gross rental revenue and equal to the overall rent paid by the tenant. Other income is e.g. an additional parking space or storage unit let to the tenant. Together, this is equal to the gross potential income. Deducting the average vacancy rate results in the gross effective income. After the subtraction of the operating expenses, the result is equal to the NOI. Adjustments of the different elements used to calculate the NOI for future periods are based on forecasted data of rental value changes in the local market. The impact of the current lease is higher on the valuation of the building when the terms in the contract are longer and the tenant has rights to renew. Lease events that have a significant impact on the cash flow (e.g. early lease termination by tenant) and their probability need to be estimated.[21]

Gross rental revenue
+ Other income
= Gross potential income
- Vacancy
= Gross effective income
- Operating expenses
= Net operating income

Figure 1: Calculation of the net operating income (NOI)[22]

The estimation of the resale price becomes more difficult with a longer holding period. The most common method to calculate the resale price is the capitalization rate approach. This approach is defined by the following equation:

$$MV_T = NOI_{T+1}/cr_T \quad (2)$$

MV stands for the market value of the building in period T, the time period the building is sold. This market value is equal to the NOI expected in the year following the sale (T+1) divided by the capitalization rate at the time of the sale. The estimate of the NOI in the year T + 1 is based on factors such as rental growth and cost growth. Here, depreciation impacts the rental growth factor. The annual average growth rent rate can be calculated using the following equation:

$$Average\ growth\ rate\ per\ annum = (1+g)/(1+d) \quad (3)$$

[15] Williams (1938, p. 55).
[16] Cf. Baum and Hartzell (2021, pp. 109–157).
[17] Cf. Baum and Hartzell (2021, pp. 109–157).
[17] Cf. Baum and Hartzell (2021, p. 146).
[18] Cf. Baum and Hartzell (2021, p. 148).
[19] Cf. Baum and Hartzell (2021, p. 149).
[20] Some expenses occur regularly and need to be considered when calculating the income input. They can include management cost, repair and maintenance and service costs. Depending on the country, parts of these costs are carried by the tenants. Others occur at the beginning and end of the holding period of the building. The expenses when selling the building need to be subtracted from the sales price to reach a net cash flow estimate of the sales price.
[21] Cf. Baum and Hartzell (2021, p. 149).
[22] Cf. Baum and Hartzell (2021, p. 147).

In this equation, g stands for the rental growth rate of new buildings per annum, while d represents the asset specific depreciation rate. Using this, the NOI for T + 1 can be estimated using the current rent of the building.

The capitalization rate gives the expected return of investing in the building and can be calculated using the following equation:

$$K = RFR_R + i + Rp - (G_R + i - D) \quad (4)$$

K stands for the capitalization rate, RFR_R for the real risk-free rate, i for the expected inflation, Rp for the risk premium, G_R for the real rental growth and D for depreciation. To estimate these factors for time period T is more difficult than the rent estimation.[23] To circumvent this problem, the current capitalization rate applicable for the building is adjusted based on projections regarding the overall market capitalization rate and building specific capitalization rate changes due to depreciation.[24] This concludes the discussion of the most relevant aspects regarding future cash flows. Next, the discount rate is considered briefly.

The discount rate is also called target rate or hurdle rate in a real estate context.[25] It is the summation of the risk-free rate (e.g. interest rate on a three-month U.S. Treasury Bill) and the personal risk premium of the investor. This risk premium is a combination of:

- the property market risk premium
- the sector risk premium
- the location premium
- the asset premium[26]

The asset premium is influenced by the tenant, lease, location and building risk associated with the investment.[27] Combining all, the risk premium on average has a magnitude of around 2-5%.[28]

2.3. Impact of energy efficiency on building valuation & derivation of hypotheses

As described above, the DCF method has two main parts: the cash flow and the discount rate. In the following, both parts are examined separately regarding the effect energy efficiency could have on them. When looking at one specific factor, it is considered, ceteris paribus (c.p.), what happens when increasing or decreasing the energy efficiency. Based on the impact shown, hypotheses are formulated. These hypotheses are subsequently tested in the empirical part of this thesis using datasets from the residential real estate market of the Rhein-Main Region.

First, the cash flow is considered: Cash flow is separated into the income and the capital input. The income input is defined by the NOI. The derivation of the NOI was described in subsection 2.2. The lease structure will not be considered since it varies depending on the parties involved. Including effects of energy efficiency on other income and the vacancy rate are beyond the scope of this thesis.[29] They present interesting topics for future research.

The income input is looked at first: The gross effective income (GEI) is the warm rent paid by the tenant without deducting any costs. This warm rent is divided into the cold rent of the apartment and all the allocable costs. If the energy efficiency of a building is increased, this will result in a decrease in heating costs and thus operating costs. Since these costs are allocable costs, they will reduce the warm rent paid by the tenant, which is a decrease in GEI. The NOI stays the same and therefore the income input does not change. In this scenario, solely the tenant experiences the benefit of higher energy efficiency with the investor remaining indifferent. Such a scenario appears to be unlikely in a rational market environment. Since the tenant's willingness to pay has not changed, it is likely that the tenant is willing to pay the same total expenses, i.e. the same warm rent, for housing. Following this argument, an increase in energy efficiency will lead to an increase of the cold rent while the warm rent stays the same.[30] This scenario means that energy cost savings are capitalized fully into the rent. Whether a 100% capitalization of energy cost savings is possible in all market environments is an interesting question that should be addressed in the future, since the percentage of capitalization may depend on the relative market power of tenant and landlord and may be different between local markets. Answering this question is an opportunity for future research. Going back to the calculation of the NOI, a 100% capitalization means that there is no change in GEI. The operational costs, however, would be decreased. This would lead to a higher cold rent or NOI. As the NOI is the basis for the income input, an investor should value the building higher. Decreasing the level of energy efficiency of the building would lead to the opposite effect. The first hypothesis that can thus be derived from these deliberations is: Net operating income (NOI) is – c.p. – higher for a more energy efficient and lower for a less energy efficient residential building and the valuation of the building is increased or decreased respectively.

The arguments above only included capitalization of energy savings and did not require a higher willingness to pay by the tenant, i.e. it is assumed that tenants are indifferent to the energy efficiency of a building and make decisions solely based on warm rent. A question that arises is whether tenants are willing to pay a higher rent for more energy efficient real estate based on the public opinion shift regarding climate change in the past years.[31] This would mean that addi-

[23] Cf. Baum and Hartzell (2021, p. 136).
[24] Cf. Baum and Hartzell (2021, p. 150).
[25] Cf. Baum and Hartzell (2021, p. 153).
[26] Cf. Baum and Hartzell (2021, p. 153).
[27] Cf. Baum and Hartzell (2021, p. 153).
[28] Cf. Baum and Hartzell (2021, p. 154).
[29] Thus, vacancy rate and other income are assumed to be zero. The gross rental revenue equals gross effective income in the remainder of the thesis.
[30] Cf. Cajias and Piazolo (2013, p. 56).
[31] Cf. Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit

tionally to the monetary savings because of a decrease in energy expenses, a utility for the tenant that is derived from the knowledge of living in a more energy efficient building can be identified.[32] Further, it could also be the case that signaling effects influence this market behavior: Tenants may want to show their awareness and personal commitment to other people. This increase in willingness to pay for a more energy efficient building might lead to a higher cold rent (equivalent to NOI).[33] This increase in NOI would not be compensated by a decrease in operating costs. Thus, it would c.p. lead to a higher GEI. The opposite would be true for a less energy efficient building. The tenant's willingness to pay would decrease. The second hypothesis that can be formulated based on this is the following: Gross effective income (GEI) is – c.p. – higher for a more energy efficient and lower for a less energy efficient residential building.

Next, the capital input is considered: The capital input is the estimated resale price at the end of the holding period of the building. The question is whether this resale price is also affected by an increase or decrease in energy efficiency of the building. The resale price is determined by the NOI of T+1 and the capitalization rate of T. As the first hypothesis states that an increase/decrease in energy efficiency will increase/decrease the NOI, the same must apply for the resale price when keeping the capitalization rate the same. Based on this, the third hypothesis is: The resale price is – c.p. – higher for a more energy efficient and lower for a less energy efficient residential building.

Finally, the discount rate needs to be considered: The discount rate is comprised of the risk-free rate and the personal risk premium of the investor. The risk-free rate cannot be influenced by building characteristics. Therefore, this rate is kept fixed in the following. One part of the personal risk premium of the investor on the other hand is made up of the asset premium. This premium is defined by the building characteristics. The question arises what happens to the asset premium when the energy efficiency of the building is increased/decreased. As public pressure and response from regulators regarding energy efficiency in the real estate sector has increased over the past years, even more extensive changes in regulation are to be expected as we near the emission goals of 2030 and eventually 2050 in the EU and worldwide. Changes such as the ban of oil as heating source may cause a sudden depreciation of assets equipped with oil heating. Whether such an event seems probable to the investor should be reflected in the asset premium and therefore the discount rate. Based on this, it seems reasonable to propose that less energy efficient buildings show an increased asset risk premium.[34] The asset risk premium is also a part of the equation (4) that defines the capitalization rate. Thus, the discount as well as capitalization rate should be higher for less energy-efficient real estate. The opposite should be true for more energy efficient buildings. Combining this with the hypotheses from above, the valuation of the building would increase more than the NOI. This leads to the fourth hypothesis: The market value is – c.p. – higher for a more energy efficient and lower for a less energy efficient residential building and the increase/decrease is proportionally bigger than the increase/decrease in NOI.

In hindsight, it needs to be reflected on hypothesis three and four. Hypothesis three considers the estimate of the resale price of a building. This in itself is a building valuation and therefore is hypothesis three similar to hypothesis four. An important difference is the point in time of the two valuations: The resale price is an estimation of the future market value of the building at the end of the holding period. It can only be estimated today. The market value formulated in hypothesis four is the current market value of the building. Should hypothesis four be supported, then hypothesis three would also be supported because a decrease in the discount rate and thus also a decrease of the capitalization rate has taken place. This means that only hypotheses one, two and four need to be examined. In summary, the hypotheses that will be addressed in this paper are:

A. Net operating income (NOI) is – c.p. – higher for a more energy efficient and lower for a less energy efficient residential building and the valuation of the building is increased or decreased respectively.

B. Gross effective income (GEI) is – c.p. – higher for a more energy efficient and lower for a less energy efficient residential building.

C. The market value is – c.p. – higher for a more energy efficient and lower for a less energy efficient residential building and the increase/decrease is proportionally bigger than the increase/decrease in NOI.

2.4. Assessment of the energy performance certificate as indicator for energy efficiency

Defining the energy efficiency of a building in a comparable, reliable, and accurate manner is an important basis for this research paper. Additional aspects that need to be considered are the size of the empirical sample as well as data availability.

Throughout the literature, there is a usage of formal certificates as a basis for such analyses.[35] These certificates differ regarding the focus of examination. There are certificates like the Leadership in Energy and Environmental Design (LEED) and the Building Research Establishment Environmental Assessment Methodology (BREEAM) that consider the overall sustainability of a building.[36] A different certificate, the European Energy Performance Certificate

und Verbraucherschutz and Bundesumweltamt (2020). The significant shift regarding environmental and climate awareness can be seen in 2018 compared to 2016. Thus, for the remainder of this thesis, all data starting with 01/2018 is regarded as capturing this shift in awareness. All data before 01/2018 is seen as not being able to capture this shift in awareness.

[32]Cf. Cajias and Piazolo (2013, p. 189).

[33]Cf. Cajias and Piazolo (2013, p. 56).

[34]Cf. Leopoldsberger, Bienert, Brunauer, Bobsin, and Schützenhofer (2011, p. 117).

[35]Cf. e.g. Fuerst, Oikarinen, and Harjunen (2016, p. 560). Brounen and Kok (2011, p. 169).

[36]Cf. U.S. Green-Towers Sustainable High-Rises GmbH (2021). Building Research Establishment Ltd (2021).

(EPC), focuses exclusively on the energy consumption of the building.[37] The EPC was first introduced in Europe in 2002 by the EU-Directive 2002/91/EC. The legislation regarding the EPC was changed again in 2010 by the EU-Directive 2010/31/EU to make the use of EPCs mandatory in advertisements when selling or leasing a building. In 2018 EU-Directive 2018/844/EU was amended, aiming to increase transparency and consistency of the national calculation methodologies. As this study focuses on data in the Rhein-Main Region in Germany, the respective German EPC, the "Energieausweis", is used.

Comparability: Since the EPC is based on a directive by the European Commission, member states of the EU must pass their own laws regarding its implementation.[38] Thus, data from different EU countries cannot be directly compared or combined into one dataset. Within Germany, however, the EPC is the same making it possible to compare different buildings within this country. Another point of critique is that the average climate of Germany is used for the energy consumption needs calculation.[39] This means that regions above and below the average will have a de facto energy consumption that differs from the one calculated using the rules of the EPC. This limits comparability between regions, at least between those of different climate zones. As we are only looking at data from the Rhein-Main Region, which is assumed to be one climate zone, this aspect can be disregarded.

Reliability: According to the "Gebäudeenergiegesetz" (GEG) and the previously applicable "Energieeinsparverordnung" (EnEV) in Germany, only people with specific training and professional experience are allowed to perform the assessment for an EPC. The GEG lists all requirements such a person has to meet before being considered qualified.[40] Examples include engineers, architects, physicists and craftsmen. No official accreditation is needed to perform an EPC assessment. Based on this, a general reliability between specialists assessing a single object is assumed. Differences in the result caused by people-specific errors cannot be excluded though. For the purpose of this study, it is assumed that the error term in the calculations caused by this human error is evenly spread across the sample. In this case, this error will contribute to the spread of the data but will affect neither average values nor the overall empirical results. Of note, whether this assumption is true cannot be ascertained using the empirical data available.

Accuracy: The calculation performed regarding the energy efficiency of a building is based on the usable floor space and not the living space. Additionally, warm water is sometimes not included if a building does not heat water locally and two methods of calculation within Germany exist that can lead to different values for the same building.[41] These aspects show that the energy consumption value of a building has to be judged in a broader context. This context cannot be explored in this paper because of data limitations. However, this kind of data accuracy may not be needed for the present analysis, as decisions made by the tenant or buyer are likely between similarly constructed and measured buildings.

Data availability: According to the GEG and EnEV, all owners of a residential building must provide an EPC to prospective tenants or buyers.[42] They also must include certain metrics such as the energy consumption amount of kwh / m^2 per annum in a real estate advertisement.[43] Some exceptions to these rules exist. But it can be said that most sale as well as lease offers in the past years should have an EPC available.

In sum, the EPC is a widely used framework allowing the classification of buildings in Germany based on their energy efficiency. The way of calculating the energy-consumption needs of a building has not changed significantly in the past years.[44] This shows the consistency of the certificate. Although there are points that can be criticized, the EPC is the only widely used and available measure of energy efficiency in the residential as well as other building sectors in Germany that could be identified. The EPC is consequently not a perfect but a reasonable proxy measurement for the energy efficiency of a residential building in Germany and can be used as a data source for this research.

3. Review of the extant literature

During the last ca. fifteen years, the research field examining the effects of energy efficiency or - in a broader sense - sustainability of buildings on their sales and rent performance has gained momentum. In this section, the extant literature will be discussed taking into account the following aspects:

- time period analyzed
- location of the real estate market
- building sector
- proxy used to measure energy efficiency
- whether sales or rent prices are considered

In the literature, the sales or rent prices are defined as the dependent variables and analyzed using hedonic regression models.[45]

In the research field of "sustainability and real estate", five comprehensive literature reviews were published recently. Of these five, two have been published in academic

[37] Cf. EU-Directive 2010/31/EU, Article 2, No. 12.

[38] Cf. Communication department of the European Commission (2020).

[39] Cf. Verbraucherzentrale Nordrhein-Westfalen and Verbraucherzentrale Rheinland-Pfalz (2020).

[40] Cf. GEG, §77. EnEV, §21.

[41] Cf. Verbraucherzentrale Nordrhein-Westfalen and Verbraucherzentrale Rheinland-Pfalz (2020).

[42] Cf. GEG, §80. EnEV, §16.

[43] Cf. GEG, §87. EnEV, §16a.

[44] Cf. Verbraucherzentrale Nordrhein-Westfalen and Verbraucherzentrale Rheinland-Pfalz (2020).

[45] Cf. e.g. Wahlström (2016, p. 201). Kholodilin, Mense, and Michelsen (2017, p. 3223). Hyland, Lyons, and Lyons (2013, p. 945). Only a few examples from the academic literature. Others also use this method.

journals,[46] another one is a conference paper[47] and the last two are working papers.[48] All of them support the hypothesis that a price premium for sustainability certificates or energy efficiency of buildings exists.[49] Of note, the magnitude of the price premium significantly depends on the aspects mentioned above like building sector (e.g. commercial or residential) and location.[50] This is the case within as well as between the literature reviews: Ankamah-Yeboah et al. (2014) find a global average price premium of 7,6% for buildings with some form of energy certification.[51] Fizaine et al. (2018) conclude that a premium between 3.5% and 4.5% is present in the literature when controlling for publication bias.[52] Brown and Watkins (2016), only looking at the sales prices in the residential real estate sector, report a mean weighed premium of 4.3%.[53] This is very close to the global premium of 4.2% found by Cespedes-Lopez et al. (2019) for sales prices in the residential real estate sector.[54] As these analyses are based on different studies (15 studies used by Kim et al. (2016)[55] compared to 66 studies used by Cespedes-Lopez et al. (2019)[56]), their data and conclusions cannot be directly compared. This limitation as well as the limitation regarding the accumulated price premiums in the literature reviews was formulated by Cespedes-Lopez et al. (2019) in the most recent literature review published in an academic journal:

"This document is useful in order to understand the current behavior on a global level. However, it has certain limitations due to combining data from distinct studies that are influenced by geographic area, type of qualification used, etc. Therefore, the results should be considered within the context of the analyzed documents and not as evidence of causality."[57]

Thus, it is important to, in a specific manner, define and then identify the space of the relevant academic literature based on the key aspects mentioned above.

This thesis focuses on the most recent (time period) impact of energy efficiency (proxy) on the sales and rent prices (dependent variables) of residential buildings (building sector) in the Rhein-Main Region of Germany (location). Using these parameters as a filter, the body of literature pertinent for this thesis decreases significantly. Three studies published in academic journals remain when relaxing the aspect "time" completely and the aspect "location" from the Rhein-Main Region to all of Germany.[58] The remaining publications all show that a price premium is achieved for more energy efficient buildings.[59] As the context of each study is relevant to understand the findings, a detailed review of these studies is needed to show where additional research can add insights.

Cajias and Piazolo (2013) examined the impact of energy efficiency of residential buildings on their financial performance using data from the German Investment Property Databank (IPD) ranging from the year 2008 until 2010.[60] Of note, this was the time period right after the global economy was hit by the real estate credit crisis. An important aspect of this crisis was investors quickly switching to high-quality and low risk assets in the USA. This led to a significant credit spread of commercial mortgage-backed securities and consequently to a dry up of the loan sector to nearly zero in 2008. The same had generated loans of 230 billion USD in 2007.[61] The consequence of this development was a global capital shortage.[62] The question arises in how far the underlying market conditions of this time period and therefore the findings of the study can be applied to the markets of today. Another time-related aspect of the data is the national standard regarding the levels of energy efficiency in housing. Cajias and Piazolo (2013) state that up to 200kWh, significant rent premiums can be achieved.[63] Since then, the energy classification has been revised. Today, according to the GEG, the G standard of the German EPC starts at 200kWh. This indicates that there has been a significant shift towards more energy efficient buildings that could also have had an impact on the price premium being achieved on the market. The following calculation underscores these considerations: Cajias and Piazolo (2013) state in their paper: "The hedonic results additionally show that one percent energy conservation boosts rent prices by +0.08 percent and market value by +0.45 percent, ceteris paribus."[64] For the housing and the energy standard of today, this statements needs verification, since the difference between a bad performing C rated building (100kWh/(m^2a)) and a bad performing A rated building (50kWh/(m^2a)) is equal to an energy conservation of 50%. Thus, according to Cajias and Piazolo (2013), the market value of the A rated building should be 22.5% higher than that of the C rated building. This estimate seems very high and the question arises whether results based on current data can corroborate these results for present times.

Kholodilin et al. (2017) examine the capitalization of energy savings in rent and sales prices in the regional resi-

[46] Cf. Cespedes-Lopez, Mora-Garcia, Perez-Sanchez, and Perez-Sanchez (2019). Fizaine, Voye, and Baumont (2018) – of note: journal with low impact factor.
[47] Cf. Kim, Lim, and Kim (2016).
[48] Cf. Ankamah-Yeboah, Rehdanz, et al. (2014). Brown and Watkins (2016).
[49] Cf. Ankamah-Yeboah et al. (2014, p. 20). Brown and Watkins (2016, p. 2). Cespedes-Lopez et al. (2019, pp. 53-54). Fizaine et al. (2018, p. 1033). Kim et al. (2016, p. 47).
[50] Cf. Fizaine et al. (2018, p. 1028).
[51] Cf. Ankamah-Yeboah et al. (2014, p.12).
[52] Cf. Fizaine et al. (2018, p. 1017).
[53] Cf. Brown and Watkins (2016, p. 2).
[54] Cf. Cespedes-Lopez et al. (2019, p. 1).
[55] Cf. Kim et al. (2016, p. 43).
[56] Cf. Cespedes-Lopez et al. (2019, p. 1).
[57] Cespedes-Lopez et al. (2019, p. 54).
[58] Cf. Cajias and Piazolo (2013). Kholodilin et al. (2017). Cajias, Fuerst, and Bienert (2019).
[59] Cf. Cajias and Piazolo (2013, p. 53). Kholodilin et al. (2017, p. 3234). Cajias et al. (2019, p. 189).
[60] Cf. Cajias and Piazolo (2013, p. 53).
[61] Cf. Baum and Hartzell (2021, pp. 60-62), for all statements regarding the real estate credit crisis.
[62] Cf. Baum and Hartzell (2021, p. 68).
[63] Cf. Cajias and Piazolo (2013, p. 67).
[64] Cajias and Piazolo (2013, p. 53).

dential real estate market of Berlin.[65] The data used in this publication stem from online housing portals and were collected from June 2011 until December 2014.[66] Although this is a more recent study compared to Cajias and Piazolo (2013), the current opinion shift regarding climate awareness is not yet included in their data. Furthermore, the focus is on Berlin, a regional market in Germany with local regulation limiting the rights of real estate owners: The Kündigungsschutzklausel-Verordnung protects tenants from eviction by owner-occupiers for a period of several years after purchase of the building.[67] The main insight generated by the study is that owner-occupiers and investors in rental buildings capitalize energy savings in sales prices.[68] For a rented building, where energy savings benefit the tenant, the financial savings are a 2.5 multiple of the investor's willingness to pay for a building with such savings, suggesting only a partial capitalization of energy savings in the form of increased rent.[69]

Cajias et al. (2019) examine data from 2013-2017 for all of Germany regarding the impact of energy efficiency (extracted from the EPC) on residential rent prices.[70] This enables them to differentiate between top tier markets such as Munich and Frankfurt and secondary markets. Here, they show that importance of energy efficiency is decreased in the top tier markets, potentially due to high demand and inelastic supply.[71] Another aspect relevant for investors that is introduced by the authors is "time on market" of the buildings. It is found that very energy inefficient buildings remain on the rental market longer.[72] Their study was performed with market data until 2017, which is also the period before the recent change in climate awareness. The question arises, whether we now see a stronger and more distinct premium in the rental market with current data. Further, their study only looks at rent prices. The question how energy efficiency affects the sales price of a building is left unanswered. A third aspect that needs to be considered is the perspective that was taken by the authors: Cajias et al. (2019) looked at the overall German market. They used location control variables and therefore minimized the noise between regions.[73] However, it is not possible to discern region-specific price premiums. Higher price premiums in regions where climate action is a priority for the public could exist compared to other regions where climate action is considered less important. Thus, the empirical results of the overall market analysis are interesting but only of limited use for investors, as investors have to consider local market characteristics and trends. Comparability of their study with the present study is limited since in the present study a region-specific analysis is performed.

The key takeaways from academic literature for the German residential real estate market are:

- rental and sales price premiums for energy efficient buildings are present [74]
- owner-occupiers and investors capitalize energy savings well in sales prices. The magnitude of capitalization, however, is different. This is because energy savings exceed the tenant's willingness to pay by a factor of 2.5 when looking at rent prices [75]
- tight rental markets decrease importance of energy efficiency, which has a greater effect on prices in non-metropolitan regions [76]
- very energy inefficient buildings remain on the rental market longer [77]

A brief expansion of the literature review to the European level seems reasonable since some studies also used the EPC as a proxy for energy efficiency. While doing so, it has to be kept in mind that different national implementations of the EU directive exist, limiting comparability.

Brounen and Kok (2011) performed one of the earlier studies on the residential real estate sector in Europe. Even after controlling for better quality of buildings and thermal characteristics, they found a sales premium of 10.2% for residential buildings with an A energy rating compared to D rated buildings.[78] Similarly, Hyland et al. (2013) in their study on the residential real estate market in Ireland reported a 9% sales premium and a premium of almost 2% in the rental market for properties of energy efficiency level A compared to D.[79] They further find that energy efficiency has a greater impact (almost double) in less liquid markets.[80] In Spain, de Ayala, Galarraga, and Spadaro (2016) find a sales premium of 9.8% for residential buildings that are rated in the A, B or C category compared to the rest.[81] As this is a block comparison, it's magnitude cannot be compared to the results of the other studies. This inconsistency in EPC levels used for comparison was already criticized by Cespedes-Lopez et al. (2019), as it was one of the reasons why the findings of their meta-regression for Europe were inconclusive.[82] Another study that compares the A, B and C rated buildings to the reference level D was done by Fuerst et al. (2016) with data from the residential market in Helsinki, Finland. They find a sales price premium of up to 3.3% for these buildings.[83] The more interesting finding is that

[65] Cf. Kholodilin et al. (2017, p. 3218).
[66] Cf. Kholodilin et al. (2017, p. 3224).
[67] Cf. Kündigungsschutzklausel-Verordnung, §2.
[68] Cf. Kholodilin et al. (2017, pp. 3232–3234).
[69] Cf. Kholodilin et al. (2017, p. 3232).
[70] Cf. Cajias et al. (2019, pp. 177 + 182).
[71] Cf. Cajias et al. (2019, p. 186).
[72] Cf. Cajias et al. (2019, p. 189).
[73] Cf. Cajias et al. (2019, p. 179).
[74] Cf. Cajias and Piazolo (2013, p. 53). Cajias et al. (2019, p. 177).
[75] Cf. Kholodilin et al. (2017, pp. 3232-3234).
[76] Cf. Cajias et al. (2019, p. 189).
[77] Cf. Cajias et al. (2019, p. 189).
[78] Cf. Brounen and Kok (2011, p. 176).
[79] Cf. Hyland et al. (2013, p. 950).
[80] Cf. Hyland et al. (2013, p. 949).
[81] Cf. de Ayala et al. (2016, p. 22).
[82] Cf. Cespedes-Lopez et al. (2019, p. 53).
[83] Cf. Fuerst et al. (2016, p. 567).

even after controlling for neighborhood characteristics and maintenance costs (this includes energy costs), a sales price premium of 1.3% was identified.[84] The authors argue that this premium is evidence for significant signaling effects for energy efficient buildings in the residential real estate market.[85] Contrary findings regarding a premium for lower energy consumption values were found by Wahlström (2016) in Sweden. This author included several building characteristics (e.g. new façade or new roof) having an impact on the energy efficiency. For these characteristics, price premiums were found.[86] For a lower calculated energy consumption itself, no price premium was found.[87] Thus, in Sweden, the buyer values the actual attributes of the building more than its energy consumption needs reflected by the EPC.[88]

Coming back to the market of interest in this study, i.e. the Rhein-Main Region, the question arises how the energy efficiency of buildings is valued in this market and whether significant changes can be identified compared to studies performed with data before 2018. A representative survey published by the Bundesumweltamt in Germany shows that 68% of respondents see environment and climate protection as a very important challenge in 2019 compared to 53% in 2016.[89] Thus, different findings seem plausible. The findings of this analysis will also be compared to Kholodilin et al. (2017) as they looked at another regional market, i.e. Berlin, in Germany. This will help to understand whether the impact of energy efficiency is similar in metropolitan areas.

4. The hedonic price model and its application

In section two, the application of the DCF in a real estate context was discussed. Analyzing how energy efficiency might affect the outcome of this method led to four hypotheses of which three will be further addressed in this thesis:

A. Net operating income (NOI) is – c.p. – higher for a more energy efficient and lower for a less energy efficient residential building and the valuation of the building is increased or decreased respectively.

B. Gross effective income (GEI) is – c.p. – higher for a more energy efficient and lower for a less energy efficient residential building.

C. The market value is – c.p. – higher for a more energy efficient and lower for a less energy efficient residential building and the increase/decrease is proportionally bigger than the increase/decrease in NOI.

Addressing these hypotheses requires analyzing how energy efficiency of buildings is valued in the real estate market of the Rhein-Main Region. Hedonic price models are often used for such an analysis.[90] The statistical methodology employed is a regression analysis and in the case of the present paper a multiple linear regression analysis. Janssen, Söderberg, and Zhou (2001) describe the hedonic model as a framework to analyze goods with a specific set of differentiable characteristics that make up the market value of the good but do not possess a market price on their own. Every characteristic has a certain utility for the user and changes the overall value of the product considered. This includes tangible as well as intangible characteristics.[91]

The earliest applications of the hedonic price model were used to estimate farmland values in Minnesota[92] and Iowa.[93] Another early use resulted in the development of hedonic price indexes for automobiles.[94] Long after their publication, the influence of these early papers on the development of hedonic models and whether Haas (1922) and Wallace (1926) can be regarded as hedonic applications was discussed.[95] These application oriented studies were followed by publications focusing on the consumer[96] and economic[97] theories behind hedonic price models. Lancaster (1966) writes that "(. . .) consumption is an activity in which goods, singly or in combination, are inputs and in which the output is a collection of characteristics. Utility or preference orderings are assumed to rank collections of characteristics and only to rank collections of goods indirectly through the characteristics that they possess."[98] He viewed the characteristics of the good as source of utility instead of the good in itself. Regarding the prices of these characteristics Rosen (1974) states: "Hedonic prices are defined as the implicit prices of attributes and are revealed to economic agents from observed prices of differentiated products and the specific amounts of characteristics associated with them. They constitute the empirical magnitudes explained by the model. Econometrically, implicit prices are estimated by the first step regression analysis (product price regressed on characteristics) in the construction of hedonic price indexes."[99] Regressing the product price (rent or sales price) on its characteristics will be the basis of the empirical analysis in this paper.

For the estimation of the coefficients of the product characteristics, different methods can be used. In this thesis, the widely used ordinary least squares (OLS) method is applied. It minimizes the squared residuals between estimated and observed values.[100] This method produces the best linear unbiased estimator if the following assumptions are met:

[84] Cf. Fuerst et al. (2016, p. 567).
[85] Cf. Fuerst et al. (2016, p. 560).
[86] Cf. Wahlström (2016, pp. 201-202). Also for the previous sentence.
[87] Cf. Wahlström (2016, pp. 201-202).
[88] Cf. Wahlström (2016, p. 197).
[89] Cf. Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz and Bundesumweltamt (2020).
[90] Cf. e.g. Wahlström (2016, p. 201). Kholodilin et al. (2017, p. 3223). Hyland et al. (2013, p. 945). Only a few examples from the academic literature. Others also use this method.
[91] Cf. Janssen et al. (2001, p. 344).
[92] Cf. Haas (1922, p. 1).
[93] Cf. Wallace (1926, p. 389).
[94] Cf. Leavens (1939, p. 169).
[95] Cf. Colwell and Dilmore (1999, p. 620).
[96] Cf. Lancaster (1966).
[97] Cf. Rosen (1974).
[98] Lancaster (1966, p. 133).
[99] Rosen (1974, p. 34).
[100] Cf. Urban and Mayerl (2018, p. 38).

1. Linearity: The estimated coefficients are of a linear nature.
2. Exogeneity: The mean of the error term is equal to zero.
3. Homoscedasticity: The variance of the error term is constant.
4. Autocorrelation: There exists no covariance between error terms.
5. Multicollinearity: There exists no perfect multicollinearity between explanatory variables.
6. Normality of residuals: The error terms are normally distributed. [101]

Before developing applicable models for analysis, data quality needs to be considered. Data quality is of the essence, since an inappropriate database must by default lead to invalid results and conclusions, regardless of the statistical method employed.

5. Evaluation of the data source & presentation of the descriptive statistics

5.1. Review of the data generating process

Finding pertinent and reliable real estate data for hedonic models is difficult. Real estate brokers are not inclined to give away critical information, including transaction data of brokered deals in the past. Although this problem may be fixable, e.g. by introducing a non-disclosure agreement, this does not solve the second problem: If data from only a small group of real estate brokers is analyzed, a selection bias could be introduced, e.g. observations from real estate brokers with regional specializations or brokers covering only a subsegment of buildings on the market. This could weaken the explanatory power of the model and might lead to a biased estimator. Ideally, an unbiased data set representing the overall market should be analyzed. Kholodilin et al. (2017) collect this information for the German market from online housing portals that have grown significantly in the past.[102] Hyland et al. (2013) collect the data for the Irish residential real estate market from the biggest national housing portal present in Ireland.[103] To increase the comparability between their findings and the findings of this study, a similar approach was used and observations from e.g. major internet portals were used for this analysis. The Real Estate Pilot AG provided the micro-data on the real estate market of the Rhein-Main Region.[104] The time period considered is from January 2019 until December 2020. More specifically, this time period is defined by the date the offer was first seen on the market. The Rhein-Main Region was defined by the counties and cities listed on Statista.[105] The data collected by the Real Estate Pilot AG is extracted from different internet platforms as well as regional and transregional newspapers.[106] A data update is performed by the Real Estate Pilot AG once per day.

Since raw data from the internet are extracted automatically, observations may not always be complete and may even contain erroneous data. Accordingly, others who have used such databases pointed out that the raw data might be biased by duplicated observations, that the online platforms could be used as marketing instruments for future development projects and that there might be discrepancies between the asked rental and sales prices and the actual transaction prices.[107] With respect to the first of these aspects, i.e. duplicates, the data received from the Real Estate Pilot AG was already processed to exclude duplicates.[108] This was done using a multistage process that considers the type of offer (rent or sale) as well as the information on various characteristics that is available. Overall, it can be said that the type of building, the address, the amount of living space and the price play an important role in this exclusion process. When deciding between two offers for the same building, the one with more information entered is chosen. A blending of the information provided in two different offers does not take place and no other substantial changes are done regarding the micro-data. With respect to the second of theses aspects, i.e. the use as a marketing instrument for future development projects, this could be partially resolved by only including buildings up to a construction year of 2021. The construction year 2021 is included since observations towards the end of 2020 may include newly constructed buildings to be finished in 2021. It seems plausible that rent as well as sales agreements regarding such buildings have already been signed. Another consideration that accounts for the second aspect is that the regression analysis is performed using EPC data. Observations that do not include data on energy performance are discarded. This also helps to eliminate general advertisements of development firms that cannot provide an energy consumption value since the building does not yet exist. However, this elimination also shows a limitation of the sample used for analysis. It cannot be excluded that information regarding buildings with high energy consumption and a bad EPC level is left out on purpose. Whether this is true cannot be proven and it appears to be a general and very basic limitation of an internet-based data extraction strategy – if a person does not enter critical information, it cannot be collected. A general comparison of the mean of the energy consumption of the sample with the overall building stock would also lack validity since the data used is so current that official statistics for this time period regarding the building stock could not be found. Finally, regarding the third aspect, i.e. discrepancies between asked prices and actual prices: Using appraised values and not transaction prices can be an

[101] Cf. Urban and Mayerl (2018, pp. 116 + 135).
[102] Cf. Kholodilin et al. (2017, p. 3224).
[103] Cf. Hyland et al. (2013, p. 945).
[104] Cf. Real Estate Pilot AG (2020).
[105] Cf. Statista Research Department (2020).
[106] Cf. Real Estate Pilot AG (2020). These include e.g. Immobilienscout, Ebay, Augsburger Allgemeine, Donaukurier.
[107] Cf. Kholodilin et al. (2017, p. 3224).
[108] Cf. Real Estate Pilot AG (2020).

accepted way of substitution because only small discrepancies between the two values exist, especially during upward cycles and in big cities.[109] This is assumed to be the case for the data in this paper and supported by the bulwiengesa real estate price index that has shown an increase for the 16. year in a row.[110] Further, by setting higher prices than the market value, time on market increases and often the later transaction value is lower.[111] Thus, the seller has an incentive to price their building at market value and not above.

5.2. Presentation of the descriptive sample statistics & plausibility check

The data received from the Real Estate Pilot AG covers the time period of January 2019 until December 2020 for the Rhein-Main Region in Germany. The Rhein-Main Region was defined by the counties and cities listed on Statista.[112] In total, two datasets were received. One dataset includes the rental market information for the Rhein-Main Region and the other the sales market information. There are 244 277 rental object observations and 123 308 sales object observations in the raw datasets. First, data were analyzed for plausibility. The individual steps of this assessment are shown in Appendix 15, including the R code used. For the benefit of readers of the code, explanations on the steps performed have been added as comments. As a part of this process, observations with missing values were also deleted. The outcome was a significant drop in observations available for the analysis. The final rental market sample includes 44 442 observations. The final sales market sample includes 31 426 observations. This reflects the fact that many rent and sales offers were incomplete and have considerable improvement potential regarding transparent communication of object characteristics to potential tenants or buyers. In the following, the descriptive sample statistics are presented. These refer to the final samples of 44 442 and 31 426 observations for the rent and sales datasets respectively.

The critical variables in the datasets needed to address the hypotheses developed in this thesis are rent and sales prices and energy efficiency. As the German real estate market is analyzed, all prices in this paper are in Euros. The energy efficiency is defined as the amount of kwh needed per square meter per annum by the building considered. Based on this information, the corresponding EPC level of the building is calculated (see Appendix 15). The information regarding the current energy efficiency levels was taken from the exhibit 10 in the GEG.[113] The calculation of the EPC levels on the basis of energy consumption data was done to circumvent the problem of different regulations in Germany. Over the years, the requirements for the EPC levels have tightened and, thus, the actual energy usage of the buildings needs to be converted into the current EPC level to achieve comparability. The distributions of the observations regarding EPC levels for the rent and the sales datasets are shown in Figures 2 and 3. Two statements can be made based on the distributions:

First, most sales and rent observations have an energy performance corresponding to levels D or E. This is also supported by the summary statistics in Table 1, which indicate that mean energy consumption is equal to EPC level D for the rent and EPC level E for the sales dataset. The second interesting observation can be made by comparing Figures 2 and 3, which reveals that the sales market has more offerings compared to the rent market in the very bad performing levels of G and H as well as in the top performing level of A+. One explanation could be that owners are selling off assets with a very bad energy performance e.g. due to higher risk associated with them. The increased amount of assets that are in the top performing category of A+ could indicate that development and refurbishment firms have already realized the importance of energy performance for the current and future market and have adjusted their projects accordingly. Both explanations seem reasonable but are speculative and interesting topics for future research.

Beyond the price and energy variables, building-specific characteristics are also included in the datasets as well as whether a commission fee must be paid for sales objects. Information regarding the location of the object (postal code) and the upload date of the observations are also part of the datasets. The summary statistics regarding most of the variables are presented in Table 1 and 2. Variables not shown in the table include the postal code of the buildings, the time the offer was first posted online and the type of building (e.g. detached house or apartment).

From the summary statistics in Table 1, it can be concluded that the average rental building in the sample costs 885.26 € of cold rent and 1 074.35 € including operational costs. The average construction year is 1981 and the energy consumption of that building is 117.50 kwh/m^2 per annum and thus equal to an energy performance level of D. Overall, the average 2.73 rooms of the building stretch across 79.44m^2. 13% of buildings have not been occupied before and were newly constructed. 30% of all buildings have been refurbished. While 3% of buildings are furnished, only very few are landmarked buildings. 27% of all buildings are equipped with an elevator and 52% have a parking space available. A comparison of the mean and the median of the rent prices indicate a positive skewness of the data. This is supported by maximum values ranging up to 9 800.00 € and 13 310.00 € for cold and warm rent respectively.

The summary statistics of the sales price sample in Table 2 show that compared to the average rental building, the average building up for sale is much bigger with 141.57 m^2 stretching across 4.92 rooms. The construction year of the buildings is the same (1981) and the energy consumption is on average higher (130.30 kwh / m^2 per annum). This corresponds to an energy performance level of E. 10% of all buildings have not been occupied before and were newly con-

[109] Cf. Henger and Voigtländer (2014, p. 15).
[110] Cf. bulwiengesa AG (2021, p. 1).
[111] Cf. Knight (2002, p. 213).
[112] Cf. Statista Research Department (2021).
[113] Cf. GEG, exhibit 10.

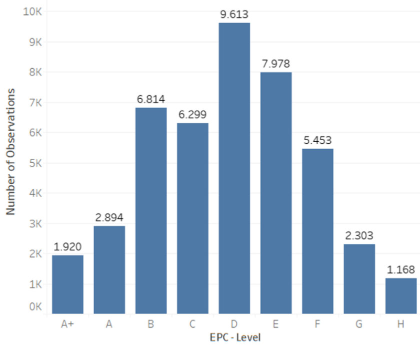

Figure 2: No. of observations in rent sample per EPC – Level (Source: Selfmade)

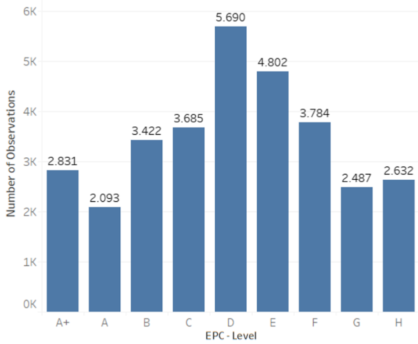

Figure 3: No. of observations in sales sample per EPC – Level (Source: Selfmade)

Table 1: Summary statistics of the rent data sample

Variable	Unit	**Mean**	**Median**	**st.Dn.**	**Minimum**	**Maximum**
Dependent variables						
Cold Rent	Price in Euros (€)	885.26	760 00	493.61	112.80	9 800.00
Warm Rent	Price in Euros (€)	1074.35	940.00	563.49	142.80	13 310.00
Building-specific independent variables						
Energy Consumption	kwh/(m^2 *annum)	117.50	114.10	58.42	5.10	487.40
Living Space	m^2	79.44	74.00	35.63	9.00	707.00
Number of Rooms	Numeric	2.73	3.00	1.11	1.00	12.00
Furnished	Binary, reference = 0; true = 1	0.03	0	0.18	0	1
Refurbished	Binary, reference = 0; true = 1	0.30	0	0.46	0	1
First Occupancy	Binary, reference = 0; true = 1	0.13	0	034	0	1
Landmarked Building	Binary, reference = 0; true = 1	0.00	0	0.01	0	1
Elevator	Binary, reference = 0; true = 1	0.27	0	0.45	0	1
Parking Space	Binary, reference = 0; true = 1	0.52	1	0.50	0	1
Construction Year	Numeric	1981	1984	30.68	1871	2021

Number of observations rent sample: 44 442

structed. 15% of all buildings have been refurbished. This amount of 25% of either newly build or refurbished buildings is much less than the 43% in the rent data. The difference in refurbishment might be a part of the reason why the energy consumption is 12.80 kwh / m^2 per annum lower for the buildings in the rent data. Only 1% of all buildings for sale are a landmarked building. Compared to the rental buildings, a smaller amount of buildings is equipped with an elevator (18%), but more have a parking space available (61%). While 12 % of all buildings are currently being rented by a tenant, 22% of buildings can be purchased without having to pay a commission fee.

Table 2: Summary statistics of the sales data sample

Variable	Unit	**Mean**	**Median**	**st.Dev.**	**Minimum**	**Maximum**
Dependent variable						
Sales Price	Price in Euros (€)	467 315.00	385 000.00	392 455.80	20 000	16 160 000.00
Building-specific independent variables						
Energy Consumption	kwh/(m^2 *annum)	130.30	119.90	80.98	5.30	496.60
Living Area	m^2	141.57	125.00	94.73	13.64	5447.00
Number of Rooms	Numeric	4.92	4.00	3.43	1.00	300.00
Refurnished	Binary, reference = 0; true = 1	0.15	0	0.35	0	1
First Occupancy	Binary, reference = 0; true = 1	0.10	0	0.31	0	1
Landmarked Building	Binary, reference = 0; true = 1	0.01	0	0.08	0	1
Elevator	Binary, reference = 0; true = 1	0.18	0	0.38	0	1
Parking Space	Binary, reference = 0; true = 1	0.61	1	0.49	0	1
Construction Year	Numeric	1981	1983	30.50	1871	2021
Active Lease	Binary, reference = 0; true = 1	0.12	0	0.32	0	1
Contract-specific independent variables						
Commission Free	Binary, reference = 0; true = 1	0.22	0	0.41	0	1

Number of observations sales sample: 31 426

The explanatory variables in the datasets were also checked for correlation. A very high correlation could decrease the significance for both independent explanatory variables considered.[114] The correlation matrix for both samples is shown in Appendix 2 and 3. For the rent data (see Appendix 2), there exists a very high correlation between the living space of a building and the number of rooms (86%). This seems plausible, as both variables are a measure of building size. The question that arises is whether these two variables are valued differently by the market. This might be the case e.g. for city center apartments where a second room might be valued more than having a bigger single room apartment. Further, as the focus of this paper is the impact of energy efficiency, it is more important to control for different characteristics than to minimize correlation between control variables. These two reasons would suggest including both variables in the analysis. A similarly high correlation is present in the sales price data (see Appendix 3) between the number of rooms and the living space (90%). Again, the two reasons mentioned above support including both variables in the analysis. Besides the correlation between these two variables, there is no strong correlation present between explanatory variables. Moderate correlation can be found between the two explanatory variables construction year and energy consumption for the rent data (-55%) and the sales data (-67%). As the energy consumption is the focus of this analysis, this could be problematic regarding the significance of the coefficients. The values computed were also used as a first indicator for multicollinearity (a high correlation coefficient indicates potential multicollinearity). The multicollinearity assumption will be tested in detail after the model specification is defined (see subsection 7.2).

6. Specification of the hedonic price models used for analysis

Based on the theoretical fundamentals of hedonic models explained above, empirical models that can help test the major hypotheses of this paper will now be defined. The heterogeneous good considered is a residential building with certain characteristics and a sales price or rent price. It is essential to identify these characteristics and account for them in the hedonic model. The main categories to consider are a) building-specific characteristics b) location-specific characteristics, c) time-specific characteristics and d) contract-specific characteristics.[115]

The three hypotheses of interest need to be investigated using three different models. The reason for this is that each hypothesis looks at the impact of energy efficiency on the valuation of a building on a different level. Each level has a different dependent variable. In hypothesis A, the net operating income is considered. This will be tested using the cold rent of a building as the dependent variable in the hedonic model. An increase in cold rent, c.p., is equivalent to an increase in the NOI of the building. Hypothesis B considers the GEI of the building. Here, the dependent variable will be the warm rent of a building. As the warm rent is the total incoming cash flow, an increase is, c.p., equivalent to an increase in GEI. The dependent variable of the hedonic model for hypothesis C will be the sales price of a building. Based on the DCF method discussed above, an implication of hypotheses A and B is that the value and therefore the sales price of the building is, c.p., increased. This implication would have to be visible in the sales price dataset. To make the following empirical analysis as well as the discussion more intuitive, the models will be named "Cold Rent Model", "Warm Rent Model" and "Sales Price Model". All models include data transformations to improve interpretation and compliance with the regression assumptions as well as dummy control variables to account for location and time effects. Of note, the indexes used in the equations and the meaning of the variables remain the same for all three models. Details on the coding and data transformations and an overview of which variables are used in each model are summarized in Appendix 1.

The Cold Rent hedonic model is expressed by the following equation:

$$\begin{aligned}
\ln\left(cold_rent_{ilt}\right) &= \alpha + \beta_1 epc_level_i \\
&+ \beta_2 \ln\left(living_space_j\right) + \beta_3 no_rooms_i + \beta_4 furnished_i \\
&+ \beta_5 refurbished_i + \beta_6 first_occupancy_i \\
&+ \beta_7 landmarked_building_i + \beta_8 elevator_i \\
&+ \beta_g parking_space_i + \beta_{10} building_type_i \\
&+ \beta_{11} construction_year_i + \gamma_l + \delta_t + \varepsilon_{ilt}
\end{aligned} \tag{5}$$

The dependent variable, *"cold_rent"*, is transformed as the natural log. This helps to account for potential non-linearity present in the model.[116] The implications for the interpretation of the results will be discussed later. They also depend on the independent variable considered and whether it is transformed or not. In the model, i is the index for the single building observation. The index l defines the location while the t index defines the date of the observation. The constant in the model is represented by α. This is followed by the various building-specific characteristics that were already mentioned in the summary statistics of the data above, a control variable for the building type (*"building_type"*), the location effects ("γ_l"), the time effects ("δ_t") and the error term ("ε_{ilt}"). The independent variable relevant for the assessment of the hypothesis is the first building-specific characteristic, i.e. a dummy variable indicating the EPC-level of the building. The EPC level of the building is equivalent to the one calculated on the basis of the energy consumption of the building (see subsection 5.2). The reference level of this variable is set to D. Any comments regarding energy

[114] Cf. Fahrmeir, Kneib, and Lang (2009, p. 154).
[115] Cf. Sopranzetti (2010, pp. 1202–1203).
[116] Cf. Fahrmeir et al. (2009, pp. 22-23).

(in)efficiency are made with respect to this reference level. This was also recommended by others to increase comparability between studies.[117] The quantitative variable *"living_space"* in m^2 is log-transformed. This is again done to account for non-linearity.[118] The other building specific characteristics are all categorical as well as dummy variables. The *"no_rooms"* variable is coded as a categorical variable to account for premiums or discounts associated with different levels of this variable. The variables *"furnished", "refurbished", "first_occupancy", "landmarked_building", "elevator" and "parking_space"* only have two levels, zero and one. Zero is the reference value. This would mean that the respective building characteristic is not applicable for this observation. The variable *"building_type"* has ten different levels and serves as a control variable for different building types, e.g. the difference between a detached house and an apartment. The last building-specific variable, i.e. *"construction_year"*, helps to control for depreciation of the building. Following Cajias et al. (2019), the construction dummies are coded in ten-year steps.[119] The remaining two variables in the Cold Rent Model account for the location effects of the building on a postal code level ("γ_l") and the time effects on a monthly level ("δ_t").

The equation of the warm rent model uses *"warm_rent"* as dependent variable. This results in the following equation:

$$\begin{aligned} &\ln\left(warm\_rent_{ilt}\right) = \alpha + \beta_1 epc\_level_i \\ &+ \beta_2(\ln living\_space_i) + \beta_3 no\_rooms_i + \beta_4 furnished_i \\ &+ \beta_5 refurbished_i + \beta_6 first\_occupancy_i \\ &+ \beta_7 landmarked\_building_i + \beta_8 elevator_i \\ &+ \beta_g parking\_space_i + \beta_{10} building\_type_i \\ &+ \beta_{11} construction\_year_i + \gamma_l + \delta_t + \varepsilon_{ilt} \end{aligned} \tag{6}$$

The empirical analysis in this paper starts with NOI and then looks at the GEI before considering the sales price. Since a comparison between the different results is needed, it would not be meaningful to generate a fundamentally different model for the analysis of the sales price. However, it seems expedient to include or exclude variables that are only relevant for the respective transaction (rent or sale). Therefore, a variable indicating the current rent status (*"rent_status"*) of the building is added to the Sales Price Model as well as a control variable for the contract-specific characteristic regarding the sales commission (*"commission_free"*). The variable *"rent_status"* is a two-level dummy variable with a reference value of zero indicating that no one is currently renting the building. The contract-specific variable is a two-level dummy variable with zero, not commission free, as the reference value. The variable *"furnished"* is dropped, as this is assumed to be an uncommon feature for buildings that are sold and not let. This leads to the following equation:

$$\begin{aligned} \ln\left(sales\_price_{ilt}\right) &= \alpha + \beta_1 epc\_level_i \\ &+\beta_2 \ln\left(living\_space_i\right) + \beta_3 no\_rooms_i \\ &+\beta_4 rent\_status_i + \beta_5 refurbished_i \\ +\beta_6 first\_occupancy_i &+ \beta_7 landmarked\_building_i \\ &+\beta_8 elevator_i + \beta_g parking\_space_i \\ +\beta_{10} building\_type_i &+ \beta_{11} construction\_year\_ \\ &+\beta_{12} commission\_free_i + \gamma_l + \delta_t + \varepsilon_{ilt} \end{aligned} \tag{7}$$

7. Presentation of the empirical results & assessment of the model assumptions

7.1. Empirical results of the hedonic regression models

As the level of analysis differs for each model, the empirical results should also show different effects of energy efficiency on the rent or sales price. If the hypotheses tested in this paper are true, a positive impact of energy efficiency should be visible and significant in all models. Further, the effect should be rather small for the Warm Rent Model and somewhat bigger for the Cold Rent Model because of the capitalization of energy savings. For the Sales Price Model, the effect should be the largest, as additional factors such as risk of depreciation are included. Energy inefficiency on the other hand should have a negative impact on the rent and sales prices. Here, cold rent should decrease to account for higher operational costs while staying competitive with the warm rent in the market. The question arises whether signaling effects are also present for these buildings. With negative signaling effects being present for energy inefficient buildings, the warm rent of these buildings should be lower compared to buildings of reference level D. The sales price of an energy inefficient building should also decrease. The magnitude of the decrease of the sales price should, similar to the efficiency premium, be bigger than the decrease in cold rent as additional factors such as exposure risk to future regulation changes are increased. In the remainder of this subsection, the empirical results of the models are presented. After the presentation of results, the assumptions regarding the linear models are discussed.

Table 3 shows the results of the linear models defined by equations (5) – (7). All the dependent variables were transformed using the natural logarithm and, thus, the coefficient of the estimator of an explanatory variable is equal to the increase of the natural log of the dependent variable. To facilitate the understanding of the economic meaning of the results, coefficients are converted into percentage values in the text. The non-converted values can be found in the respective table for comparison purposes. The standard errors reported in the table are beneath the coefficients and robust White standard errors that correct for heteroscedasticity.[120] See Appendix 15 for computational details.

[117]Cf. Cespedes-Lopez et al. (2019, p. 53).
[118]Cf. Fahrmeir et al. (2009, pp. 22-23).
[119]Cf. Cajias et al. (2019, p. 184).
[120]Cf. Fahrmeir et al. (2009, pp. 135 – 136).

The Cold Rent Model shows an overall statistical significance between the independent explanatory variables and the dependent variable cold rent (F (539, 43 902) = 776.20, $p < 2.2e-16$, $R^2 = .9050$). The F-statistic is highly significant with a value of 776.20 and there is only a chance of less than 2.2e-16 that the Cold Rent Model does not have any explanatory power.

The degrees of freedom equal 539 for the regression and 43 902 for the error. Further, 90.50% of the variance present in the data can be explained by the model. As the model includes various explanatory variables, the adjusted R^2 is also considered. This is done to account for the possibility that a high number of explanatory variables is the cause for the high R^2 value.[121] The Cold Rent Model shows an adjusted R^2 of 0.9039. As this value is not very different from the R^2 value ($R^2 = .9050$), it is highly unlikely that the model includes variables that increase the value of the explained variance only by chance. When looking at the independent explanatory variables, a significant cold rent price premium is present for EPC levels above reference level D. For EPC levels A+, A, B and C the cold rent premium is equal to 5.82%, 2.04%, 3.06% and 0.69% respectively. For A+, A and B this finding is highly significant at the 0.1% level. For EPC level C this finding is significant at the 1% level. The magnitudes of the coefficients below the EPC level of D are much smaller, but all of them are negative. The overall discounts are -0.58%, -0.28%, -0.70% and -0.15% for the EPC levels of E, F, G and H respectively. The values below D do not show a clear linear decrease of cold rent and indicate that the magnitude of the effect of energy efficiency on cold rent might be smaller compared to EPC values above D. The significance of results is smaller with only E being significant at a 5% level. Thus, it cannot be excluded that EPC values of F, G and H have no impact on the cold rent of the building. Overall, the Cold Rent Model shows a significant premium for energy efficient homes of up to 5.82% but does not indicate significant cold rent discounts for energy inefficient buildings.

The Warm Rent Model shows an overall statistical significance between the independent explanatory variables and the dependent variable warm rent (F (539, 43 902) = 796.20, $p < 2.2e-16$, $R^2 = .9072$). The F-statistic is highly significant with a value of 796.20 and there is only a chance of less than 2.2e-16 that the Warm Rent Model does not have any explanatory power. The degrees of freedom equal 539 for the regression and 43 902 for the error. Further, 90.72% of the variance present in the data can be explained by the model. As the model includes various explanatory variables, the adjusted R^2 is also considered. The Warm Rent Model shows an adjusted R^2 of 0.9060. As this value is not very different from the R^2 value ($R^2 = .9072$), it is highly unlikely that the model includes variables that increase the value of the explained variance only by chance. When looking at the independent explanatory variables, a significant warm rent price premium is present for some of the EPC levels that are above the reference level D. For EPC levels A+, A, B and C the coefficient of the estimator is equivalent to a 3.86%, 0.38%, 1.98% and 0.21% increase in warm rent respectively. For A+ and B this finding is highly significant at the 0.1% level. The magnitudes of the coefficients below the EPC level of D are all smaller than 1% and not significant. The coefficients do not show a clear linear trend. Compared to the coefficients of the Cold Rent Model, they are smaller and closer to zero. An effect of lower EPC levels on warm rent cannot be assumed. Overall, the Warm Rent Model shows a significant premium for energy efficient homes in the categories A+ and B with a maximum of 3.86% and no significant discounts for the energy inefficient buildings below the reference level of D.

The Sales Price Model shows an overall statistical significance between the independent explanatory variables and the dependent variable sales price (F (605, 30 820) = 336.70, $p < 2.2e-16$, $R^2 = .8686$). The F-statistic is highly significant with a value of 336.70 and there is only a chance of less than 2.2e-16 that the Sales Price Model does not have any explanatory power. The degrees of freedom equal 605 for the regression and 30 820 for the error. Further, 86.86% of the variance present in the data can be explained by the model. As the model includes various explanatory variables, the adjusted R^2 is also considered. The Sales Price Model shows an adjusted R^2 of 0.8660. As this value is not very different from the R^2 value ($R^2 = .8686$), it is highly unlikely that the model includes variables that increase the value of the explained variance only by chance. When looking at the independent explanatory variables, a significant sales price premium is present for some of the EPC levels that are above the reference level of D. For the EPC levels of A+, A and B the sales premium is significant and equal to an increase of 6.81%, 3.14% and 1.52% of the sales price respectively. For A+ and A this finding is highly significant at the 0.1% level and for B at the 5% level. The estimated coefficient for the EPC level C is equal to 0.09% and not significant. When considering the EPC levels below the reference level of D, the coefficients are equal to -0.70%, 0.69%, -1.73% and -8.80% for E, F, G and H respectively. The finding for EPC level G is significant at the 5% level and the finding for the EPC level H is significant at the 0.1% level. For EPC levels of C, E and F no significant difference was seen. Thus, these EPC levels do not seem to have an impact on the sales price of a building. Overall, the Sales Price Model shows a significant premium of up to 6.81% for energy efficient buildings with an EPC level of B and above. It finds neither a significant discount nor premium for buildings with an EPC level ranging from C to F. Starting with G, the Sales Price Model finds significant discounts for energy inefficient buildings with discounts of up to -8.80% for EPC level H.

The empirical results regarding the control variables of the models are also highly significant. In the Cold Rent Model, there is a significant increase in rent for more living space (100% increase in living space, increases cold rent by 73.19%) and for furnished apartments (20.27% increase). Renting out newly constructed buildings comes with a premium of 8.92%, while refurbished apartments are 4.00%

[121] Cf. Urban and Mayerl (2018, p. 91).

Table 3: Empirical results of hedonic regression models

Dep. Var.:	**Cold Rent**	**Warm Rent**	**Sales Price**
	(1)	(2)	(3)
EPC Level A+	0.05660055***	0.037870311***	0.065838973***
	0.00437359	0.004078778	0.007952356
EPC Level A	0.02021563***	0.003763821	0.030892444***
	0.00396247	0.003716371	0.008115774
EPC Level B	0.03010108***	0.019579393***	0.015110583*
	0.00306967	0.002882431	0.006249028
EPC Level C	0.00682597***	0.002068312	0.000932055
	0.00247206	0.002320161	0.004804528
EPC Level E	−0.00583240*	−0.001800472	−0.007051507
	0.00227909	0.002128358	0.004499839
EPC Level F	−0.00277893	0.004343243	0.006825412
	0.00267550	0.002493251	0.005271737
EPC Level G	−0.00702567	0.000472069	−0.017478196*
	0.00382009	0.003588644	0.006900535
EPC Level H	−0.00145708	−0.001764933	−0.092088491***
	0.00541184	0.005129463	0.007701151
Ln(Living Space)	0.79237579***	0.762227770***	0.860093156***
	0.00459536	0.004387214	0.008272612
Furnished	0.18452401***	0.174828571***	-
	0.00558676	0.005187815	
Refurnished	0.03925094***	0.034063595***	0.051384371***
	0.00168391	0.001576583	0.003985229
First Occupancy	0.08546231***	0.074777163***	0.048026681***
	0.00234633	0.002189902	0.005424765
Landmarked Building	0.01843539	0.038014154	0.047517962***
	0.02055397	0.028272040	0.019778178
Elevator	0.02467841***	0.040704650***	−0.016977286***
	0.00201453	0.001862656	0.004077302
Parking Space	0.03101226***	0.030620634***	0.007289280*
	0.00165583	0.001546589	0.003011203
Rent Status	-	-	−0.060121281***
			0.004287139
Commission Free	-	-	0.015091733***
			0.003507405
Intercept	2.64195778***	2.910135919***	7.929795028***
	0.09239100	0.115792996	0.053315457
Categorical Control Variables			
No. of Rooms	1	1	1
Building Type	1	1	1
Construction Year	1	1	1
Location	1	1	1
Upload Date	1	1	1
R squared	0.9050	0.9072	0.8686
Adjusted R squared	0.9039	0.9061	0.8660
No. of observations	44 442	44 442	31 426

Significance level: (*) $p < 0.05$; (**) $p < 0.01$; (***) $p < 0.001$

more expensive than non-refurbished ones. A landmarked building does not provide any significant value, while an elevator increases cold rent by 2.50% and an available parking space increases cold rent by 3.15%. In the Warm Rent Model, the magnitude of significant coefficients decreases for all control variables except for the elevator. An elevator being present increases warm rent by 4.15% compared to the 2.50% in the Cold Rent Model. This seems plausible, as an elevator has an impact on the operating costs, and thus its relative influence on the rent increases when considering the warm rent. In the Sales Price Model, the control variables are also highly significant. A 100% increase in living space increases the sales price by 81.52%. A refurbished building is valued 5.27% higher by the market while a newly built building has a 4.92% higher sales price. Regarding the sales price, landmarked buildings have a premium of 4.87%. This might be the case because they may have a historic importance that is valued with a premium. An elevator decreases the sales price of a building by -1.68 % while an available parking space only comes with a premium of 0.73%. A building with an active lease agreement costs 6.20% less and a commission free building is offered for 1.52% more on the market.

7.2. Assessment of the model assumptions

To assess the explanatory power of the three different models, the assumptions underlying multiple regression need to be validated. Each assumption will now be considered for all three models.

1. Linearity: The estimated coefficients are of a linear nature.

The linearity assumption is tested by plotting the residuals of the models on the y-axis against the fitted values on the x-axis.[122] Doing this can help detect previously overlooked non-linear influences of explanatory variables. The plot of the Cold Rent Model (see Appendix 4) shows randomly distributed residuals for the most part. When looking at the highest as well as lowest fitted values, there is a small indication of a weak quadratic relationship also shown by the fitted line. As this deviation from linearity is insignificantly small, the linearity assumption is considered fulfilled. Like the plot of the Cold Rent Model, the plot of the Warm Rent Model (see Appendix 5) shows a small deviation at the top and bottom of fitted values. Still, the assumption of linearity for the Warm Rent Model is approximately fulfilled. The plot of the Sales Price Model (see Appendix 6) shows randomly distributed residuals and an almost perfect horizontal line indicating a linear relationship. The linearity assumption is fulfilled for the Sales Price Model.

2. Exogeneity: The mean of the error term is equal to zero.

According to Urban and Mayerl (2018) the exogeneity assumption cannot be tested as the expected value of zero for the mean of the error term refers to the actual population model.[123] This model is unknown. Only an estimation of the population model based on a sample, the regression model, is known. For technical reasons, the mean of the error term is always equal to zero for the regression model. Not having a mean equal to zero of the error term would only bias the intercept estimation.[124] As the focus of this thesis is the impact of energy efficiency, a potentially biased intercept estimation would not impact the results regarding the EPC levels. Thus, even in this worst case, the findings of this thesis would still be valid.

3. Homoscedasticity: The variance of the error term is constant.

Not fulfilling the homoscedasticity assumption has an impact on the validity of the significance tests of the linear model. Thus, with strong heteroscedasticity present in the model, no statement can be made regarding the significance of estimated coefficients.[125] To minimize this effect, the dependent variables are log-transformed.[126] Again, residual plots can be used for diagnosis (see Appendix 7 - 9).[127] Here, the square root of the absolute values of the standardized residuals are plotted on the y-axis and the fitted values of the models are plotted on the x-axis. A random and linear distribution around the value of 1 is indicative of homoscedasticity. All three models show a slight deviation from linearity. This is a known limitation of multiple linear regression and it is recommended to take a heuristic approach for diagnosis by considering statistical test values (e.g. Breusch Pagan test) and graphical representations.[128] Nonetheless, to ensure that the significance of the test statistics regarding the linear models can be regarded as valid, robust White standard errors were computed and are presented in the Table 3 with the empirical results. The use of this method is recommended as it also does not need information regarding the form of heteroscedasticity.[129] Based on heuristic arguments and the additional computation and use of robust White standard errors, the homoscedasticity assumption for all three models can be seen as sufficiently fulfilled or, at the very least, not critical for the interpretation of the results of the model.

4. Autocorrelation: There exists no covariance between error terms.

The Durbin-Watson test is often used for diagnosing autocorrelation.[130] The value of the test statistic ranges from

[122] Cf. Urban and Mayerl (2018, pp. 199-200).

[123] Cf. Urban and Mayerl (2018, p. 196), also for the following 3 sentences.

[124] Cf. Urban and Mayerl (2018, p. 196).

[125] Cf. Urban and Mayerl (2018, pp. 253-254), also for the previous sentence.

[126] Cf. Fahrmeir et al. (2009, p. 132).

[127] Cf. Urban and Mayerl (2018, p. 299).

[128] Cf. Fahrmeir et al. (2009, pp. 131–132).

[129] Cf. Fahrmeir et al. (2009, pp. 135 – 136).

[130] Cf. Fahrmeir et al. (2009, pp. 141 – 142).

0 to 4 with the middle value of 2 indicating no autocorrelation. Further, the null hypothesis states that autocorrelation is equal to zero while the alternative hypothesis states that autocorrelation is unequal to zero. The computation is equal to 1.98 and significant at the 5% level (p = 0.012) for the Cold Rent Model, 1.98 and significant at the 5% level (p = 0.046) for the Warm Rent Model and 1.99 and not significant (p = 0.422) for the Sales Price Model. The computation was done using the "durbinWatsonTest" function from the "car" package in R. The result for the Sales Price Model is clear: No autocorrelation present and a value of close to 2. The test for the Cold and Warm Rent Models also show values very close to 2. However, here the significance at the 5% level indicates that the null hypothesis has to be rejected. Because of the test value being very close to 2, this result needs to be interpreted. In case of large datasets, statistical tests may become significant even with very small effect sizes.[131] This is the case here and the test has detected a minor autocorrelation. Although this may be present, the fact that the values are almost ideal, i.e. close to 2, shows that this autocorrelation will not have a major impact on the interpretation of the results and can be discounted accordingly.

5. Multicollinearity: There exists no perfect multicollinearity between explanatory variables.

As a first indication, the correlation matrix was used. Several correlations between variables were found (see Appendix 2 and 3) indicating potential multicollinearity. Multicollinearity can impact the stability of the estimated coefficients.[132] Thus this needs to be investigated further. It is suggested taking the variance inflation factor (VIF) into account when diagnosing multicollinearity.[133] However, the models used in this analysis include various categorical variables with more than one degree of freedom. This leads to a measure of collinearity that is partly artifactual.[134] To overcome this problem, the generalized VIF (GVIF) and $GVIF^{(1/(2*DF))}$ for the three linear models were computed. The values of the $GVIF^{(1/(2*DF))}$ were used, as is suggested.[135] Fahrmeir et al. (2009) state that for any VIF higher than 10 there is a significant multicollinearity problem.[136] No value indicating problematic multicollinearity was found (see Appendix 13-14). In particular, the values for construction year and energy efficiency were found to be small. The computations were done using the "vif" function of the "car" package in R. Based on these calculations, the multicollinearity assumption is sufficiently fulfilled for all three models.

6. Normality of residuals: The error terms are normally distributed.

The normal distribution of residuals is important for the explanatory power of the test statistics.[137] A graphical analysis of this assumption can be done using the quantile-quantile plot.[138] Here, the standardized residuals are plotted on the y-axis while the theoretical quantiles are plotted on the x-axis. Based on this graph, all three models show good normality for most of the data (see Appendix 10 - 12). At the bottom and top theoretical quantiles, the normality assumption is violated. However, in the case of large samples, conclusions drawn from the models are still valid: Fahrmeir et al. (2009) argue that with a large number of observations, the OLS estimator approximately shows the same normal distribution as with fulfilling the normality assumption of the error term.[139] This is important for the validity of the test statistics. The needed conditions for this approximation can be seen as fulfilled if the observations and thus their variables come from a random sample, as is the case in this empirical analysis.[140] The examples used by Fahrmeir et al. (2009) include samples with less than 5000 observations.[141] With six-fold larger sample sizes in the present analysis, the approximation is possible. In conclusion, even though the normality assumption of the error term is not fulfilled, we can assume a normal distribution for the OLS estimator.

8. Discussion of the empirical results & limitations of the thesis

In the following, the empirical results of the three hedonic models are discussed in the context of the literature. The limitations of this thesis work are also considered.

Hypothesis A states that the net operating income (NOI) is – c.p. – higher for a more energy efficient and lower for a less energy efficient residential building and the valuation of the building is increased or decreased respectively. To analyze the first part of this hypothesis, the Cold Rent Model was defined. Assuming that the participants of the rental market act purely rational, there should be a clearly visible positive linear trend from EPC level H to A+ as a landlord will recoup energy cost savings by increasing cold rent. For EPC levels above the reference value D, this hypothesis is supported by the empirical results (see Table 3). For EPC values E-H there is no clear relationship between EPC levels and cold rent, suggesting that landlords of H rated buildings can charge the same cold rent as landlords of D rated buildings despite of higher energy costs. Since it is unlikely that rational acting market participants are indifferent to higher energy costs, this finding may reflect the tight real estate market in the Rhein-Main Region[142] and, thus, tenants, must accept higher operational costs. Furthermore, with no clear discount present for energy inefficient houses, a landlord has little incentive to improve the EPC level of e.g. a H rated building to a D rated building. For a landlord to see financial benefit, EPC ratings of the upper segments A+ through

[131] Cf. Urban and Mayerl (2018, p. 131).
[132] Cf. Urban and Mayerl (2018, p. 252).
[133] Cf. Fahrmeir et al. (2009, pp. 170 – 171).
[134] Cf. Fox and Monette (1992, p. 180).
[135] Cf. Fox and Monette (1992, p. 180).
[136] Cf. Fahrmeir et al. (2009, p. 171).
[137] Cf. Urban and Mayerl (2018, p. 187).
[138] Cf. Fahrmeir et al. (2009, p. 169).
[139] Cf. Fahrmeir et al. (2009, pp. 105 – 106).
[140] Cf. Fahrmeir et al. (2009, pp. 105 – 106).
[141] Cf. Fahrmeir et al. (2009, p. 5).
[142] Cf. Manus (2020). Cajias et al. (2019, pp. 186-187).

C need to be achieved. Whether such investments are financially viable needs to be assessed in future research. Thus, hypothesis A is partially supported by data: better energy efficiency c.p. increases cold rent and NOI for buildings rated above D. Less energy efficient buildings show no significant discount. The implications of these findings for building valuation are straightforward: Above D rated buildings should be valued higher because of a higher NOI and below D rated buildings should receive no or only small discounts regarding their valuation. This will be discussed further in the context of hypothesis C.

Hypothesis B states that the gross effective income (GEI) is – c.p. – higher for a more energy efficient and lower for a less energy efficient residential building. To analyze this hypothesis, the Warm Rent Model was used and its findings were compared with those of the Cold Rent Model (previous paragraph). Since warm rent is equal to cold rent plus all operational costs the tenant is charged, and since c.p. operational costs should rise with energy inefficiency, i.e. lower EPC levels, the Warm Rent Model combined with the Cold Rent Model provides some insight into the allocation of operational costs by landlords. As far as energy efficient buildings are concerned, the Warm Rent Model revealed significant warm rent premiums for EPC levels of A+ and B, indicating that c.p. the increase in cold rent exceeded the reductions in operating costs of the building. This indicates that additional factors are at play enabling the landlord to charge a premium, e.g. signaling effects. Although the present analysis does not identify these factors, it is clear that they add value for the tenants as the D and A+ rated buildings compete in the same market. Of note, this effect is only present for EPC levels of A+ and B. EPC levels A and C were not significantly different from D, indicating that for such buildings the landlord recouped the energy cost savings by increasing the cold rent (see Table 3 and compare (1) and (2)). At the other side of the scale, i.e. EPC levels below D, no coefficients are significant. This is a surprising finding because the increasing energy consumption from D to H neither affected cold nor warm rent. The reasons for this are unclear and a more detailed study taking the exact mix of operating costs of the different buildings into account will be needed. Some follow up hypotheses that could be addressed to better understand the absence of an increasing warm rent at low rated EPC building levels are:

- the landlord financially offsets some of the operating costs for energy inefficient buildings so that the building stays competitive in the rental market
- the operating costs entered in the rental offer is lower than the actual operating costs charged by the landlord
- the actual energy consumption and operating costs of energy inefficient buildings is not higher than D rated buildings because higher energy costs are offset by a reduction in other operating costs (e.g. lower technology level with no IT infrastructure)

Hypothesis C states that the market value is – c.p. – higher for a more energy efficient and lower for a less energy efficient residential building and the increase/decrease is proportionally bigger than the increase/decrease in NOI. To test this hypothesis, the Sales Price Model was defined. The empirical results (see Table 3) show that there is – as predicted – a premium for more energy efficient buildings (see EPC levels A+, A, B) and a discount for energy inefficient buildings (see EPC levels G and H). However, these effects are only seen at each end of the scale. For a wide range of energy consumption values, the sales price does not show a premium or discount (see EPC levels C – F). Of note, the empirical results of the Sales Price Model reflect the results of the rent models only at the energy efficient end of the scale. Energy inefficient buildings, which did not show a discount for rent, showed a significant discount for sales prices. This suggests that other factors, e.g. asset risk factors could be involved. It appears plausible that potential buyers see an increased asset risk[143] in the energy inefficient buildings, since future policy changes may force them to invest heavily into their property to make them more energy efficient. In the mid-range other factors could play a role besides investment principles since the owner-occupier rate is higher than 45% in Germany[144] and they may prioritize other building aspects over its energy efficiency.

As with all empirical studies, there are limitations. First, the sample used for this analysis only includes data from the Rhein-Main Region. More regional analyses need to be performed to understand whether differences are present between regional markets. This will help to assess the generalizability of the results. Second, the sample consists of rent and sales offers. This limitation was already discussed in subsection 5.1 regarding the data generating process. Data from real transactions should yield results with greater generalizability. Such data are currently not publicly available. Third, many observations were lost because offerings were incomplete and missing values regarding the energy consumption or other variables of the buildings led to their subsequent deletion from the data set used for analysis.

In line with previously published literature, this thesis supports the conclusion that energy efficient residential buildings are sold and let for a premium.[145] It now shows this for the Rhein-Main Region in Germany using the current energy efficiency classification for buildings. Compared to Cajias and Piazolo (2013), who also based their analysis on data from Germany, this thesis shows a smaller impact of energy efficiency on the rent and sales prices.[146] Further, this study shows – at least for the Rhein-Main Region in Germany – that the impact of the categorical variable *"epc_level"* cannot be described as linear, as suggested by other authors.[147]

[143] This would entail an increased discount rate and subsequently a decrease in valuation of the building.
[144] Cf. Statistisches Bundesamt (2020).
[145] Cf. e.g. Cajias and Piazolo (2013, p. 53). Cajias et al. (2019, p. 189).
[146] Cf. Cajias and Piazolo (2013, p. 65).
[147] Cf. Kholodilin et al. (2017, p. 3231).

In this earlier study, an increase of 1 kwh/m^2 per annum was calculated to decrease the sales price by 0.05% and rent by 0.02%.[148] Comparing a D rated building with an A+ rated building (difference of around 100 kwh/m∧2 per annum), this would be equal to a 2% rent price and a 5% sales price premium. The findings in this thesis show values that are larger for the rent and the sales price premium. This difference between the analysis presented here and the earlier analysis could be the result of the linear and categorical descriptions or be caused by an increased awareness regarding climate and environment since the study was performed. Indeed, a few years later, but still before the most recent awareness shift, small effects of energy efficiency on the rental prices in regions such as Frankfurt were shown,[149] speaking for the latter hypothesis. Compared to the findings of this second study, the current analysis shows stronger impacts of energy efficiency, especially for the EPC levels of A+ through B. This may be the result of the level of analysis since nationwide data were analyzed[150] or it may be the result of a real change during the last few years driven by the change in climate awareness.

Unfortunately, there are nation-specific implementations of the EPC which make it difficult to directly compare the results of this study with results from other European countries. A comparison with studies not using the EPC as a proxy is even more limited. With all necessary caution, it can be said the sales prices in the Rhein-Main Region show a smaller premium compared to the sales price premium reported for other European countries. For example, the 6.5% premium found here is smaller than the 10.2% for the best performing EPC level found in the Netherlands[151] and the 9% premium found in Ireland.[152] Thus, the effect of energy efficiency on building valuation shows clear nation- and region-specific differences, which need to be considered by actors in these specific markets. It would be interesting to follow these nation-specific developments to find out if European policy changes will harmonize these developments across the European real-estate market.

9. Conclusion & outlook

The fundamental questions addressed by this paper are (1) whether and (2) how energy efficiency changes building valuation in the residential sector. To assess the potential impact of energy efficiency on building valuation, three different target variables were identified and used as read outs: The NOI, the GEI, and the market value. These target variables were chosen based on the valuation fundamentals of real estate. If energy efficiency has an effect on these target variables, it will be indicative that the energy efficiency of buildings influences their valuation. Further, the sign of the target variables, i.e. positive or negative, will show in which direction energy efficiency affects the valuation. Based on these deliberations, testable hypotheses were formulated for the NOI, GEI, and market value respectively (see p. 10). To address these hypotheses, three hedonic regression models were generated and two large empirical datasets of real estate offerings in the Rhein-Main Region in Germany were analyzed. The empirical results were presented and discussed in the context of the literature. In the following, this thesis concludes by summarizing the main implications of the findings for the real estate market and policy makers and the potential for future research.

This paper contributes to the literature with a detailed analysis of how the energy efficiency of buildings impacts their valuation in the residential real estate market of the Rhein-Main Region, one of the metropolitan areas of Germany, using the most recent data available. The study captures the impact of recent trends in the finance industry and in the German society in general on the real estate market of this region, making the results of the study relevant for stakeholders in the residential real estate market, e.g. developers, investors and regulators. Further, this paper has identified several areas of research that are of interest to understand the difference in or the non-existence of premiums/discounts in the future. In a nutshell, the following conclusions can be drawn:

- Landlords of average buildings can improve their current rental income by investing in energy efficiency. This investment shows a significant additional return if an A+ or B EPC level can be achieved. This premium goes beyond recouping energy cost savings and needs to be included when checking investments for financial viability.
- Developers can increase sales prices of their buildings by increasing energy efficiency above an EPC level of C. This needs to be considered in the profitability analysis. If the additional cost of construction for achieving EPC level A+, A or B is lower than the premium achieved, profitability can be increased.
- Private and institutional owners of G and H rated buildings should consider improving the energy efficiency of these buildings to increase their value and reduce exposure to future risks.
- Regulators and policy makers in Germany need to improve data transparency, availability and consistency regarding the residential real estate market to make financial implications of energy (in)efficiencies more visible.
- Regulators and policy makers on a European level need to introduce and implement a homogeneous EPC rating to increase comparability between literature and the different real estate markets in general.

[148] Cf. Kholodilin et al. (2017, p. 3231).
[149] Cf. Cajias et al. (2019, p. 187).
[150] Cf. Cajias et al. (2019, p. 182).
[151] Cf. Brounen and Kok (2011, p. 176).
[152] Cf. Hyland et al. (2013, p. 950).

Future research in this area should analyze the impact of energy efficiency in greater detail and should take the specific differences present in the real estate market and in societies into account. Different perspectives should be explored that will help to refine the results. These include but are not limited to looking at differences regarding energy efficiency premiums for different building types, the impact of socioeconomic factors on these premiums, differences between the energy source used in the building (e.g. oil, gas or pellets etc.) and the impact of CO_2 prices on energy efficiency premiums.

The underlying theme of sustainability will, based on current developments, very likely become more important in the years to come. As a direct consequence of this societal development, the energy efficiency of buildings will also become more relevant and differences in valuation will be even more pronounced in the future. The change in the real estate market has just begun as much of the current building stock has to be refurbished to reach climate targets set by the EU.[153] This also makes stricter regulations for new builds and a rise in cost for CO_2 intensive energy sources likely. Research in this area is urgently needed and this thesis may have contributed to this discussion by highlighting the effects of the energy efficiency of buildings on their valuation in the residential real estate market in a major metropolitan region of Germany.

[153] Cf. European Commission (2020a, p. 1).

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