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The economic losses of energy-efficiency renovation of Germany's older dwellings: The size of the problem and the financial challenge it presents

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ABSTRACT

Germany has ambitious goals to steeply increase the thermal energy efficiency of its older residential buildings, to reduce CO2 emissions and bring heating costs down, especially for low-income households who are over-represented in such dwellings. However, existing scholarship suggests it is doubtful whether the costs of renovation are offset by energy cost savings, even when renovating to only the most basic energy-efficiency standard. Renovating to more ambitious standards further increases the gap between costs and savings. This study offers a first attempt to quantify the dimensions of the problem and what it means for financing this ambitious goal. It analyses publicly available data on case studies of three of Germany's typical 1940s-1970s-era multi-apartment building types and three typical 1900s–1970s house types, retrofitted to a range of energy-efficiency standards in 2020–2021. It updates these for 2023 construction costs, energy prices, carbon prices and interest rates, and shows how rebound and prebound effects exacerbate the situation. Using cost-benefit analyses based on net-present values, payback is not achieved within 75 years in any scenario. The study concludes that Germany's goal can only be achieved through large financial inputs, i.e., sunk costs which will not be fully returned through energy savings.

1. Introduction

Germany has ambitious aims to decarbonize its residential building stock through energy-efficiency renovation of existing homes. As of 2022 the government's stated aim was a 65% reduction in CO2 emissions compared to 1990 levels by 2030 and carbon neutrality by 2050 (Bundesregierung, 2022). This is a daunting task, as just over half of Germany's 41 million dwellings are in older, energy-inefficient buildings, and energy-efficiency renovation is expensive. In theory this can be paid for, in rental properties, by an increase in rent, as Germany's Civil Law 559 allows landlords/landladies to increase the annual rent by up to 8% of the cost of energy-efficiency renovations (BGB, 2022), in addition to annual rental increases of just under 5%. This would bring payback for property owners in 12.5 years and a 100% profit over a 25-year technical lifetime of the renovation measures.

However, the rental market generally does not support such large increases (Galvin, 2023a, 2023b), and they would severely disadvantage low-income households, as energy savings due to energy-efficiency renovation are generally far too small to cover such a large increase. The German Socioeconomic Panel (SOEP, 2022) finds that 17% of households earn less than 60% of the median, a percentage that has persistently increased over the past decade (Brenke, 2018).

Since low-income households tend to live in energy-inefficient, unrenovated dwellings or, if they own their own home, seldom have the capital to pay for an energy-efficiency upgrade, the government and an alliance of consumer organisations and NGOs are looking for ways that energy-efficiency upgrades can be financed without disadvantaging such households: the so-called "*Wärmewende*" (heating transition) (Gebäudeallianz, 2023).

This paper investigates how this might be possible, given the peculiarities of Germany's dominant, long-running policy discourse around the issue of energy-efficiency renovation (on which see below) and the new situation of very large increases in construction and finance costs alongside unstable but falling energy prices. The study focuses on two sets of case studies of energy-efficiency renovation costs in typical, representative multi-apartment buildings and houses in Germany, and relates these more widely to parameters that are implicated in the costs and benefits of such renovation. The study uses classic cost-benefit analysis, comparing the net-present-value of the sum of up-front costs, debt servicing and opportunity costs with the net-present value of

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expected monetary gains from energy and CO2 tax savings over the technical lifetime of the renovation measures. The full details of the case studies are available as Supplemental material.

Note that there are also non-financial obstacles to energy-efficiency renovation, such as the "hassle" factor (Wilson et al., 2015) and inadequate knowledge of costs and benefits (Jaffe et al., 2005), as well as costs that can in some cases be financial and in other cases time-based, such as the administrative costs of seeking quotes, etc. These are not included in this study, which considers only actual, quantifiable costs and benefits.

Section 2 of the paper briefly surveys literature relevant to the study. Section 3 explains the method, Section 4 gives the results, Section 5 relates these to key issues identified in the literature, and Section 6 concludes.

2. Literature review

There is a long history of literature on the economics of energy-efficiency upgrades of residential building stocks, including Germany's. Overall it appears that Germany has two major problems with this project: the high cost of renovation in relation to the financial benefits of reduced energy consumption, especially given the steep increases in construction costs and interest rates since 2020 (Statistica, 2023); and a policy narrative that says it always pays back, which is has long been difficult to challenge despite evidence to the contrary (Rosenow and Galvin, 2013; Galvin and Sunikka-Blank, 2013). A recent comprehensive study of the cost of energy-efficiency renovation in European countries found that, even with 2020 prices, cost-effective renovations tended to be limited to those that aimed only to achieve modest energy savings (Hummel et al., 2021),

Aside from recent price increases, two longstanding problems with energy-efficiency renovation in Germany are so-called "anyway" costs, and prebound and rebound effects – here abbreviated to "(p)rebound" effects. German policy assessments of the costs of energy-efficiency renovation exclude costs which, it is assumed, would have to be paid "anyway" to bring a building to an as-new standard without energy efficiency improvements. A breakdown of a typical, policy-compatible division between "anyway" costs and "energy-efficiency costs" is given in Appendix 1. This is problematic because of its embedded assumption that property owners should always keep their buildings in as-new condition. Nevertheless, this study accepts this division of costs, so as to see whether energy-efficiency measures pay back even if such costs are excluded from the calculations.

However, the study brings (p)rebound effects fully into the picture because these severely compromise the amount of energy actually saved through energy-efficiency retrofitting and are thereby real-world influences on its economic viability.

Sunikka-Blank and Galvin (2012) introduced the term "prebound effect" for the phenomenon that householders in unrenovated homes in Germany consume, on average, 30% less energy than the official energy rating (*Bedarf*) of the building. The prevalence of the prebound effect in Germany and other European countries has been confirmed in a long list of studies over the past 11 years, including Amaruso et al. (2018), Desvallées (2022), Gróf et al. (2022), Karpinska and Śmeich (2020), Weber and Wolff (2018), Geraldi and Ghisi (2020) and Guerra-Santin et al. (2016). Whatever its causes (which are reviewed in Galvin, 2023), the important point for Germany's aspirations to decarbonize its residential buildings is that due to it, estimates of energy cost savings after energy-efficiency renovation are substantially over-optimistic, as "retrofits cannot save energy that is not actually being consumed" (Sunikka-Blank and Galvin, 2012: 265).

There is also strong evidence that households in highly energy-efficient buildings consume more, on average, than the official energy rating, a phenomenon known as the rebound effect (Haas and Biermayr, 2000; Peters and McWhinnie, 2018; Reuter et al., 2021). This also leads to over-estimates of the economic viability of energy-efficiency renovation, though not as great as those due to prebound effects because the absolute value of the gap between actual and expected consumption is smaller (e.g., <20 kWh/m^2/y compared to >60 kWh/m^2/y). As long as German policymakers continue to estimate energy savings without taking prebound and rebound effects into account, their estimates are substantially over-optimistic and their claims that certain types of retrofit are economically viable are questionable.

More generally, there is a prevalent discourse among policymakers in Germany, and to some extent in scholarship worldwide, that energy-efficiency upgrade measures are always economically viable. In academic literature this tends to lean on arguments proposed by Jaffe and Stavins (1994a,b). These authors "take it as given" that energy-efficiency upgrades – which they call "improved thermal insulation materials" – are economically viable and therefore failure to implement them is an "energy-efficiency gap" or "energy-efficiency paradox" due to market failures, irrational consumer behaviour and/or non-market barriers.

In a recent review, Solà et al. (2021) explore literature that applies this approach to household-level energy-efficiency upgrades in buildings and appliances. They interpret Jaffe and Stavins to mean that the energy-efficiency gap "arises when a technology *that may be profitable for consumers in terms of EE [energy efficiency]* is available, but consumers do not take advantage of it" (Solà et al., 2021: 5, italics added). This is a very useful clarification, as it makes the point that failure to embrace energy efficiency measures implies there is something wrong with the market or with consumers' economic behaviour *only* in cases where the energy-efficiency upgrade technology is profitable. If it is not profitable, then failure to embrace it is the rational thing to do.

However, in cases where energy efficiency upgrades are not profitable in themselves but would bring *a wider societal benefit,* Solà et al. (2021) and others propose market interventions to shift non-profitable energy-efficiency upgrades towards being economically viable. There may or may not be a specific higher-level economic calculation of societal benefit behind these cases, but it can be reasonably assumed that the benefits to society, such as climate change mitigation, occupants' health or cleaner air, would justify at least some level of intervention.

A number of authors have therefore proposed specific types of intervention to drive energy-efficiency renovation forward in cases where property owners are avoiding it. The most obvious and least costly to society are *regulatory instruments*. Papineau (2013) proposed these for the US, Lang (2004) for China, and Rosenow et al. (2018) globally. The German government uses regulatory instruments very sparingly for energy-efficiency retrofitting, even where it claims such renovation is economically viable for the building owner. The two main regulations are (a) if 10% or more of any feature of a building is being repaired, such as a wall or roof, it must be upgraded to new-build energy-efficiency standard, and (b) if a multi-apartment building is sold, its new owner must upgrade the thermal efficiency of the roof within two years. However, these measures are seldom enforced, as Germany does not have a building inspection regime.

So-called "soft" or "hybrid" regulatory measures have also been proposed, in particular the role of Corporate Social Responsibility (CSR) among large rental housing providers. Galvin (2023c) reports that the CSR framework of Vonovia, Germany's largest such firm, obliges it to support the Government's climate goals by upgrading all its properties to near-climate-neutrality by 2050 (Vonovia, 2022a, 2022b). To finance this and general maintenance it puts around 30% of the basic rent into a building upgrade fund, thereby limiting the dividends it pays to shareholders. CSR is an interesting quasi-regulatory instrument because, while the EU makes it compulsory for large firms to commit to a CSR framework and report annually on its functioning, there is wide choice as to the content of the framework (European Commission, 2021, 2022).

There is no equivalent system for Germany's small private landlords or owner-occupiers, but the Scottish government runs a "Code of practice" scheme, where landlords/landladies can get accreditation for adhering to a set of standards which include specified energy-efficiency measures (Scottish Association of Landlords, 2022; Landlord

Accreditation Scotland, 2022).

Another set of interventions are *financial instruments*, including direct subsidies, subsidised loan interest rates, tax incentives and a CO2 tax. Tax incentives have been explored by Villca-Pozo and Gonzales Bustos (2018) for financing energy efficiency in the housing sector in Spain. Germany recently introduced a CO2 tax on home heating energy consumption (Böhringer et al., 2021), currently at 30 €/tCO2.

Of course, financial incentives should not be needed where energy-efficiency upgrades pay for themselves through energy savings. The German government's Development Bank therefore only subsidises very high-energy-efficiency renovations, which are extremely expensive and do not pay back through energy savings. Its assumption is that renovations to a basic standard of about 70 kWh/m^2/y (labelled the "EH140" standard) do pay back and therefore do not need subsidies.

A further set of financial instruments may be grouped under the general heading of "revolving funds". These are identified in Bertoldi et al.'s (2021) survey of the main financial instruments used to incentivise energy-efficiency in EU countries. They have the form of a temporary investment from an outside investor, such as a utility or private agency, which is paid back to the investor through energy cost savings and can then be used again for further investment in another energy-efficiency upgrade. The assumption behind these instruments is that the upgrade will pay back but that the property owner does not have the up-front cash or creditworthiness to invest in the upgrade from their own resources, or that they have good reason to be highly risk-averse. These instruments include "energy performance contracting", where an energy service company invests in the upgrade, gives a guarantee of its energy performance and receives a pay-back from the energy savings (Robinson et al., 2015; Pätäri and Sinkkonen, 2014), but must compensate the client if the energy performance fails to bring the expected return (Tsoutsos et al., 2017). Similar instruments include "energy efficiency obligations", which can earn tradeable White Certificates (Bertoldi et al., 2010) and "energy services agreements", where the investor carries the full risk of energy under-performance (Kim et al., 2012).

For all such instruments, it is assumed that the upgrade will pay back on its own merit within a relatively short time so that, after the investor has got their return, the homeowner can then enjoy the financial benefits of the upgrade for the remaining years (or decades) of its technical lifetime. As Bertoldi et al. (2021) note, however, a number of these schemes have failed due to an over-estimate of the expected energy savings – much of which is due to prebound and rebound effects (Solà et al., 2021: 6).

The question then arises as to how these types of interventions could work in the specific situation of a country's quest to upgrade the energy-efficiency of its residential building stock, in this new era of high construction costs and interest rates, modestly higher (and now falling) energy prices, and the reality of (p)rebound effects. As noted below, renovation costs have increased by at least 43% in Germany since 2020 and are still trending upwards. The interest payable on loans has increased by around 300% and there is disagreement among forecasters on their likely future trajectory (European Central Bank, 2023). Meanwhile natural gas energy prices today are about 33% higher than in 2020 but with a falling tendency, as the government is strongly committed to making household heating bills affordable (Bundesregierung, 2022a).

To explore how these instruments could apply to the financing of energy-efficiency renovation in the current economic climate, this study analyses publicly available data on three exemplar case study apartment buildings, and three exemplar house types, which provide a credible cross-section of the costs and benefits of retrofitting Germany's stock of apartment buildings and houses. It models renovation to four different energy-efficiency standards for each of the apartments and to three different standards for each house, based on 2023 prices, both including and excluding (p)rebound effects. It then relates the results to the interventions outlined above, to see what resources and instruments may be available to move energy-efficiency renovation forward. Two research questions emerge from these concerns.

(a) Are energy-efficiency renovations in Germany's residential buildings, to even the basic minimum standard, likely to pay back in today's economic climate, with or without (p)rebound effects?
(b) If they clearly do not pay back, how can financial and regulatory instruments, of the types mentioned above, be used to accelerate the rate of energy-efficiency renovation?

3. Method

3.1. Data sources for renovation costs

I used three main data sources for the study. The first is a publicly accessible technical report, offered by the Institute for Housing and Environment (IWU – *Institut Wohnen und Umwelt*), of energy-efficiency renovation projects in 2020 on three different types of **multi-apartments building** in Augsburg which are well-represented throughout Germany (Enseling et al., 2020). The three are called MFH57, GMFH68 and GMFH78 in this study.[1] They have floor areas 353 m^2, 1777 m^2 and 2297 m^2 and contain 6, 24 and 42 apartments respectively. Buildings of each type were built throughout western Germany in 1949–1957, 1958–1968 and 1969–1978 respectively.

For each building, IWU had engaged a team of engineers, architects and financiers to estimate the costs of retrofitting to four different levels of energy-efficiency standard, and the likely energy-efficiency standard achieved for each of these standards, for each type of building. Although the cost estimates pertained to specific buildings located in Augsburg, they provide a credible guide for costs for similar buildings throughout Germany at that time. Key characteristics of these buildings are given in Table 1.

The second data source is a technical report, also offered by IWU, of energy-efficiency renovation scenarios in 2021 for three different but common types of **detached and semi-detached house** which are each widely represented throughout Germany (Hinz and Enseling, 2021). These are called ZFH48, EFH68 and EFH78 in this study. ZFH48 represents two dwellings in a semi-detached house,[2] while EFH68 and EFH78 are detached houses. The buildings have floor areas of 275 m^2, 110 m^2 and 157 m^2 respectively. The ZFH48 type was built extensively throughout Germany in 1919–1948, and the EFH68 and EFH78 were built extensively in western Germany in 1958–1968 and 1969–1978 respectively.

For each of these house types, IWU used a team of technical and economic experts to estimate energy-efficiency retrofit costs for reaching three different standards of energy efficiency based on 2021 prices. They used averages of Germany-wide building costs and assumed each house was in a typical state of repair for its age. Key characteristics of these buildings are given in Table 2.

3.2. Types of costs

Tables 1 and 2 give costs for two different aspects of the renovations, for each building: the "anyway" costs and the costs more directly related to increasing the energy efficiency of the building.

As noted above, I follow the government's method of excluding these

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[1] MFH is an abbreviation for "Mehrfamilienhaus", meaning "multi-apartment building", and GMFH is an abbreviation for "Grossmehrfamilienhaus", meaning "large multi-apartment building".

[2] ZFH is an abbreviation for "Zweifamilienhaus", meaning "two-dwelling building", and EFH is an abbreviation for "Einfamilienhaus", meaning "one-dwelling building". Note that the data source, Hinz and Enseling (2021), confusingly calls ZFH48 both EFH48 and ZFH48 in different parts of the report, but the substance of the report confirms it is a two-dwelling building, i.e., a semi-detached house.

Table 1
Data for costs in 2020 of retrofitting three different types of multi-apartment building to four different energy efficiency standards. Note that "anyway costs" are the costs that would need to be paid to bring the building up to a safe and liveable standard, without the additional costs for energy efficiency improvements. Data source: Enseling et al. (2020).

Standard label		Original	EH-140	EH-100	EH-70	EH-55
Building MFH 57						
Energy system		Gas	Gas	Gas	Pellets	Pellets
Floor area	m^2	353	353	353	353	353
Average U-value	$W/m^2/K$	1.47	0.33	0.25	0.33	0.27
Primary energy (Bedarf)	$kWh/m^2/y)$	290.8	97.9	68.6	32.5	30.9
Cost/m^2 of retrofit at the time	€/m^2	223	405	627	582	637
Cost of retrofit (excl anyway costs)	€		64,246 €	142,612 €	126,727 €	146,142 €
Anyway costs	€	78,719 €	78,719 €	78,719 €	78,719 €	78,719 €
Cost of retrofit (incl anyway costs)	€		142,965 €	221,331 €	205,446 €	224,861 €
Energy price pre-and post-retrofit	€/kWh	0.06	0.06	0.06	0.06	0.06
Building GMFH 68						
Energy system		Gas	Gas	Gas	Gas	Heat pump
Floor area	m^2	1778	1778	1778	1778	1778
Average U-value	$W/m^2/K$	1.28	0.4	0.41	0.24	0.28
Primary energy (Bedarf)	$kWh/m^2/y$	217.3	91.2	63.1	39.0	51.2
Cost/m2 of retrofit at the time	€/m^2	144	266	419	518	409
Cost of retrofit (excl anyway costs)	€		216,916 €	488,950 €	664,972 €	471,170 €
Anyway costs	€	256,032 €	256,032 €	256,032 €	256,032 €	256,032 €
Cost of retrofit (incl anyway costs)	€		216,916 €	488,950 €	664,972 €	471,170 €
Energy price pre-retrofit	€/kWh	0.06	0.06	0.06	0.06	0.06
Energy price post-retrofit	€/kWh	0.06	0.06	0.06	0.06	0.33
Building GMFH 78						
Energy system		Gas	Gas	Gas	Gas	Heat Pump
Floor area	m^2	2297	2297	2297	2297	2297
Average U-value	$W/m^2/K$	1.18	0.39	0.27	0.24	0.32
Primary energy (Bedarf)	$kWh/m^2/y$	161.6	83.0	61.1	34.9	49.2
Cost/m^2 of retrofit at the time	€/m^2	183	254	418	513	362
Cost of retrofit (excl anyway costs)	€		163,087 €	539,795 €	758,010 €	411,163 €
Anyway costs	€	420,351 €	420,351 €	420,351 €	420,351 €	420,351 €
Cost of retrofit (incl anyway costs)	€		583,438 €	960,146 €	1,178,361 €	831,514 €
Energy price pre-retrofit	€/kWh	0.06	0.06	0.06	0.06	0.06
Energy price post-retrofit	€/kWh	0.06	0.06	0.06	0.06	0.31

anyway costs from the cost-benefit analyses, as this gives a lowest estimate of the costs of energy-efficiency renovation and therefore provides a very useful extreme case study. It shows whether energy-efficiency renovation pays back, through energy cost savings, even if only the most obviously energy-relevant aspects of the costs are accounted for. The definition of what counts as an "anyway" cost is itself controversial, but I use the definitions adopted by IWU in this study, which are outlined in Appendix 1.

3.3. Recent cost increases

Because construction costs, interest rates and energy prices have increased markedly since these studies were done in 2020 and 2021, I updated these costs for mid-2023 values and performed a set of estimates based on these, in addition to the original estimates. Regarding energy prices, the gas price in Germany was around 0.06 €/kWh for some 10 years up to and including 2021, and has settled at around 0.09 €/kWh currently, after substantial oscillations in 2022 (Statista, 2023a). The electricity price, which is relevant to renovations that include a transition to heat pumps, has not changed significantly and is currently 0.32 €/kWh.

Figures from Statista (2023) indicate that renovation costs have increased by 43% since May 2020 and a 34% since May 2021. Estimates by the building research institute ARGE-eV (2022), which only go to mid-2022, confirm this trajectory, with a 23% increase from mid-2020 to mid-2022.[3] For the analysis I therefore increase the renovation costs for the apartments by 43% and the houses by 34%.

Since money is likely to be borrowed for large renovations, recent increases in interest rates need to be taken into account. Average interest rates on 25-year loans for owner-occupiers have risen from around 1% in 2015–2021, to around 4% in 2023 (Wohnglück, 2023), and rates at the time of writing range from a low of 3.84% to a high of 4.33%, depending on location and bank (Vergleich, 2023). For consistency I use the figure of 4% in this study.

Another important metric is the discount rate. This is the percentage by which an investor, which in this case can be a household, landlord/landlady or rental housing firm, assumes that income or expenditure made one year from how is reduced in value as seen from today's standpoint. Hamamoto (2023) recently estimated consumers' discount rates in respect of energy-saving investments using hedonic pricing and qualitative choice models, and found these ranged from 10.7% to 13.6% but could be as high as 50%. A more objective approach to estimating discount rates is offered by Zhu (2022), who notes, however, that "While the appropriate discount rate in a valuation exercise has always been a highly contested issue between valuation experts, significant changes in the macro-economy and the financial markets since the outbreak of the COVID-19 pandemic have added another layer of complexity to an already intricate matter." (pp. Cit.: 23) She proposes adding an equity risk premium of around 5% to the yield on the "risk-free" investment of government bonds. Since German government bonds are currently yielding 2.7%, this would give a discount rate of just under 8%. However, as the bond yield fell to under 1% in 2020 and could again fall in the future, I make a conservative estimate of 6% for the discount rate. For comparison, for commercial buildings Fujita K.S (2023) estimates discount rates at 8%–10%. Further, there are opportunity costs in investing in a project that may or may not bring a positive return. By investing in the renovation project the investor foregoes the opportunity

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[3] 1.062 × 1.159 = 1–23.

Table 2

Data for costs in 2020 of retrofitting three different types of house to three different energy efficiency standards. Note that "anyway costs" are the costs that would need to be paid to bring the building up to a safe and liveable standard, without the additional costs for energy efficiency improvements. Data source: Hinz and Enseling (2021).

Standard		Original	EH-85	EH-70	EH-55
Building ZFH48					
Energy system		Gas	Gas	Gas	Gas
Floor area	m^2	275	275	275	275
Primary energy (Bedarf)	kWh/m^2/y)	250	42.5	35	27.5
Cost/m^2 of retrofit at the time	€/m^2	0	318	333	412
Cost of retrofit (excl anyway costs)	€		87,450 €	91,575 €	113,300 €
Anyway costs	€	86,900	86,900 €	86,900 €	86,900 €
Cost of retrofit (incl anyway costs)	€		174,350 €	178,475 €	200,200 €
Energy price pre- and post-retrofit	€/kWh	0.06	0.06	0.06	0.06
Building EFH68					
Energy system		Gas	Gas	Gas	Gas
Floor area	m^2	110	110	110	110
Primary energy (Bedarf)	kWh/m^2/y	229.0	42.5	35.0	27.5
Cost/m2 of retrofit at the time	€/m^2	0	416	462	524
Cost of retrofit (excl anyway costs)	€		45,760 €	50,820 €	57,640 €
Anyway costs	€	48,180 €	48,180 €	48,180 €	48,180 €
Cost of retrofit (incl anyway costs)	€		94,160 €	99,000 €	105,820 €
Energy price pre- and post-retrofit	€/kWh	0.06	0.06	0.06	0.06
Building EFH78					
Energy system		Gas	Gas	Gas	Gas
Floor area	m^2	157	157	157	157
Primary energy (Bedarf)	kWh/m^2/y	209.0	42.5	35.0	27.5
Cost/m^2 of retrofit at the time	€/m^2	0	398	432	511
Cost of retrofit (excl anyway costs)	€		62,486 €	67,824 €	80,227 €
Anyway costs	€	56,677 €	56,677 €	56,677 €	56,677 €
Cost of retrofit (incl anyway costs)	€		119,163 €	124,501 €	136,904 €
Energy price pre- and post-retrofit	€/kWh	0.06	0.06	0.06	0.06

of getting a better return elsewhere. A return on a high-risk investment can be very high, or very low on a low-risk investment. Since this is real estate, an appropriate measure could be the annual increase in market value of an investment in property. Galvin (2003a) found a long-term return on Germany's apartments of 6.82%/y over the period 2007–2021, increasing to 9.15% in 2019–2021. As a rule of thumb I therefore estimate opportunity costs at 7%. This only pertains to cash-in-hand which the investor invests in the renovation project, because money that is borrowed for an energy-efficiency upgrade may not be used for an alternative purpose. Further, since this represents a loss, I assume that for each building the investors use their up-front cash for only 10% of the total project cost.

3.4. Carbon tax

There is currently a carbon tax of 30 €/tCO2 on domestic heating. For gas heating I use the figure of 0.182 kg CO2/kWh to estimate CO2 emissions, and for electrical heating 0.400 kg CO2/kWh, as the CO2 intensity of the electricity grid has fluctuated around this value in recent years (Umweltbundesamt, 2022), though it could be argued that this is also included in the retail electricity price. Note that for a heat pump the electricity demand is reduced in proportion to the coefficient of performance but increased again by up to 20% due to its different heating profile (Terry and Galvin, 2023). The combined effect of these two factors is that the energy consumption and therefore the CO2 tax can be lower with a heat pump even if the heat demand of the radiators is slightly higher than that for gas heating.

For rented properties the tax is apportioned between tenant and property owner, the proportions depending on dwelling's energy-efficiency standard. However, the proportions are not relevant in this study, as calculations are performed on the basis that the dwellings are regarded as owner-occupied, where the owner-occupier pays 100% of the tax regardless of the building's energy rating. By modelling all the dwellings in the building as owner-occupied we can get a clear view of the degree to which energy savings mitigate renovation costs. Note that the carbon tax adds to the benefit side of the cost-benefit calculation since energy-efficiency renovation reduces the amount of carbon tax due.

3.5. Rebound and prebound effects

A further important issue with these data sources is that they assume that the actual levels of energy consumption before and after renovation are the levels estimated by engineering calculations, i.e. that the *Bedarf* (officially estimated energy demand) is identical to the *Verbrauch* (actual energy consumption). For example, they assume that all the occupants of apartment building GMFH68 were consuming 217.3 kW h/m^2/y for heating prior to the energy-efficiency upgrade, and 91.2 kW h/m^2/y after it had been retrofitted to the standard labelled EH-140. These were its officially calculated ratings based on heating all rooms to 19 C all year round. However, due to prebound effects, pre-retrofit consumption is likely to be much lower than 217.3 kW h/m^2/y, and post-retrofit consumption might be a little higher than the estimated 91.2 kW h/m^2/y.

For this reason, I utilized a third data source, to provide estimates of likely prebound and rebound effects. Data was provided by Immoscout24, Germany's largest online real estate advertising portal, which gives either *Bedarf* or *Verbrauch* figures for each dwelling advertised for sale or rent in 2007–2021, a total of over 4 million dwellings. I consider apartments built after 1945, and houses built since 1900. There were effectively no energy efficiency regulations until 1980, so the vast majority of homes built in 1946–1979 have poor energy efficiency (though some have been renovated to various degrees). They represent the main cohort of residential buildings needing renovation and are representative of the case study renovations considered in this study. By matching each building's type and date of construction with its *Bedarf* or *Verbrauch* within the database, the average differences between *Bedarf* and *Verbrauch* could be estimated, both for apartment buildings and for houses, for each year of build. This will not give a pure estimate of prebound effects in un-renovated apartments, since apartments from these years that have been renovated will cloud the picture, but it at least shows the lower limits of likely prebound effects.

Further, since energy efficiency standards were mandated for apartments built after 1979, the *Bedarf* ratings should correspond to the legal standard, and the *Verbrauch* figures built in this period should fairly accurately show the deviation from this.

Approximate estimates of average rebound or prebound effects could thereby be calculated using a modified form of the prebound effect formula first introduced by Sunikka-Blank and Galvin (2012):

$$R_f = \frac{Verbrauch - Bedarf}{Bedarf} \times 100(\%) \quad (1)$$

If, for example, the average *Verbrauch* for buildings of a particular type built in a particular year is C kWh/m^2/y and the average *Bedarf* for buildings of this type built in this year is D kWh/m^2/y, the average rebound effect for this type of building in that year can be estimated as:

$$R_{f(ave)} = \frac{C - D}{D} \times 100(\%) \tag{2}$$

In cases where $R_{f(ave)}$ is negative, the prebound effect is occurring. For example, if $R_{f(ave)} = -33$, this is a prebound effect of 33%.

This provided a reasonably reliable way to estimate actual consumption (*Verbrauch*), given theoretical consumption (*Bedarf*), at least in terms of averages.

3.6. *Calculation method and tool*

There are two possible ownership types among the actors paying for the renovations considered in this study: owner-occupiers and landlords/landladies. Each pays the costs of renovation, but the benefits accrue to owner-occupiers through energy savings, and to landlords/landladies through rent increases. This study considers owner-occupiers only, as it gives estimates of benefits based entirely on the building's expected performance. How this is reflected in rental market (and sales) markets has been investigated in other studies (Taruttis and Weber, 2022; Kholodilin et al., 2017; Cajias et al., 2019; Galvin, 2023, 2023a, 2023b).

The calculation method estimates net-present-values of costs and benefits. The algorithms for the different aspects of this are as follows.

The monthly payment *P* on a loan of value *L* with interest rate *R*% for a term of *Y* years is given by:

$$P = \frac{L \times R/1200 \times \left(1 + R/1200\right)^{Y\times12}}{\left(1 + R/1200\right)^{Y\times12}) - 1} \tag{3}$$

The net present value *M* of these loan repayments, which in this case are spread over a 300-month period, is then:

$$M = \frac{P \times \left(1 - F^{300}\right)}{1 - F} \tag{4}$$

where *F* is a factor based on the discount rate *D*, namely:

$$F = 1 - D/1200 \tag{5}$$

Opportunity costs *U*, which can be considered a net present value in themselves, are given by:

$$U = Q \times \frac{D_U}{1200} \times \frac{\left(1 - F^{Y\times12}\right)}{(1 - F)} \tag{6}$$

Where *Q* is the amount of the property owner's own up-front capital invested in the renovations and D_U is the expected annual rate of return for an alternative investment.

The net present value K_{npv} of the total investment cost is therefore:

$$K_{npv} = M + Q + U \tag{7}$$

The monthly energy savings S_m as a result of the energy-efficiency upgrade are given by:

$$S_m = \frac{(V_2 - V_1) \times W \times C}{12} \tag{8}$$

Where V_1 and V_2 are the actual pre-and post-retrofit consumption (*Verbrauch*) in kWh/m^2/y, *W* is the liveable floor area of the building in m^2, and *C* is the cost of energy per kWh.

The monthly savings S_T through reduced carbon taxes are given by:

$$S_T = T \times E/1000 \times (V_2 - V_1)/12 \times A \tag{9}$$

where *T* is the tax rate in €/tCO2, *E* is the CO2 emissions rate of the energy carrier in kgCO2/kWh, V_1 and V_2 are pre-and post-retrofit energy consumption (*Verbrauch*) in kWh/m^2/y, and *A* is the floor area in m^2.

Again we use our discount rate *D*, giving the factor *F*, as above. The net present value S_{npv} of *Y* years' worth of energy and tax savings, i.e., *Y* × 12 months' worth, is given by:

$$S_{npv} = \frac{(S_m + S_T) \times \left(1 - F^{Y\times12}\right)}{1 - F} \tag{10}$$

The author developed a desktop software tool, incorporating these formulas, to perform cost-benefit analyses for each of the energy-efficiency retrofit scenarios. The tool was extensively tested by research teams in two universities and an international business consultancy in Germany, and was made publicly available for feedback and critique. A screenshot of the user interface is given in Appendix 2.

In all, 84 cost-benefit analyses were performed for these buildings, since for each building and energy-efficient standard, analyses were performed using the original years' costs and todays' costs, and using both *Bedarf* and *Verbrauch* values for pre-and post-retrofit energy consumption. For one of the buildings a sensitivity analysis was also performed, to see how far interest rates, discount rates, alternative investment returns would have to reduce, and CO2 tax would have to increase, to reduce the payback time to 25 years. As noted above, the full details of the results are available in the Supplemental material.

4. Results

4.1. *Prebound and rebound effects*

Fig. 1 shows average *Bedarf* and *Verbrauch* as it stood in the building stock 2019–2021, for apartments built between 1946 and 2019, by year of build, based on an analysis of Immoscout24 data. The figure shows that, for apartments, the average *Verbrauch* was substantially lower than the average *Bedarf* for apartments which had a *Bedarf* greater than about 140 kW h/m^2/y. Hence the prebound effect dominates in this group.

For apartments with average *Bedarf* 80–140 kWh/m^2/y neither prebound nor rebound effects tend to dominate. However, rebound effects are substantial for apartments with average *Bedarf* lower than about 75 kWh/m^2/y.

On average in this dataset, *Verbrauch* is 18.3% below *Bedarf* for apartments with average *Bedarf* 140 kWh/m^2/y or higher. However, prebound effects are likely to be higher than this in unrenovated apartments because the data is contaminated with rebounds from apartments of these years which have been renovated. I use, therefore, a prebound effect of 20%.

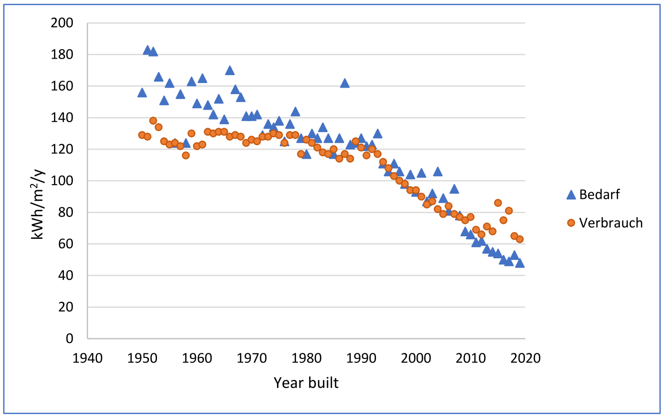

Fig. 1. Average Bedarf (official energy rating) and average Verbrauch (actual energy consujmption), by year built, of apartments built after 1945 and advertised for sale in 2019–2021. Author's calculations from Immoscout24 data.

Using a similar approach for houses, the dataset indicates a prebound of around 34%. These values are in accord with estimates for Germany by others such as Sunikka-Blank and Galvin (2012).

Table 3 gives prebound and rebound estimates for the four different energy efficiency renovation standards used in the analysis.

4.2. *The economics of energy-efficiency renovation*

Figs. 2–4 give the net present values of financial gains for energy-efficient renovation of apartment buildings MFH-57, GMFH68 and GMFH78 respectively, without and with (p)rebound effects, based on 2023 costs. All these results give negative net present value of gain, indicating that renovating these apartments to any of the four efficiency standards incurs a net financial loss. The net present value of the gains through energy savings and CO2 tax savings are not sufficient to defray the net present value of the costs. In all cases payback does not occur within 75 years (after which the computer program trips out to prevent overrun).

The losses range from 13,381 € for the smallest building renovated to the lowest standard, without (p)rebound effects, to 121,389 € for the largest building renovated to the highest standard, with (p)rebound effects. Perhaps the most important result is the loss of 40,063 € for the smallest building renovated to the lowest standard, with (p)rebound effects. (P)rebound effects are virtually inevitable, and there is little point in renovating to a standard lower than this.

Meanwhile, Figs. 5–7 give the net present values of the losses as a percentage of the net present values of the costs, without and with (p) rebound effects. When (p)rebound effects are taken into account, renovating to the lowest standard incurs losses of over 40% for all three buildings. This means that it costs 1.40 € for every 1.00 € worth of energy saved over 25 years. For renovations to the highest energy standard the losses are over 120% for the largest two buildings: it costs more than 2.20 € for each 1.00 € worth of energy saved.

The same pattern of results is obtained for the case study houses, but more severe. Again payback is not achieved within 75 years, and the minimum percentage losses are 41.9%, in the case of house ZFH48 without prebound or rebound effects. Using the original prices of 2021 and no (p)rebound effects, there is no case that pays back within less than 75 years. We should note, however, that for the houses the lowest energy-efficiency standard considered here is reasonably high, at 42.5 kWh/m^2/y (full results available in the Supplemental material).

Table 3
Prebound and rebound effects used in the analysis.

Apartments						
Policy label of energy efficiency standard		Original	EH-140	EH-100	EH-70	EH-55
Bedarf (official energy efficiency rating)	kWh/m^2/y	various, generally >140	70	50	35	27.5
(p)rebound effect (-ve if prebound)	%	−20	3	10	20	30
Likely Verbrauch (actual energy consumption)	kWh/m^2/y	various, generally <115	72.1	55	42	35.75
Houses						
Policy label of energy efficiency standard		Original		EH-85	EH-70	EH-55
Bedarf (official energy efficiency rating)	kWh/m^2/y	various, generally >210		42.5	35	27.5
(p)rebound effect (-ve if prebound)	%	−34		10	15	20
Likely Verbrauch (actual energy consumption)	kWh/m^2/y	various, generally <150		46.8	40.3	33

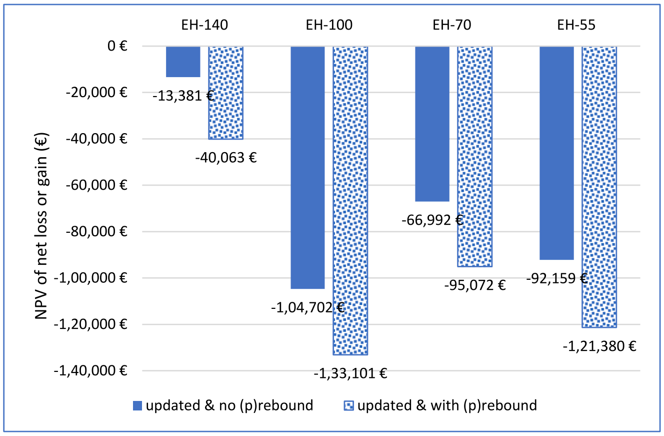

Fig. 2. Net present value of net gains or losses for energy-efficient renovation of MFH-57 apartment building in Augsburg, based on 2023 energy and construction prices, excluding and including rebounds/prebounds.

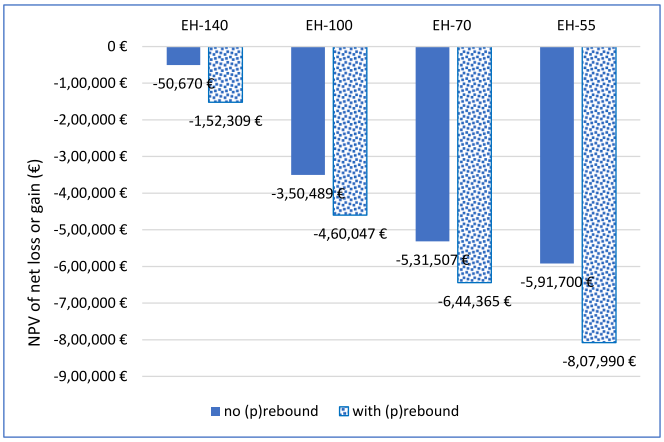

Fig. 3. Net present value of net gains or losses for energy-efficient renovation of GMFH-68 apartment building in Augsburg, based on 2023 energy and construction prices, excluding and including rebounds/prebounds.

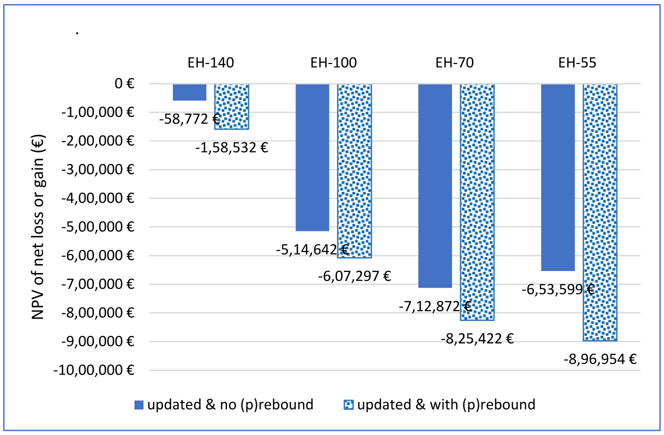

Fig. 4. Net present value of net gains or losses for energy-efficient renovation of GMFH-78 apartment building in Augsburg, based on 2023 energy and construction prices, excluding and including rebounds/prebounds.

It is interesting to compare these results with those for 2020 prices. In the Supplemental material, for each of the six types of building, there are

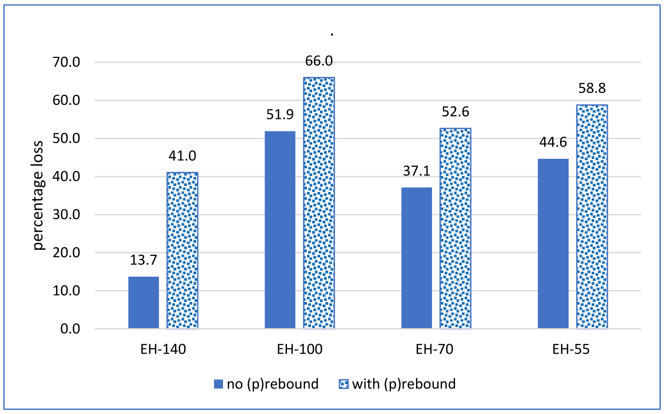

Fig. 5. Apartment building MFH57 NPV losses as percentage of NPV cost, 2023, without and with (p)rebound. Note that losses are displayed as positive on the graph.

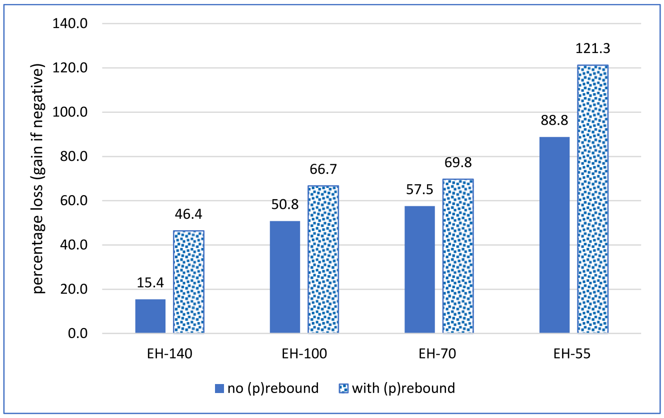

Fig. 6. Apartment building GMFH68 NPV losses as percentage of NPV cost, 2023, without and with (p)rebound.

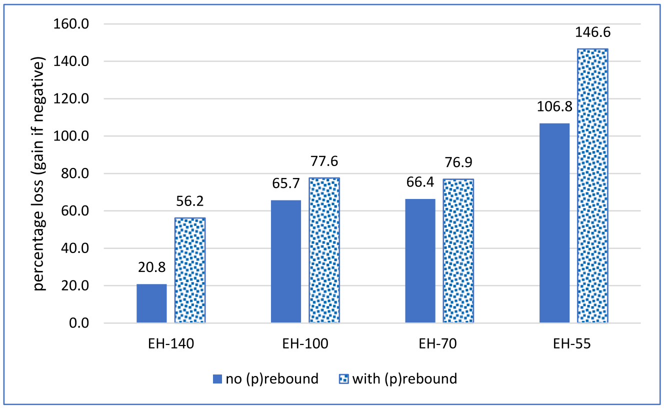

Fig. 7. Apartment building GMFH78 NPV losses as percentage of NPV cost, 2023, without and with (p)rebound.

graphical displays of net present value of net gains or losses for energy-efficient renovation based on 2020 energy and construction prices, excluding and including rebounds/prebounds. These are alongside the graphs of the same parameters based on 2023 prices. As shown there, the only two cases where payback is achieved are for renovation to the lowest energy-efficiency rating with apartment buildings MFH57 and GMFH 78, and only if prebound effects are not taken into account – meaning they exaggerate the amount of energy saved. For the 19 other cases the losses are large, especially for renovation to the highest energy-efficiency standards.

Table 4 gives the cost of CO2 abated, in €/tCO2, for each of the apartment renovations, in each case including (p)rebound effects. The lowest is 561 €/tCO2, for the smallest building renovated to the lowest standard, of 70 kWh/m^2/y. This is substantially higher than the current levy of 30 €/tCO2 for home heating in Germany and the current market price of around 100 €/tCO2. The highest is 1707 €/tCO2, for building GMF78 renovated to the EH100 standard, i.e. aiming for a consumption rating of 50 kWh/m^2/y.

For all these cases we should note that “anyway” costs are not taken into account in the calculations, and that these costs are very generously defined. In reality, a property owner would need to find the money for these costs too.

4.3. *Mitigating the problem*

The above results answer our first research question: energy-efficiency renovation of typical, exemplar apartment buildings in Germany, to the basic standard does not pay back. Nor does renovation of typical houses to a more ambitious standard. In light of this finding, the second research question needs to be addressed: what changes would need to be made to enable Germany to renovate its apartments economically, at least to a modest standard of energy-efficiency? I will only consider apartments here, as the data covers the most basic standard. However, the principles can also be applied to houses renovated to slightly higher standards.

Table 5 gives the magnitudes of different types of changes that would, theoretically, make renovations to the lowest two standards pay back in 25 years. Both cases consider the smallest building, MFH57. Case 1 considers a retrofit to the minimum standard of around 70 kWh/m^2/y (labelled EH140) and Case 2 considers the same building retrofitted to the higher standard of 50 kWh/m^2/y (EH100). The effects of changes to CO2 tax, post-retrofit gas price and subsidies are each considered separately, but the financial percentages are considered together as a package (shaded in the table), as these tend to track each other in the economy.

As Table 5 shows, for retrofitting to the minimum standard (EH140), one option would be for the loan interest rate to be reduced from the current 4% to a lower figure of 0.6%, with the investor’s discount rate consequently reduced from 6% to 1% and the likely return on alternative investment reduced from 7% to 2%. In other words, the economy would need to go into very low interest mode with very low investment returns.

Alternatively, payback would be achieved if the CO2 tax rate were increased to 403 €/tCO2, or the post-retrofit gas price were increased to 0.125 €/kWh, or a subsidy of 49,000 € were provided. Such a subsidy would amount to 54% of the energy-efficiency upgrade costs (but would not cover the “anyway” costs).

Note that these alternatives would bring payback within 25 years, making the renovations just cost-neutral (if “anyway” costs are excluded). They would not allow for revolving funding mechanisms such as those explored by Bertoldi et al. (2021) as they do not bring any profit.

The second half of Table 5 indicates that renovating to the higher standard of 50 kWh/m^2/y would require far more radical financial

Table 4
Cost of CO2 abatement (€/tCO2) for three different apartment buildings renovated to four different energy efficiency standards.

Standard label	EH140	EH100	EH70	EH55
Target consumption (kWh/m^2/y)	70	50	35	27.5
Building MFH57	461 €	799 €	581 €	668 €
Building GMFH68	491 €	770 €	847 €	671 €
Building GMFH78	617 €	1207 €	1175 €	897 €

Table 5
Sensitivity analysis on MFH57. Changes required to achieve payback in 25 years.

Case 1. Retrofit to EH140 (70 kW h/m^2/y)				simultaneous changes?
	Units	original	altered	
NPV losses as percentage of NPV cost	%	41	0	
Interest rate on loan	%/y	4	0.6	Yes
Discount rate	%/y	6	1	Yes
Alternative investment return	%/y	7	2	Yes
CO2 tax	€/tCO2	30	403	No
Post-retrofit gas price	€/kWh	0.09	0.125	No
Subsidy	€	0	49,900	No
Case 1. Retrofit to EH100 (50 kW h/m^2/y)				
	Units	original	altered	
NPV losses as percentage of NPV cost	%	66	0	
Interest rate on loan	%/y	4	−5.5	Yes
Discount rate	%/y	6	1	Yes
Alternative investment return	%/y	7	2	Yes
CO2 tax	€/tCO2	30	1050	No
Post-retrofit gas price	€/kWh	0.09	0.276	No
Subsidy	€	0	162,200	No

changes to achieve payback in 25 years. This would require either Interest rates to be negative, at −5.5%, or the CO2 tax to increase to over 1000 €/tCO2, or the gas price to treble to 0.276 €/kWh, or a subsidy of 162,200 €. None of these seem likely options. In all the retrofit cases considered here, the carbon tax would need to be increased substantially, and well above current market rates, to make a substantial impact on the economics of energy-efficiency renovation. Increasing the carbon tax would also impact harshly on low-income households.

A further option worth exploring is the owner-investment model used by large corporate rental housing providers in Germany such as Vonovia (see Section 2). These corporations put a substantial percentage of the basic rent, around 30%, into a fund for ongoing building maintenance and climate goals. Table 6 shows the percentage of basic rent that a landlord/landlady would have to put aside, or the percentage of the rentable value of a property that an owner-occupier would have to save, over 25 years, to accumulate sufficient funds for an energy-efficiency retrofit to pay back in 25 years, and also in 10 years, excluding and including “anyway” costs. The basic rent is assumed to be 6.50 €/m^2 of floor area, which is typical for an unrenovated apartment. Calculations are shown for the basic standard (EH140) and the next highest standard (EH100).

The calculations show that, for the building MFH57, 7.25% of the rent (or rentable value, in the case of an owner-occupier) would have to be saved continually over 25 years to finance an energy-efficiency retrofit to the basic standard of around 70kW h/m^2/y that would pay back in 25 years. This amounts to just under 50,000 €. If “anyway” costs are included, this rises to 162,558 €, requiring 23.62% of the rentable value to be saved.

To enable a 10-year payback, a cash injection of 78,000 € would be needed, which would require 11.33% of the rentable value to be saved over 25 years. Taking “anyway” costs into account, a cash injection of 190,568 € would be required, amounting to 27.70% of the rentable value over 25 years.

For the second case, of retrofitting to around 50 kWh/m^2/y, the amounts appear prohibitive, at 23.56%, 33.91%, 29.69% and 45.04% of the rentable value respectively.

The first of these scenarios could point a way forward for financing energy-efficiency renovation. If landlords/landladies and owner-occupiers can be persuaded to put aside just under 24% of the rentable value of their properties continually, they can finance a retrofit that pays back in 25 years, including the “anyway” costs. If they put aside 28% the retrofit will pay back in 10 years. The profit for the next 15 years can then be used to help finance subsequent retrofits, or invest in renewable energy, etc.

Table 6
Portion of basic rent (or equivalent basic rent) needed to be saved for 25 years, to finance payback in 25 years (excluding “anyway” costs) and 10 years (excluding and including “anyway” costs, for retrofit of apartment building MFH57 to two different standards.

	Case 1. Retrofit to EH140		Case 2. Retrofit to EH100	
	amount needed to be saved (€)	Percentage of basic rent to be saved (%)	amount needed to be saved (€)	Percentage of basic rent to be saved (%)
Rentable value saved for 25 years to finance 25-year payback	49,990 €	7.25	162,200 €	23.56
Rentable value saved for 25 years to finance 25-year payback, including “anyway” costs	162,558 €	23.62	274,768 €	33.91
Rentable value saved for 25 years to finance 10-year payback	78,000 €	11.33	197,500 €	29.69
Rentable value saved for 25 years to finance 10-year payback, including “anyway” costs	190,568 €	27.70	310,068 €	45.04

Note that all these calculations take (p)rebound effects into account. They thereby reflect the likely actual cost and benefits of renovation, rather than mere theoretical values which are seldom realised in practice.

Further, if the government could be persuaded to shift its subsidies from the highest energy-efficiency standards to the basic standard, this would not only save energy far more economically efficiently, it would make it easier for property owners to retrofit earlier, rather than have to wait for their cash injection to build up to a substantial level.

5. Discussion

The answer to the first research question is very clear: the evidence of the three common apartment types indicates that energy-efficient renovation of Germany’s typical apartments does not pay for itself in today’s economic climate. If (p)rebound effects are taken into account, payback does not occur within 75 years of the renovations, for all three buildings, even for the most modest energy-efficiency standard. In the highly unlikely event that (p)rebound effects do not occur, the payback times are 462 months, 504 months and 805 months for the MFH57, GMFH68 and GMFH78 buildings respectively, when renovating to the lowest standard. For all other standards, including those for houses, both with and without (p)rebound effects, payback does not occur within the first 75 years.

It could be argued that the period of 25 years, used here as the technical lifetime of the renovation measures, is too short to reflect the actual rate of deterioration of building components. Also, in cases of very high prebound effects, such as a single person using the heating frugally, 25 years is too short a period to expect payback. However, as noted above, these points are eclipsed by the fact that payback generally is not achieved within 75 years. An important consideration in this study was the exclusion of "anyway" costs, an approach which sharply reduces the apparent costs of energy-efficiency renovation. As noted above, this is controversial: for some of the scenarios, the costs would be more than double if "anyway" costs were included in the cost-benefit analysis (e.g., MF57 renovated to 100 kWh/m^2/y). From the perspective of a building owner, "anyway" costs simply have to be paid if the building is to be renovated to a more energy efficient standard. This is an area that urgently needs critical research, as there do not appear to be any peer-reviewed studies on it at present.

The findings of this study have important implications for policy discourse in Germany. As noted in Section 2, it is very difficult to dislodge the entrenched policy discourse that energy-efficiency renovation pays for itself. It should be noted that, using 2020 prices, the analysis also showed that energy-efficiency renovation paid for itself only in the case of renovating to the lowest standard, and only if (p) rebound effects did not occur and "anyway" costs were excluded from the accounting (see Supplemental material[4]). This tends to confirm that the German government has been able to purvey the notion of economic viability over the past decades only by ignoring the reality of (p)rebound effects. However, now that construction and finance costs have increased dramatically, even this notion cannot be sustained.

It would be much better for the government to openly acknowledge this and, from a position of realism, explore instruments that might be effective under these circumstances. This is where the second research question is addressed. The study found that the corporate social responsibility (CSR) model, where the property corporation dedicates up to 30% of the rentable value of its stock to an upgrade fund, gives new life to the notion of economic viability. The above analysis showed that if a property owner dedicates around 28% of the rentable value to a property upgrade fund continually, 25 years' worth of this will pay for the "anyway" costs and the energy-efficiency upgrade costs to such an extent that the energy cost savings will pay for the remainder of the investment within 10 about years – provided the energy-efficiency standard aimed for is modest.

It could therefore be argued that this is what it actually costs to own a building and keep it in a technically and societally acceptable condition. Large rental housing providers have already worked this out, but small private landlords/landladies and even owner-occupiers often neglect their buildings or run them on the bare minimum of maintenance (Galvin, 2023c; März, 2018; März et al., 2022). This is where the issue of regulatory instruments, discussed in Section 2, could be reconsidered. There is no regulation in Germany that requires landlords/landladies to practice anything like the CSR model and, unlike in Scotland, there is not even a provision for landlords/landladies to gain accreditation that might include such a provision. This needs to be addressed.

A complementary move would be to reorient federal subsidies. These are currently given only for the highest energy-efficiency standards, which are economically the most inefficient (Hummel et al., 2021). Giving them instead for renovations to the basic standard would (a) reduce CO2 emissions far more deeply than the current practice (Galvin, 2023d), and (d) enable property owners who follow the CSR savings model to renovate earlier, avoiding having to wait 25 years for their savings to be sufficient. A variation would be subsidised interest rates, bringing interest payments on loan money down to a level that would enable a property owner to start a renovation project before accumulating the full 25-years' worth of savings.

An alternative would be to use revolving funds, also discussed in Section 2, in conjunction with the CSR savings model. Provided the property owner's saving pattern has been established, revolving funds could be invested to get the renovation underway, and repaid through a combination of energy cost savings and the CSR-type savings.

Other instruments explored in Section 4.3 for improving economic viability do not seem reasonable. Increasing the CO2 price to over 400 €/tCO2 would harshly penalize households, especially those on low incomes, as would allowing energy prices to double or triple.

There is also a prolific literature on the co-benefits of energy-efficiency renovation (Kuckshinrichs et al., 2010). These include: physical health benefits of warmer homes (Howden-Chapman et al., 1996; Baniassadi et al., 2022); mental health benefits (Curl et al., 2014); the benefits to society of reduced CO2 emissions and reduced fine particulate emissions (Trechera et al., 2022; Caracci et al., 2022; Prinz and Richter, 2022); and the national-societal benefit of reduced dependence on imported energy carriers such as gas and oil (Krebs, 2022; Halser and Paraschiv, 2022). There is as yet no consensus on the extent to which these benefits make up for the economic losses of energy-efficiency renovation, and this is the topic of forthcoming research by the author.

A related question is, how can net-zero CO2 emissions be achieved if it is economically non-viable to do this at the level of the individual building? While this question is beyond the scope of this paper, readers may begin to explore it in studies such as Rosenow and Hamels (2023) and Galvin (2022).

With regard to CO2 emissions, the EU plans to extend the Emissions Trading Scheme to the building sector in 2027 (European Commission, 2023). This could enable property owners to regain some of their energy-efficiency investment through emissions trading. However, their gain might be quite small due to the relatively small energy savings. For example, renovating building GMFH68 to a standard of 35.1 kWh/m^2/y costs 599 €/m^2 and saves 127 kWh/m^2/y, or 3175 kWh over 25 years. This reduces CO2 emissions by 0.58 t/m^2, which would be worth about 58 € in an emissions trading scheme in which CO2 trades at 100 €/t. Hence about one-tenth of the costs might be regained through the Emissions Trading Scheme, but about one-third of this gain would be lost through the cessation of gains from the current carbon tax reductions.

A strength of this study is its focus on standard renovation strategies in specific case study buildings with publicly accessible input data drawn from teams of relevant professionals. Its main limitation is that it is therefore somewhat narrow and only refers to exemplary cases. There may well be buildings where energy-efficiency renovation to the basic standard pays back, though these are likely to be outliers that are not representative of the dimensions of the problem in Germany. There are other cases, known to the author, where the losses incurred through energy-efficiency renovation are substantially higher than those reported here.

6. Conclusion and policy implications

There are two broad areas where the findings of this study have implications for Germany's policy aim to increase the energy efficiency of its building stock, especially among homes occupied by low-income households: one on the level of discourse, and the other technical and economic.

On the discursive level, the German government needs to adopt a realistic view of the economics of energy-efficiency renovation. Denying that it is economically viable on its own terms is often seen as tantamount to climate change denial or as a basic objection to energy efficiency. There often seems to be an underlying belief that as long as policymakers can maintain it is economically viable, they occupy the high moral ground for persuading property owners to renovate. However, this is counterproductive, as increasing numbers of professionals in the industry recognise that it simply does not pay back, through energy cost savings, within its technical lifetime. It would be much better to start with realism. The discourse should first acknowledge the financial problem and, starting from there, engage people in finding creative ways to pay the very high cost of energy-efficient renovation.

On the technical level, the government could learn from large

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[4] The Supplemental material can also be downloaded from: http://justsolutions.eu/JPOsupplement/.

corporate rental housing corporations, which have to make renovation profitable in order to survive in business while fulfilling their obligations in corporate social responsibility. These practitioners have learnt that a considerable sum of money needs to be put aside annually, to keep their properties modern and to support climate goals. It is very interesting that the study found that the sum needing to be put aside to ensure payback in 25 years while also covering "anyway" costs, i.e., a sum equal to around 24% of the equivalent rental value, is within range of the percentage put aside by these corporations. The government needs to devise ways to encourage, cajole and support small private landlords/landladies to do similar. This could follow and build on the form of Scotland's "Code of practice for landlords" but go further, giving landlords/landladies accreditation for committing themselves to putting aside sufficient funds to keep their properties modern and energy efficient.

The government could also promote a similar idea among owner-occupiers: if you own a house, you should build up a realistic fund for modernisation and energy efficiency, not to mention basic maintenance.

The government also needs to avoid mechanisms that disadvantage low-income households. The idea of adding 8% of the energy upgrade costs to the rent annually may make mathematical sense for entrepreneurial investors, but it demands that households pay four or five times over for the energy cost savings that renovation brings.

The government should also avoid using the CO2 tax as a lever to induce property owners to renovate. To be effective, the tax would need to be over 400 €/tCO2 and in some cases well over 1,000 €/tCO2. This would be 4–10 times as high as the current market rate and would severely penalize low-income households.

A further important policy shift would be to direct federal subsidies away from super-high-energy efficiency renovations toward renovations that meet basic energy-efficiency standards. This would not only bring a far higher return in terms of CO2 abated per euro invested, but would also help property owners who have not yet saved sufficient capital to undertake a basic standard renovation.

This study appears to be the first that challenges Germany's prevailing government discourse about the economic viability of energy-efficient renovation, on the basis of professionally estimated costs and energy savings in a set of renovation scenarios that cover typical, representative residential buildings. However, it does not leave the matter there but, based on the findings, makes constructive suggestions as to how the building stock can be renovated despite the hurdle of economic non-viability.

No conflict of interest

The author declares that he has no conflict of interest in the research, writing or publication of this article.

CRediT authorship contribution statement

Ray Galvin: All the research, Formal analysis, calculations and writing of the article is the work of the sole author.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix 1. The "anyway" costs

In estimating the cost of energy-efficiency renovation, German policymakers do not include the costs of work and components that would be incurred if an old building were being brought up to a good standard without energy-efficiency improvements. These are called "anyway" costs (*ohnehin- or umsonst-* or *sowieso-Kosten*). A typical definition of these costs, as given by the Institut Wohnen und Umwelt (www.iwu.de) is outlined in Table A1.

Table A1
"Anyway" costs as defined by the Institut Wohnen und Umwelt, as given in Hinz et al. (2021), P. 26.

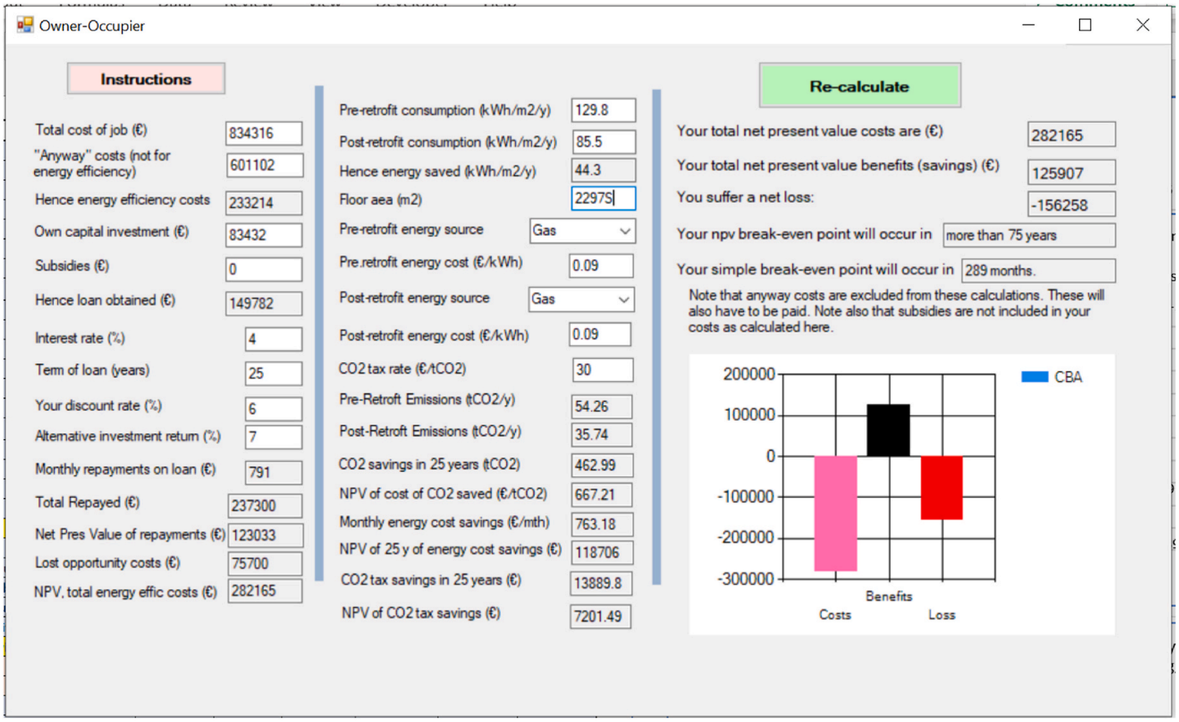
Component or work	"Anyway" costs, and commentary
External wall insulation	The render and paint and their application are regarded as "anyway" costs but the insulation an its application is an energy-efficiency cost – regardless of the condition of the original render and paint.
Replacing double-glazed windows	All are regarded as "anyway" costs, regardless of the condition of the existing windows.
Replacing double-glazed with triple-glazed windows	Only the difference in cost between a new double-glazed and a new triple-glazed window is regarded as energy-efficiency costs; the rest are "anyway" costs.
Replacing double-glazed with passive house windows	All the costs are regarded as energy-efficiency costs
Replacing the building's main entrance door	50% of the costs are regarded as "anyway" costs, regardless of the condition of the existing door.
Upgrading a pitched roof	About half the costs are regarded as "anyway" costs, depending on the new energy-efficiency standard.
Insulation of cellar ceiling	No "anyway" costs; all costs are regarded as energy efficiency costs.
Eliminating thermal bridges	No "anyway" costs; all costs are regarded as energy efficiency costs.
Replacement of boiler	All costs are regarded as "anyway" costs, regardless of the condition of the existing boiler.
Replacement of boiler with heat pump	The equivalent cost of a new boiler is regarded as "anyway" costs and is subtracted from the cost of the heat pump, regardless of the condition of the existing boiler.
Installing a solar thermal system	No "anyway" costs; all is regarded as energy upgrade costs.
Changes to the heating circulation system (distribution pipes, radiators, fittings)	50% of these costs are regarded as "anyway" costs, regardless of the condition of the existing heating circulation system.

(*continued on next page*)

Table A1 (*continued*)

Component or work	“Anyway” costs, and commentary
Scaffolding	50% of the cost is regarded as “anyway” costs, due the assumption that the building would have been due to be painted anyway.
Architectural services	Costs architectural services such as construction supervision and acceptance, energy consulting, thermal bridge calculations and applications for subsidies are counted 50 % as “anyway” costs and 50% as energy-related additional costs.

Appendix 2. Screenshot of cost-benefit calculation tool developed for the analysis. The tool can be downloaded from www.justsolutions.eu/TenantCBA (along with two other tools, one for tenants and one for landlords/landladies). The user inserts values in the white text boxes, and the calculated results appear in the grey text boxes and the graph. The values for the calculation below are for the building GMFH78, with 2023 prices, retrofitted to standard EH140, taking prebound and rebound effects into account



Total cost of job (€)	834316
"Anyway" costs (not for energy efficiency)	601102
Hence energy efficiency costs	233214
Own capital investment (€)	83432
Subsidies (€)	0
Hence loan obtained (€)	149782
Interest rate (%)	4
Term of loan (years)	25
Your discount rate (%)	6
Alternative investment return (%)	7
Monthly repayments on loan (€)	791
Total Repayed (€)	237300
Net Pres Value of repayments (€)	123033
Lost opportunity costs (€)	75700
NPV, total energy effic costs (€)	282165

Pre-retrofit consumption (kWh/m2/y)	129.8
Post-retrofit consumption (kWh/m2/y)	85.5
Hence energy saved (kWh/m2/y)	44.3
Floor aea (m2)	2297S
Pre-retrofit energy source	Gas
Pre.retrofit energy cost (€/kWh)	0.09
Post-retrofit energy source	Gas
Post-retrofit energy cost (€/kWh)	0.09
CO2 tax rate (€/tCO2)	30
Pre-Retroft Emissions (tCO2/y)	54.26
Post-Retroft Emissions (tCO2/y)	35.74
CO2 savings in 25 years (tCO2)	462.99
NPV of cost of CO2 saved (€/tCO2)	667.21
Monthly energy cost savings (€/mth)	763.18
NPV of 25 y of energy cost savings (€)	118706
CO2 tax savings in 25 years (€)	13889.8
NPV of CO2 tax savings (€)	7201.49

Your total net present value costs are (€)	282165
Your total net present value benefits (savings) (€)	125907
You suffer a net loss:	-156258
Your npv break-even point will occur in	more than 75 years
Your simple break-even point will occur in	289 months.

Note that anyway costs are excluded from these calculations. These will also have to be paid. Note also that subsidies are not included in your costs as calculated here.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2023.113905.

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