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Simulating retrofit incentives and distributional effects of four tenancy law policies

A model analysis using concrete buildings and retrofit options within the German regulatory context

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Abstract

Due to rent control, the primary landlord-tenant dilemma prevents landlords from recovering costs of energy-efficiency retrofits, which mainly benefit tenants. This necessitates tenancy law to allocate retrofit and energy costs adequately. We analyze the impact of Germany's current system and three reform options on both parties' finances using simulations across various building sizes and retrofit ambitions. We find that, in general, investment costs exceed energy savings. Only two of the reform options consistently incentivize landlord investment, albeit at tenants' expense, while the status quo system and the third reform option almost always incentivize landlords to forego retrofits. A sensitivity analysis shows these systems' effectiveness is barely affected by the details of German general tenancy law and local rent markets' characteristics (rent levels and their inflation, valuation of energy efficiency). Designing landlords' retrofit premia to depend on the technically estimated energy demand cost savings is especially promising, contingent on reliable energy performance data.

Highlights

We simulate four tenancy law policies allocating investment and energy costs between landlords and tenants.

Two novel allocation systems can quite reliably set retrofit incentives for landlords at tenants' costs, independent of general tenancy law and local rent markets.

The demand-based partially inclusive rent system scales the retrofit incentive with project profitability, making it the most robust policy option if demand-based energy performance certificates are widely available.

Keywords

Landlord-tenant dilemma

Tenancy law

Allocation of retrofit and energy costs

Simulation model

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1 Introduction

The residential building sector in Germany contributes significantly to annual greenhouse gas emissions, with 11% in 2023 (German Environment Agency, 2024). In addition, since 1990, emissions within the sector have decreased drastically less than, e.g., in the energy sector. Emissions stagnated in the 2010s, with most reductions only due to newly constructed buildings. The existing building stock, thus, requires significant retrofit activity to meet the legally binding climate policy goal of greenhouse gas neutrality by 2045. Assuming the climate protection goal as given, the legislator must implement an incentive structure that either forces building owners to invest via regulatory law or that reliably rewards retrofitting owners financially. Besides policies directly influencing the retrofit costs (subsidies) and the comparative advantage of a climate friendly building (carbon pricing) arises a third option in the rented housing sector: making the tenant pay a rent premium for a retrofit to ensure the landlord to recouperate the costs. Pursuing this third strategy, however, requires careful consideration of distributional effects to ensure widespread acceptability of the policy across the population.

Housing in Germany is characterized by an extraordinarily high rental rate compared to the EU average (53,5 % to 30,9 % of the population in 2022, Destatis, 2024). The rented building stock naturally separates the building owner from the occupant into landlord and tenant. Only the former can influence the building's energy efficiency, and the latter can affect consumption behavior. This gives rise to the landlord-tenant dilemma, i.e., why one party should undertake efforts to reduce energy costs if it only directly benefits the other party.

We follow the differentiation by Reutter (2025) into the primary and the secondary dilemma. While the secondary dilemma refers to the empirically observable undervaluation of energy efficiency in the new rental market (Kholodilin et al., 2017; Sieger and Weber, 2023), which sets insufficient retrofit incentives, the primary landlord-tenant dilemma arises in many European tenancy law regimes where rent levels in ongoing tenancies are capped to protect tenants bearing energy costs. If the landlord cannot increase rent levels after a retrofit, she[1] only bears the investment cost while the tenant benefits from decreased energy costs. Therefore, these jurisdictions often implement allocation schemes to distribute the costs or benefits of retrofits between landlords and tenants (BBSR, 2016) to address the inadequate retrofit incentive. Tenancy law is the appropriate legal arena, as its rent control is the inherent source of the problem. We, therefore, focus our analysis on the primary landlord-tenant dilemma.

We found no thorough economic analysis that compares and analyzes incentives from different tenancy law regimes. The economic literature tends to review and suggest policy options that either focus on regulatory law, subsidization, and regulation and services that ease an owner's retrofit experience (Ástmarsson et al., 2013; Bird and Hernández, 2012) based on an intuitive analysis of existing policies, or in addition to other measures touch upon a more drastic proposal of an inclusive rent system as a brief verbal discussion after a thorough empirical survey of the rental stock's energy efficiency compared to the owner-occupier's (Charlier, 2015).

Legal scholars mainly undertake more detailed analyses of tenancy law regimes. Comparative studies (BBSR, 2016; SIR, 2016; Universität Bremen, 2015) focus on detailed descriptions of different allocation systems, eliciting differences in how various jurisdictions approach rent control and sharing heating and retrofit costs. They refrain from giving concrete policy recommendations and instead conclude that countries with "specific and effective legal regulations on the allocation of the costs of energy

[1] To avoid ambiguity when using pronouns to refer to the agents, we assign female pronouns to the landlord and male pronouns to the tenant.

renovation" tend to have favorable conditions for a "successful energy implementation strategy" (BBSR, 2016) considering the individual legal and socio-economic context of the countries studied.

Concrete policy suggestions for changes in tenancy law tend to focus on a single jurisdiction and legal and practical applicability. For the German legal framework, studies either explore the effect on retrofit incentives verbally (Gaßner et al., 2019; Klinski et al., 2009; Thomaßen et al., 2020) or with simple numerical estimations for exemplary cases (Braungardt et al., 2022; Henger et al., 2023). Both approaches make it difficult to derive general conclusions on how different allocation systems impact retrofit incentives and how they affect the distribution of costs and benefits between landlords and tenants.

Our paper fills this research gap by developing a simulation model to assess the financial impact of various allocation systems on landlords and tenants after energy efficiency retrofits. We provide a twenty-year analysis, reflecting a typical heating system's lifespan. Complementing Reutter's (2025) abstract approach, we simulate effects on five typical buildings, identifying which system best incentivizes retrofits under German tenancy law and realistic pricing. This also allows us to substantiate claims on distributional effects and anticipate political resistance from landlords or tenants.

The remainder of this paper is structured as follows: we first overview German tenancy law regarding energy costs and define the examined allocation systems. We proceed with the simulation method, followed by the baseline simulation results and the sensitivity analysis. We conclude with policy recommendations.

2 Regulatory environment

The German Civil Code (*Bürgerliches Gesetzbuch*, BGB) defines German tenancy law for residential homes. Furthermore, the allocation of energy consumption costs to the tenant is given by the Heating Costs Ordinance (*Verordnung über Heizkostenabrechnung*, HeizkostenV), and the CO_2-price costs are shared between landlords and tenants according to the Carbon Dioxide Cost Allocation Act (*Kohlendioxidkostenaufteilungsgesetz*, CO_2KostAufG).

German tenancy law is characterized by relatively strict rent control for ongoing tenancies and less strict upper limits for new rental agreements. In ongoing tenancies, rent levels may generally be increased by the landlord up to the reference rent but not by more than 20 percent over three years (section 558 BGB, Unnerstall, 2025).

Section 558 BGB defines the "reference rent customary in the locality" to indicate the "usual payments that have been agreed or […] that have been changed in the last six years in the municipality or in a comparable municipality for residential space that is comparable in type, size, furnishings, nature and location, including the energy systems and its characteristic features."[2] It thus represents the lagged legal market value of a rental property depending on the local market and the quality of the apartment. It refers both to new tenancies and changed (usually increased) rents and thus not only depends on the lagged relation of supply and demand (i.e., the theoretically feasible market value) of housing but also on the legal norms that limit new rent levels and rent increases in ongoing tenancies. The six-year reference period serves practical reasons, as an instantaneous market valuation is not feasible, and to smooth out sudden price shocks (Unnerstall, 2025).

The level of new rents is also generally limited, with a stricter limit in certain jurisdictions. Section 5 of the Economic Offences Act (*Wirtschaftsstrafgesetz*, WiStG) prohibits new rent levels that exceed a 20

[2] Official translation from the Federal Ministry of Justice, accessible via: https://www.gesetze-im-internet.de/englisch_bgb/englisch_bgb.html#p2513.

Table 1: Overview of allocation systems and cost allocation between landlords and tenants.

Allocation System	**Modernization Surcharge (MS)**	**Consumption-based Partially Inclusive Rent System (CB)**	**Demand-based Partially Inclusive Rent System (DB)**	**Rent-independent Modernization Apportionment (RIMA)**
Energy consumption costs	Tenant	Landlord	Tenant	Tenant
CO_2-price costs	Landlord and tenant	Landlord	Tenant	Tenant
Retrofit investment costs	Landlord	Landlord	Landlord	Tenant (via apportionment)
Maintenance costs	Landlord	Landlord	Landlord	Landlord
Operational costs	Tenant	Landlord	Tenant	Tenant
System-specific payments (T: Tenant, L: Landlord)	T → L: Modernization surcharge	T → T: Neighborhood incentive system (=0 for average tenant)	T → L: Demand cost levy; L → T: Demand cost reimbursement	T → L: Rent-independent modernization apportionment
Retrofit incentive in ongoing tenancy	Rent premium via interaction modernization surcharge and reference rent; reduced CO_2-price and maintenance costs	Reduced Energy consumption, CO_2-price, maintenance, and operational costs	Reduced energy demand and maintenance costs	Reduced maintenance costs

percent premium over the current reference rent. In addition, federal state governments may identify areas in which the housing market is under pressure. Barring some exemptions, new rent levels may not exceed the reference rent by more than 10 percent, according to section 556d BGB (Unnerstall, 2025). We assume that the latter limit does not apply to our baseline simulation. The sensitivity analysis explores the effects of new rent level limitations that are even stricter than 10 percent.

Regarding the allocation of energy consumption costs, 50 to 70 percent of a building's heating costs must be billed depending on the tenant's actual metered consumption, according to the HeizkostenV. The tenants must pay all heating costs as the rest is to be allocated based on apartment size. For our simulation, we assume uniform consumption behavior across all apartments of a multi-family home, rendering the differentiation between the two billing algorithms obsolete. The requirement to allocate most heating costs based on metered consumption makes sense to incentivize energy-conscious consumption behavior while acknowledging heat transmission effects between apartments. It derives from the European Union's Energy Efficiency Directive (EED).

The CO_2KostAufG of 2022 exempts some rules of the HeizkostenV by requiring landlords to share carbon price costs of heating based on emissions per square meter. This aims to incentivize landlords to lower CO_2 emissions. While considering general rent limitations and the HeizkostenV as fixed, we view the CO_2KostAufG as addressing the landlord-tenant dilemma. We, therefore, consider integrating it into a comprehensive overhaul of allocation systems to improve retrofit incentives.

3 The allocation systems

We scrutinize four allocation systems to assess how they incentivize landlords to invest in energy efficiency retrofits necessary for climate change mitigation and how these retrofits affect the tenant's costs of living. We begin with the status quo regulation in Germany and proceed by presenting three reform options. Table 1 provides an overview of the examined allocation systems.

3.1 The German modernization surcharge (MS)

The baseline allocation system is the current German regulation: the modernization surcharge. While the landlord may generally not increase the rent in ongoing tenancies above the reference rent, a modernizing retrofit warrants an exemption. Eight percent of the retrofit's costs exceeding general maintenance and after the deduction of subsidies may be levied onto the tenant every year. This surcharge must not exceed 3 €/m²/month for the first six years.[3] If that cap is binding, the rent payment remains constant until six years have passed, when the remaining costs may be levied onto the tenant (Unnerstall, 2025). In any case, once the reference rent has risen sufficiently, the landlord may again increase the rent following the reference rent. The immediate modernization surcharge depends only on the retrofit costs and not its effect. However, in the long run, the retrofit's effectiveness affects the landlord's income via the reference rent, reflecting better energy efficiency.

3.2 The consumption-based (CB) partially inclusive rent system

Braungardt et al. (2022) propose a consumption-based (CB) partially inclusive rent system. It shifts the building's full heating costs onto the landlord. In the long run, we expect that the rental market compensates for this by generally achieving higher rent payments equivalent to the expected consumption costs. The inclusive rent aspect implies decreased heating costs after a retrofit directly benefit the landlord. To still abide by the EED, Braungardt et al. (2022) examine a neighborhood incentive system, where a building's occupants who consume more energy than the average have to compensate those who live more frugally. Although theory suggests that this decreases the tenant's incentive to behave energy consciously, especially in small buildings (Reutter, 2025), we cannot predict how consumption behavior changes. Therefore, we assume tenants behave as in the current system, where their living costs directly depend on their consumption behavior. As we are interested in the financial effects of each allocation system on the average tenant, we can refrain from explicitly modeling the neighborhood incentive.

3.3 The demand-based (DB) partially inclusive rent system

The demand-based partially inclusive rent system has first been defined by Reutter (2025). Its idea is to levy a retrofit's theoretical effect onto the tenant, regardless of the metered benefits, because the landlord can only affect her building and not the tenant's behavior. The implementation requires demand-based energy performance certificates (EPC) before and after a retrofit. With each billing period, the tenant pays the landlord the demand cost levy: the costs that the theoretical energy demand present when moving in would have caused, i.e., taking the initial energy system and current prices. Likewise, the landlord pays the tenant the demand cost reimbursement, which is the cost that the current theoretical energy demand would have caused based on the current energy system and prices. Without any retrofit, the two payments directly offset each other. After a retrofit, however, the costs of providing the energy demand usually decrease. This means that the demand cost levy exceeds the reimbursement. This difference is the landlord's return on her retrofit investment, which flows as long as the tenancy continues. Once a new tenant moves in, both payments again align as the new tenant's

[3] The permissible surcharge is only 2 €/m²/month if the initial rent is less than 7 €/m²/month.

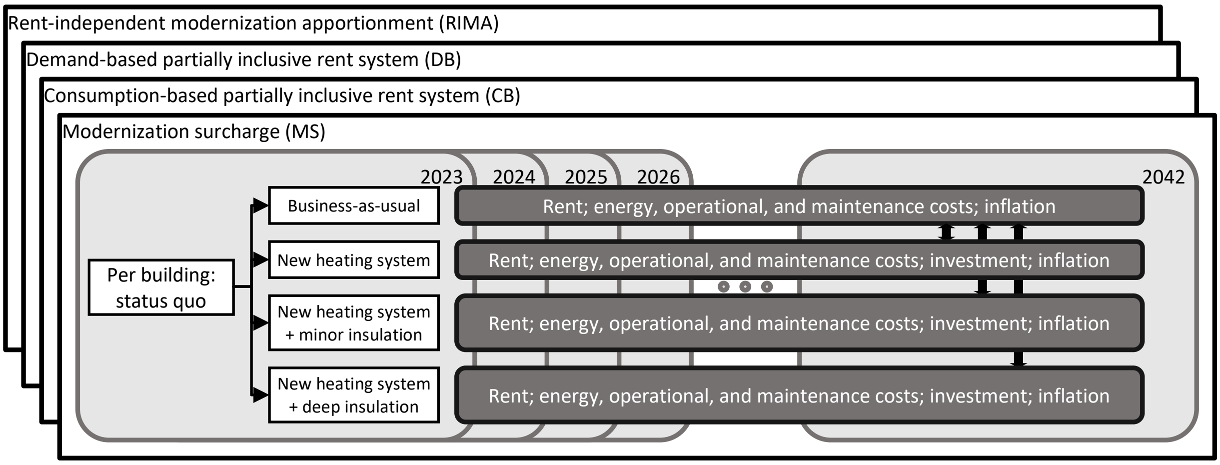

Figure 1: Schematic overview of the simulation approach

demand cost levy now depends on the retrofitted EPC. An introduction via the HeizkostenV seems promising.

3.4 The rent-independent modernization apportionment (RIMA)

The rent-independent modernization apportionment is a concrete operationalization of a proposal by Klinski et al. (2009). The policy is very similar to the current modernization surcharge. However, the main difference is to decouple the rent premium paid for the modernization from the general dynamics of the reference rent. After a retrofit, the landlord may demand the apportionment equal to the annuity cost of the pure investment (i.e., without maintenance and subsidies) on top of the initial rent. As time goes by, she may refer to the reference rent of the now hypothetical non-retrofitted apartment to justify ordinary rent increases. This enables the landlord to charge the same rent as if she did not invest, plus the steady flow of the rent-independent modernization apportionment. Since the premium is intended to approximate the actual investment cost, the landlord can rely on recouping the investment until the tenant moves out. As with the demand-based partially inclusive rent system, the RIMA proposal could be implemented via the HeizkostenV.

4 Method

We simulate the distributional effects of three retrofit options for five exemplary buildings over twenty years, depending on the allocation system. Each project (a combination of a retrofit option and a building) is evaluated to determine whether it leaves the landlord, tenant, or both financially better off than maintaining the energetic status quo. We estimate costs, including rent, energy, maintenance, and investment, adjusting for inflation and energy price scenarios. Figure 1 provides an overview of the simulation approach. The next section describes the buildings and retrofit options, followed by an overview of the modeling approach.

4.1 Buildings and retrofit options

We study five buildings that vary in size, age, thermal envelope, and heating system and, with that variance, represent the existing German residential building stock. They include a single-family home (SFH) and multi-family homes that house six (MFH-6), eight (MFH-8), 16 (MFH-16), and 32 (MFH-32) apartment units. The two smallest buildings are based on theoretical models, and the larger ones exist in Bavaria, Germany. Table 2 provides an overview of the examined buildings, and Table 5 in the ap-

Table 2: Overview of examined buildings.

	Designation	SFH	MFH-6	MFH-8	MFH-16	MFH-32
	Image					
Status quo	Heating system	Low temperature (oil)	Low temperature (gas)	Low temperature (gas)	Low temperature (gas)	District heating
	Thermal envelope	Age-appropriate for the 1960s	Age-appropriate for the 1960s	Age-appropriate for the 1990s	Age-appropriate for the 1970s	Age-appropriate for the 1980s
Retrofit 1	Heating system	Condensing boiler (oil*) + air-water heat pump	Condensing boiler (gas*) + air-water heat pump	Air-water heat pump	District heating	District heating
	Thermal envelope	No change	No change	No change	No change	No change
Retrofit 2	Heating system	Air-water heat pump	Air-water heat pump	District heating	District heating	District heating
	Thermal envelope	New windows, wall insulation	New windows, basement ceiling insulation	New windows	Wall insulation, new windows	Wall insulation, new windows
Retrofit 3	Heating system	Air-water heat pump	Air-water heat pump	Air-water heat pump	Air-water heat pump	District heating
	Thermal envelope	Deep insulation	Deep insulation	Deep insulation	Deep insulation	Deep insulation
* Requires renewable fuel to achieve climate neutrality in the long run.						

pendix reports the technical details. According to the German Buildings Energy Act (*Gebäudeenergiegesetz*, GEG)[4], the multi-family homes currently achieve an energy performance rating of E to F. In contrast, the single-family home achieves the worst possible rating of H.

We estimate the maintenance and operational costs for each building in 2023[5] and the expected metered energy consumption. The latter depends non-linearly on the technical energy demand according to BBSR (2019): For low-demand buildings, metered consumption usually approximately equals the energy demand; as the energy demand increases, metered consumption diverges and increases more slowly. Similar observations apply, e.g., to the Swiss building stock (Cozza et al., 2020). Energy costs are estimated accordingly. These estimates provide the business-as-usual scenario where mainte-

[4] The 2024 recast of the EU Energy Performance of Buildings Directive (EPBD) requires Member States to re-scale their energy performance classes to improve comparability across the Union. The studied buildings and retrofit options might therefore achieve slightly different energy performance classes if they were translocated to another Member State.

[5] We collected data in 2023. Energy prices and project costs have various data sources. Therefore, fully updating the data set is beyond the scope of the paper. The sensitivity analysis addresses the issue of cost uncertainty and explores how the project costs and allocation systems' distributive effects respond to varying cost levels.

nance and operational costs increase over time with general inflation and energy costs develop according to a proprietary and coherent energy price prognosis kindly provided by ITG Dresden and FIW München[6].

In collaboration with the ITG Dresden and FIW München teams, we model three retrofit options for each building. All retrofit projects comply with the goal of climate neutrality (i.e., producing no direct greenhouse gas emissions at the building or using renewable fuels) but vary in approach and ambition. Retrofit 1 encompasses only a modernization of the heating system. Retrofit 2 also includes minor changes to the thermal envelope with new windows for all buildings, wall insulations for SFH, MFH-16, and MFH-32, and insulation for the basement ceiling in MFH-6. Retrofit 3 combines an improved heating system with deep thermal envelope insulation. We estimate how the technical energy demand and the expected metered consumption changes due to the retrofit.

ITG Dresden and FIW München provide investment costs for each project based on their available data and expertise. We model the projects' funding with the currently offered subsidies and an annuity loan with 4 % p.a. interest rates over twenty years, reflecting the new heating system's life span. We estimate that new windows will not require replacement for thirty years, and the rest of the thermal envelope's life span extends to forty years. This poses the issue of residual value after the funding and simulation period. We set the annual investment costs as the difference between the annuity payment for the entire project and one-twentieth of the residual value, assuming linear depreciation. This ensures that interest is paid for the entire investment cost.

4.2 Simulation model

While the examined buildings and the retrofit options outlined above dictate the energy consumption costs, retrofit costs, and maintenance and operational costs, their allocation and general rent levels vary depending on the allocation system. We proceed in five steps to estimate rent levels across time and the allocation systems.

Firstly, the simulation is based on a concrete assumption of the rent level for the building in question without retrofits in the base year 2023 within the current German regulatory landscape. We assume a new rental market value of 8.50 €/m², less than the nationwide average of new market rents of 9.22 €/m² (Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen, 2024) as we are interested in the existing building stock with subpar energy efficiency which, ceteris paribus, is rented at a discount. As the reference rent lags behind the market value, it is initially below that rent level.

The second step is to evaluate the market value of the same apartment if it had no associated energy costs. We assume that ceteris paribus allocation systems would yield the same rent levels if no energy costs accrued. From empirical analyses of parts of the German housing market, we know there is a rental discount for energy-intensive buildings, but that discount likely undervalues energy cost savings.[7] Kholodilin et al. (2017) and Sieger and Weber (2023) find valuation factors around 0.2 to 0.3, i.e., one euro more in energy costs translates to a discount of about a quarter euro in monthly rents. A more recent policy brief by Amaral et al. (2024) find a value much closer to unity. We account for this ambiguity in our sensitivity analysis, but for now, assume a market valuation of energy efficiency of 25 percent. We estimate that the current new market value of 8.50 €/m² reflects a discount for the energy

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[6] ITG Dresden is a private research institute with extensive and in-depth knowledge and experience in the energetic and economic evaluation of energy saving measures with a focus on building services engineering and the related standards. FIW München is a think tank for thermal insulation, heat transfer, and heat optimization.

[7] The exact drivers of this undervaluation are not clear, neither from theory nor from the empirical studies. Most plausible is missing reliable information for prospective tenants who cannot easily assess and value the true energy costs of an apartment compared to more tangible qualities such as a balcony. Reutter (2025) discusses the potential drivers in more detail.

costs, the operational costs, and the share of the carbon costs paid for by the tenant and a premium for the share of the carbon costs paid for by the landlord. Inverting those yields the new market value of the hypothetical zero-energy building.

The third step is to apply the current German modernization surcharge to ascertain the initial rent increase and how the costs of energy, carbon pricing, financing, operating, and maintaining the apartment change for the landlord and the tenant. Knowing the costs of financing each retrofit project and its impact on the variable costs, we can apply the legally prescribed modernization surcharge to the initial rent.

To simulate the initial rent level before the retrofit (fourth step), we apply discounts and premia to the new rental value of a hypothetical zero-energy building, depending on the allocation system. For RIMA and DB, we assume full allocation of energy, carbon, and operational costs to the tenant, warranting larger discounts. In contrast, CB warrants a rent premium as the landlord bears all variable costs. We model the effects of retrofit projects by applying the rules of each allocation system to estimate rent payments. For CB, rent levels remain unchanged. For DB, only the landlord's reimbursement payment changes. For RIMA, the rent level increases by the annuity costs of the retrofit.

In the fifth step, we advance time, assuming the energy-independent rent portion increases with general inflation. Energy costs and energy-specific rent portions grow according to the energy price scenarios and retrofit project. We apply premia and discounts to each project's new rental market value, considering the undervaluation of energy efficiency. The reference rent customary in the locality is the arithmetic mean of the previous six years' new rental prices for each project with linear backwards extrapolation for the first six years of the simulation. We consider that the new rental price may only exceed the reference rent by twenty percent in all simulated allocation systems and that the landlord may only increase the rent to the reference rent, barring exceptions due to a retrofit. Given the reference rent for each retrofit project and allocation system, we can estimate how the rent level in the ongoing tenancy changes over time.

5 Results of the baseline simulation

In the baseline simulation, we assume the same value for exogenous variables for each building and retrofit option.

5.1 Project profitability

In the baseline simulation, we assume a unified perspective of landlord and tenant, ignoring distributional effects. We focus on the project profitability of each retrofit option for the five buildings studied, with the key variable being the comparative advantage of retrofitting versus maintaining the status quo. Figure 2 shows the discounted profitability of three retrofit options over time for each building. Four trends emerge: 1) Retrofitting the SFH incurs the highest costs, barely outperforming the status quo near the end. 2) Larger buildings benefit from economies of scale. 3) Most retrofits remain unprofitable for much of the timeline, but rising carbon prices improve profitability. 4) Short-term profitability for MFHs 6-16 spikes due to unusual natural gas prices following Russia's attack on Ukraine, but high electricity costs challenge heat pump profitability until carbon pricing becomes more influential.

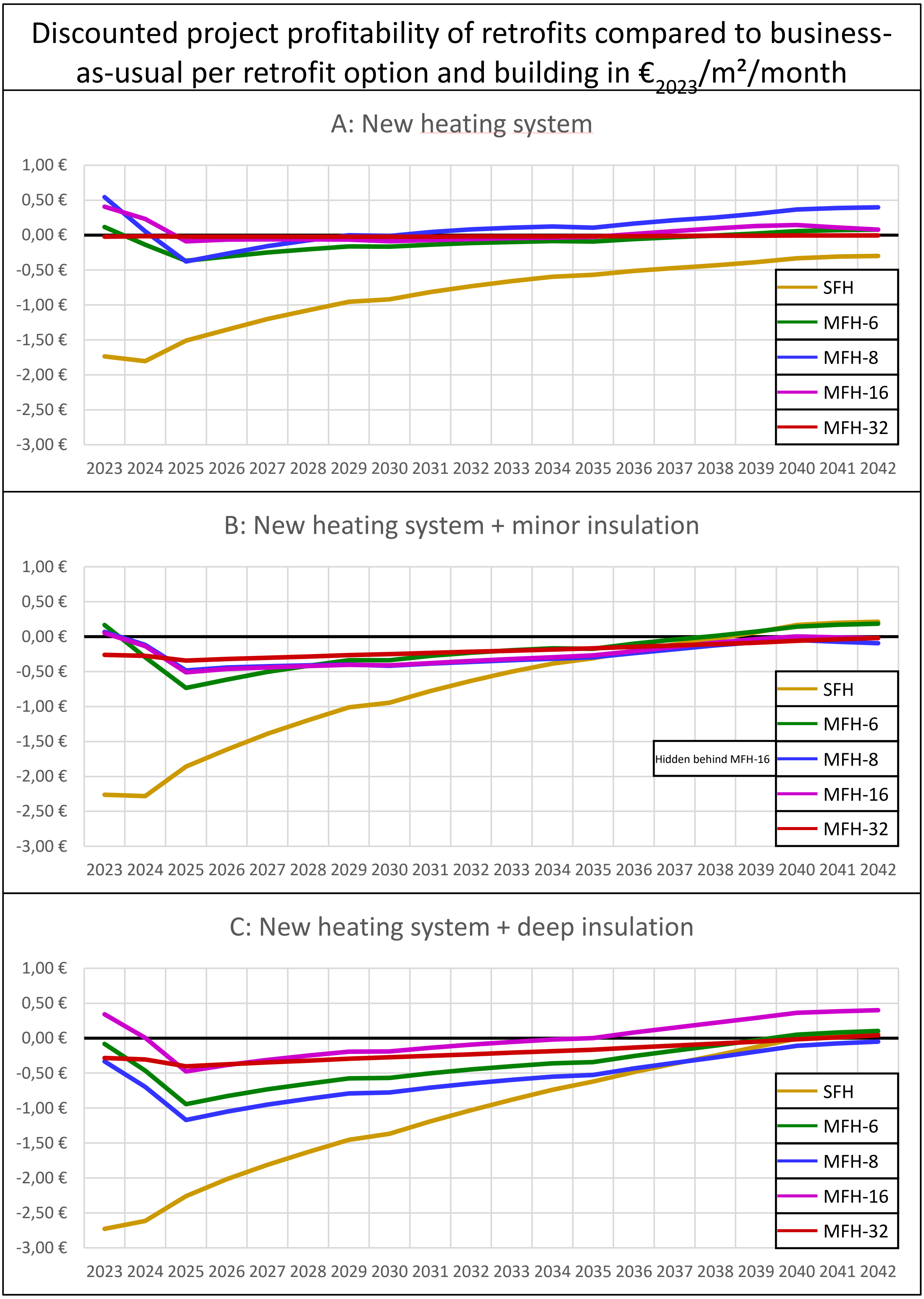

Figure 2: Discounted project profitability of retrofits compared to business-as-usual per building and retrofit option in €$_{2023}$/m²/month. Plot A: Retrofit option 1 (New heating system), Plot B: Retrofit option 2 (New heating system + minor insulation), Plot C: Retrofit option 3 (New heating system + deep insulation).

Table 3: Average discounted profitability of retrofit projects over 20 years compared to business-as-usual per building and allocation system. Positive numbers indicate that the project is preferable over business-as-usual. Bold digits emphasize a non-negative profitability from the respective perspective. Grey highlights indicate where the landlord would choose the retrofit.

Profitability in €2023/m²/month			SFH	MFH-6	MFH-8	MFH-16	MFH-32
Retrofit 1	Project		-0.83	-0.09	**0.11**	**0.03**	-0.02
	MS	Landlord	-0.72	-0.30	-0.35	-0.00	-0.08
		Tenant	-0.11	**0.21**	**0.46**	**0.04**	**0.06**
	CB	Landlord	-0.83	-0.24	-0.17	-0.01	-0.05
		Tenant	**0.00**	**0.15**	**0.29**	**0.04**	**0.03**
	DB	Landlord	**0.11**	**0.27**	**0.57**	**0.10**	**0.01**
		Tenant	-0.94	-0.37	-0.46	-0.06	-0.03
	RIMA	Landlord	**0.01**	-0.02	-0.02	**0.01**	**0.01**
		Tenant	-0.85	-0.07	0.14	**0.02**	-0.03
Retrofit 2	Project		-0.74	-0.18	-0.26	-0.24	-0.19
	MS	Landlord	-0.59	-0.55	-0.43	-0.44	-0.49
		Tenant	-0.16	**0.37**	**0.17**	**0.20**	**0.30**
	CB	Landlord	-1.38	-0.52	-0.43	-0.50	-0.50
		Tenant	**0.64**	**0.34**	**0.17**	**0.26**	**0.30**
	DB	Landlord	**0.57**	**0.32**	-0.02	**0.10**	**0.11**
		Tenant	-1.31	-0.50	-0.23	-0.34	-0.30
	RIMA	Landlord	**0.89**	**0.35**	**0.24**	**0.59**	**0.55**
		Tenant	-1.64	-0.53	-0.50	-0.83	-0.74
Retrofit 3	Project		-1.07	-0.36	-0.56	**0.01**	-0.20
	MS	Landlord	-0.97	-0.52	-0.52	-0.40	-0.42
		Tenant	-0.10	0.16	-0.04	**0.41**	**0.22**
	CB	Landlord	-2.07	-0.84	-1.05	-0.51	-0.60
		Tenant	**0.99**	**0.48**	**0.49**	**0.52**	**0.41**
	DB	Landlord	**0.39**	**0.22**	**0.02**	**0.52**	**0.19**
		Tenant	-1.46	-0.58	-0.58	-0.52	-0.39
	RIMA	Landlord	**2.05**	**0.95**	**1.18**	**0.91**	**0.80**
		Tenant	-3.12	-1.31	-1.74	-0.90	-1.00

5.2 Overview of allocation systems' distributional effects

To analyze how each allocation system distributes the retrofit projects' many losses and few gains compared to the business-as-usual case, we first present a cumulative result of the average discounted profitability per agent and allocation system before we study the example of the deep thermal retrofit and heating system modernization in the MFH-16 to examine the temporal effects. Table 3 presents the aggregated data.

Looking at the project profitability averaged over time reveals that only three of the 15 retrofit projects studied outperform the business-as-usual maintenance case: the pure heating system change in MFHs 8 and 16 and the deep retrofit in the latter building. Note that these three projects' profitability is pretty small in magnitude with an advantage of at most 0.11 €/m²/month compared to the average net costs incurred by the other retrofit projects, reaching up to -1.07 €/m²/month when it comes to the deep retrofit of the SFH.

In terms of how the allocation systems distribute costs between landlords and tenants, the current modernization surcharge (MS) usually benefits tenants. Conversely, landlords see no financial gains, even when projects are profitable. The consumption-based partially inclusive rent system (CB) similarly benefits tenants, not landlords. The demand-based partially inclusive rent system (DB) has the opposite effect, consistently benefiting landlords but disadvantaging tenants. The rent-independent modernization apportionment (RIMA) also benefits landlords, often at tenants' expense, especially with unprofitable retrofits. RIMA's profitability for landlords increases with more extensive retrofits. In the

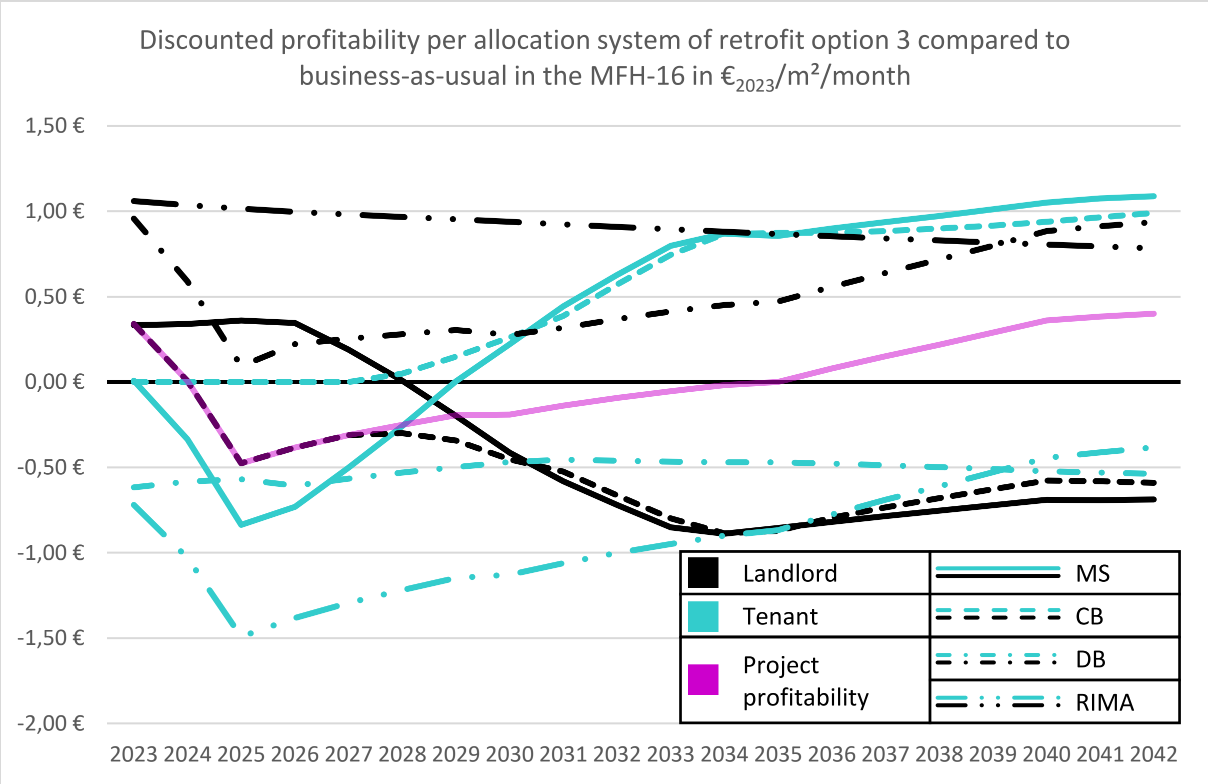

Figure 3: Discounted profitability per allocation system of retrofit option 3 compared to business-as-usual in MFH-16 in €$_{2023}$/m²/month. Project profitability (magenta line) equivalent to magenta line in Figure 2C. Landlord's (cyan) and tenant's (black) lines per allocation system sum up to the project profitability (magenta).

deep retrofit of the SFH, incurring the highest costs, landlords gain the most among all 60 cases, while tenants bear the highest costs.

Referring to the deep retrofit in the MFH-16, shown in Figure 3, we can explain how these systematic distributions of costs and benefits between landlords and tenants arise for each allocation system.

5.3 Distributional effects of the modernization surcharge

Beginning with the modernization surcharge (MS), we observe three phases for the landlord's and tenant's payoffs. The first phase in this example lasts about four years until 2026, with the second phase transition in 2034.

In the first phase, the tenant pays the initial rent plus the modernization surcharge in the retrofitted apartment, keeping the increased rent payments constant. In comparison, the rent in the business-as-usual case also remains constant as it initially surpasses the non-retrofitted reference rent. Therefore, the landlord's profits are mostly constant and positive (fluctuations are due to varying maintenance costs and the lowered carbon price costs). The tenant's payoffs in the first few years depend on the difference between the initial rent increase and the energy, carbon price, and operational cost savings. In the example, the tenant initially faces additional costs due to the modernization surcharge.

In the second phase, the reference rent in the business-as-usual scenario increases, whereas retrofitted rent remains constant as the initial rent increase was rather large. This means that the landlord's relative advantage of the modernization surcharge over the business-as-usual case decreases. On the other hand, the tenant is increasingly happy that the retrofit took place as rent levels remain constant. At the same time, energy cost savings continuously increase due to the increasing carbon price.

In phase three, the reference rent in the retrofitted apartment has increased enough that the landlord's payoffs are determined mainly by the difference in the reference rents, which are lagging images of the market valuation. The landlord benefits from that positive valuation as the retrofitted apartment is valued higher due to energy cost savings. However, as the market values energy cost savings only by a fraction and the reference rent lags, the landlord's relative benefit of the retrofit increases slower than project valuation. These effects help the tenant, whose benefit from the retrofit rises even when the reference rent determines the rent level.

As the retrofit project is too costly compared to the energy cost savings, and the tenant benefits from the interaction with the reference rent in the long run, the modernization surcharge consistently offers insufficient retrofit incentives for the landlord.

5.4 Distributional effects of the consumption-based partially inclusive rent system

The consumption-based partially inclusive rent system (CB) achieves remarkably similar distributional effects with almost the same phases as the modernization surcharge. The first phase here lasts one year longer, until 2027, with the third phase also beginning in 2034.

In the first phase, the inclusive rent aspect dominates the payoffs: the landlord may charge the same rent as before the retrofit while benefitting from the decreased energy costs. For the tenant, this causes financial indifference between renting the business-as-usual apartment and the retrofitted one, with the landlord bearing all the net costs of the retrofit.

In the second phase, as with the modernization surcharge, the reference rent in the business-as-usual scenario increases sooner than in the retrofit scenario, implying a relative benefit for the tenant and, likewise, a relative loss for the landlord.

Only after some more time, with the beginning of the third phase, does the reference rent for the retrofitted apartment exceed the initial rent level, thereby decreasing the tenant's relative benefits and the landlord's relative losses. The reference rent in the retrofitted apartment is lower than for the business-as-usual scenario as less energy costs must be internalized into the inclusive rent level. This last effect only holds if we assume the new rental market undervalues energy cost savings.

As the allocation system consistently benefits the tenant due to the interaction with the reference rent and the energy cost savings in most examined scenarios are insufficient compared to the retrofits' investment costs, the consumption-based partially inclusive rent system offers insufficient retrofit incentives for the landlord.

5.5 Distributional effects of the demand-based partially inclusive rent system

The demand-based partially inclusive rent system (DB) exhibits no phases in its distributional effects. Instead, it always abides by the same mechanism: the landlord benefits from the retrofit's theoretical energy demand cost savings.

As the energy demand systematically exceeds the tenant's metered energy consumption, the retrofit tends to be more beneficial for the landlord than for the building as a whole. As the theoretic profitability of the retrofit determines the landlord's additional profits, she bears the energy price risk after the retrofit. In contrast, the tenant bears the energy price risk of the business-as-usual apartment.

On the flip side, the demand-based partially inclusive rent system always implies additional costs for the tenant after a retrofit, as his energy cost savings are less than the net rent increase due to the landlord's decreased reimbursement payment. In a sense, the DB system makes the tenant pay for the so-called rebound effect. In the not-yet-retrofitted apartment, the tenant decides to reduce energy consumption compared to the technical demand, trading some discomfort for energy cost savings. After the retrofit, less energy costs can be saved with individual behavior, prompting the tenant to behave less energy-consciously. He thus endures less discomfort. The tenant's difference between the actualized energy cost savings and the greater loss in the landlord's reimbursement reflects this gain in comfort.

Since the landlord's additional revenue depends not mainly on the nominal rent payments but instead on the savings in the reimbursement, the interaction with the reference rent is less pronounced than with the previous two systems. While the retrofitted apartment also achieves greater market rents and thus a higher reference rent, the reference rent in both the business-as-usual scenario and the retrofitted apartment increases roughly in parallel over time, preventing the different phases due to the reference rent from occurring. Instead, the landlord can expect a steadily increasing advantage of the retrofit compared to the business-as-usual case due to the anticipated increase in the carbon price.

Since the demand-based partially inclusive rent system allocates the rebound effect solely onto the tenant, it sets slightly excessive retrofit incentives for the landlord compared to the theoretical owner-occupier at the tenant's costs.

5.6 Distributional effects of the rent-independent modernization apportionment

The rent-independent modernization apportionment (RIMA) likewise does not vary the distribution of costs and benefits much in time. As its name suggests, the landlord's additional income from the tenant after the retrofit is independent of the general development of the rent. The landlord may always charge up to the reference rent in the business-as-usual case plus the modernization apportionment, which mirrors the investment's annuity costs.

Therefore, the landlord is guaranteed to recuperate the retrofit costs. Her benefit for the retrofit lies in the usually decreased maintenance costs and the saved interest rates for the residual value of the retrofitted apartment. The landlord thus bears no energy price risk. Furthermore, her incentive does not lie in the retrofit's effectiveness in energy cost savings. On the other hand, this means that the tenant bears the entire energy price risk and the risk of an unprofitable retrofit.

5.7 Summary of allocation systems' distributional effects

In summary, the modernization surcharge (MS) and the rent-independent modernization apportionment (RIMA) are both allocation systems that base the landlord's investment incentive on the retrofit costs more than on its effect. Of the two, only the latter consistently provides a positive retrofit incentive as it does not interact detrimentally with the rest of the tenancy law. Both partially inclusive rent systems focus on the retrofit's effect on motivating investments. However, only the demand-based system (DB) consistently achieves a positive incentive for the landlord. As most retrofits studied are unprofitable from the project perspective, the tenant usually suffers financially if an allocation system incentivizes the landlord to invest.

6 Sensitivity Analysis

We now turn to the results of the sensitivity analysis. This robustness-check aims to identify how far the landlords' and tenants' payoffs of a retrofit in each allocation system vary when the twelve exogenous model variables change. We perform the sensitivity analysis as a ceteris paribus estimation, i.e., we only change one parameter, leaving the others as in the baseline scenario. We performed the robustness check individually for each building and retrofit option with twenty-one discrete steps per variable (exception: initial rent with 35 steps). The calculation then provides the project's, the landlord's, and the tenant's relative advantage of the retrofit over the business-as-usual case. The analysis showed that each changing exogenous variable has a sufficiently monotone effect on the payoffs to allow for an aggregated analysis, as shown in Table 4. It reports how each agent's payoff changes as the exogenous variable changes from its minimum to the maximum value, averaged across the five buildings with the three respective retrofit options. We proceed by explaining each row of Table 4 per

Table 4: Mean effect of variable changes on average discounted retrofit profitability across five buildings and three retrofits in €$_{2023}$/m²/month per allocation system. MS refers to the modernization surcharge system, CB to the consumption-based partially inclusive rent system, DB to the demand-based partially inclusive rent system, and RIMA to the rent-independent modernization apportionment. L corresponds to the landlord, and T to the tenant.

	Mean effect of variable changes on average discounted retrofit profitability across five buildings and three retrofits in €$_{2023}$/m²/month per allocation system				MS		CB		DB		RIMA	
	Variable	**Min**	**Max**	**Project**	**L**	**T**	**L**	**T**	**L**	**T**	**L**	**T**
Increasing retrofit's profitability	Subsidy	0 % of base case	200 % of base case	0.81	0.47	0.34	0.81	0.00	0.81	0.00	0.00	0.81
	Carbon, natural gas, oil price	+ 0.00 % p.a. from 2026	+ 5.00 % p.a. from 2026	0.55	0.10	0.45	0.30	0.25	0.76	-0.21	0.00	0.55
	Average energy consumption relative to technical demand	50 % of BBSR-estimate	150 %of BBSR-estimate	0.76	0.29	0.47	0.50	0.26	0.18	0.58	0.00	0.76
Decreasing retrofit's profitability	Retrofit and maintenance costs	50 % of base case	150 % of base case	-2.01	-1.47	-0.54	-1.97	-0.05	-1.94	-0.07	-0.27	-1.74
	Interest rate	0.50 % p.a.	5.50 % p.a.	-0.69	-0.69	0.00	-0.69	0.00	-0.69	0.00	0.00	-0.69
	Electricity, district heating price	+ 0.00 % p.a. from 2026	+ 5.00 % p.a. from 2026	-0.36	-0.04	-0.32	-0.20	-0.16	-0.41	0.05	0.00	-0.36
Rental market characteristics with no effect on retrofit's profitability	Initial rent	3 €/m²/month	20 €/m²/month	0.00	-0.28	0.28	-0.15	0.15	-0.02	0.02	0.00	0.00
	Rent inflation compared to general inflation	95 %	105 %	0.00	-0.71	0.71	-0.44	0.44	0.15	-0.15	0.00	0.00
	Rent limit new tenancies	0 % premium permissible	10 % premium permissible	0.00	-0.64	0.64	-0.34	0.34	0.01	-0.01	0.00	0.00
	Rent limit for rent increases according to reference rent	+ 0 % every 3 years permissible	+ 10 % every 3 years permissible	0.00	-0.75	0.75	-0.35	0.35	0.08	-0.08	0.00	0.00
	Undervaluation initial rent	50 % of market rent	100 % of market rent	0.00	0.45	-0.45	0.22	-0.22	-0.02	0.02	0.00	0.00
	Valuation energy cost savings	0 %	100 %	0.00	0.31	-0.31	0.41	-0.41	0.72	-0.72	0.02	-0.02

allocation system. However, the rent-independent modernization apportionment (RIMA) is an exception: Changing any variable affecting the project's profitability only affects the landlord when the post-retrofit maintenance costs increase. Otherwise, only the tenant will be affected for the better or the worse. Similarly, neither landlords nor tenants are affected if the rental market's characteristics change with no effect on the retrofit's profitability. We investigate the three other allocation systems' sensitivity below.

6.1 The German modernization surcharge (MS)

The first set of exogenous variables positively affect the retrofits' profitability as they increase: Increasing the subsidy lowers the effective investment cost, increasing the price of fossil fuels improves the retrofits' performance compared to the business-as-usual case, and increasing the occupant's actual energy consumption relative to the technical demand means that energy demand reductions are more valuable. The profitability decreases when the retrofit's investment and maintenance costs increase, if capital is costlier, or if the non-fossil fuels cost more. The model also includes a couple of variables that only describe the rental market and the surrounding tenancy law without affecting the retrofit's profitability. As with the other variables, their change does not affect the retrofit's costs and benefits distribution between landlord and tenant with the rent-independent modernization apportionment.

With the modernization surcharge, landlords and tenants benefit from more cost-efficient retrofits since both bear some investment costs and benefit from its energy savings effect. The landlord pays for the initial investment but earns the modernization surcharge, whose net effect is positive but nonlinear and depends on the investment costs. At the same time, the tenant directly benefits from energy cost savings, whereas the landlord benefits only indirectly via the reference rent. Therefore, the landlord is strongly affected by increasing subsidies and increased investment costs, and she is only perturbed by increased interest rates. In contrast, the tenant is strongly affected by variance in energy prices and consumption behavior.

If the initial rent of the apartment increases, tenants with the modernization surcharge prefer the retrofit more strongly, with the landlord equivalently tending more towards maintaining the status quo. The reason lies again in the interaction of the actual rent payments after the retrofit and the development of the reference rent.

Since we assume that the initial rent reflects the energy-independent value of the apartment with a discount partially reflecting its energy costs, a larger initial rent with no change to the building's energy efficiency means that only the energy-independent value increases. We furthermore assume that this value increases over time, parallel to inflation. A greater initial value thus means larger annual increases given the same growth rate. This applies to the reference rent of apartments without and with the retrofit.

The tenant's benefit of the retrofit remains constant as it only stems from the energy cost savings. His additional costs, however, are the difference between the rent payment with the modernization surcharge and then the retrofitted reference rent compared to the reference rent he would have to pay without the retrofit. The difference between the two reference rent levels depends on the retrofit's effect, not the initial rent level. As both reference rents increase quicker when the initial rent level is higher, the time when the initial rent plus the modernization surcharge exceeds the retrofitted reference rent is shortened, which implies that the tenant's additional costs due to the modernization surcharge decrease with greater initial rents. Note that this effect is discontinuous at 7.00 €/m²/month initial rent as the legal cap on the modernization surcharge increases from 2.00 €/m²/month to 3.00 €/m²/month, extraordinarily increasing the tenant's relative retrofit costs for larger investments.

Similarly, the tenant prefers the retrofit more than maintaining the business-as-usual case given the modernization surcharge, when the energy-independent portion of rents increases more than general inflation, when greater rent increases after a new tenancy are permissible, and when landlords may increase rent levels due to a higher reference rent more consistently. Note that for rent increases up to the reference rent, current regulation allows for up to 20 % rent increases within three years. However, the simulation has only been sensitive to much stricter regulation of up to ten percent, above which no effect is observable for any allocation system.

With the modernization surcharge, landlords prefer the retrofit more when the initial rent is closer to the current market value of the apartment or when energy efficiency is better. Both effects are again linked to the reference rent. The smaller the initial rent is compared to the new market value, the higher the new market value, as we assume a constant initial rent. This also implies a greater energy-independent value of the apartment, and the same argument applies to a greater initial rent level. Therefore, landlords prefer it if the initial rent is closer to the current market value, as this extends the effective duration of the modernization surcharge. A greater valuation of energy cost savings implies that the reference rent after the retrofit is increasingly larger than the status quo. In the long run, the landlord gains a rental premium only via this difference in the reference rents, so she intuitively prefers a greater market valuation of energy efficiency.

6.2 The consumption-based (CB) partially inclusive rent system

In the consumption-based partially inclusive rent system, the tenant's payments only depend on the reference rent, which depends on the market valuation of the retrofit's effect on the energy costs. Due to the interaction with the reference rent, the landlord and the tenant benefit from more effective retrofits. Changes in energy prices are thus roughly shared evenly, but changes in the retrofit's costs predominantly or exclusively befall the landlord.

Regarding the rental market variables, the signs of the effects above remain the same as those of the modernization surcharge. Their magnitude, however, is smaller, except for the market valuation of energy efficiency. The reason for the difference in magnitude lies in the slightly different interaction with the reference rent we assume for the CB system: after a retrofit, the landlord may charge the initial rent or the reference rent of the retrofitted apartment. As the retrofitted apartment has lower energy costs, we expect it to achieve a smaller rent level in the new rental market.

Suppose the market valuation of energy efficiency was 100 %. In that case, we assume that only cold rent systems, such as MS, reflected differences in energy efficiency in the rental market. Inclusive rent systems, such as CB, would neglect variance in energy costs. In both cases, landlords would earn precisely the energy-independent value of the apartment. As empirical analyses imply an undervaluation of energy efficiency, landlords can earn more than the energy-independent value with less efficient buildings. Therefore, the CB-reference rent after a retrofit should be lower than before as energy costs decrease.

This also implies that the landlord's benefit of the retrofit is given by how long she may charge the higher initial rent payment after the retrofit before the increasing reference rent catches up, at which point her benefit is again dictated by the difference in the two reference rents, depending only on the retrofit's effectivity. Therefore, as with the MS system, the landlord prefers market and regulatory conditions in which the reference rent grows slower, explaining the same signs as in the MS system.

The effect's magnitude is smaller as no initial rent increase after the retrofit means that the landlord's "grace period," during which she benefits from the larger rent than the reference rent, is shorter than in the MS system. The greater magnitude of an increased market valuation's effect on landlord's payoffs is also due to the interaction with the reference rent. A greater market valuation means the landlord does not lose as much rental income for dropping to a lower reference rent level due to the retrofit. The "grace period" is shorter than the modernization surcharge, so this effect is more immediate than in the MS system.

6.3 The demand-based (DB) partially inclusive rent system

In the demand-based partially inclusive rent system, retrofit profitability changes affect landlords and tenants more nuancedly. It is again only the landlord whose payoffs change with varying investment costs. Energy price variation, however, hit landlords and tenants in opposite directions. As the tenant pays for the current energy demand costs displayed in the EPC, he could observe when moving in. Still, the landlord reimburses him for the current energy demand costs reported in the current EPC, the tenant hopes for fossil fuel costs to decrease, and the landlord benefits from cheaper green energy. Furthermore, the landlord benefits from greater average energy consumption due to the interaction with the reference rent. In contrast, the tenant benefits from it as it increases energy consumption cost savings after the retrofit.

The demand-based partially inclusive rent system is virtually unaffected by variations in the initial rent level, the undervaluation of the initial rent, the rent limit on new leases, and, to a slightly greater extent, the legal cap on rent increases due to an increasing reference rent. This is because the landlord's additional income does not interact with the energy-independent portion of the reference rent: She consistently earns the difference in the energy demand costs plus, as soon as it exceeds the initial rent, the difference between the reference rent without and with the retrofit.

As the landlord's immediate rent premium is independent of the reference rent, she may charge the larger reference rent directly after the retrofit without waiting unless the legal cap for rent increases due to the very strict reference rent. As the landlord benefits from the larger reference rent from the first year onwards, she is more sensitive to a better market valuation, increasing the retrofit's benefit.

That rent levels growing quicker than general inflation is also beneficial to the landlord in the DB system is an artifact from the rent limit for new tenancies. Usually, landlords may demand the market value of an apartment for new tenancies, which drives the reference rent. However, if the market value grows too fast, only a premium of twenty percent on the reference rent is permissible, dampening the reference rent for the following years. The retrofitted apartment, however, is in a higher tier of reference rent than before the investment. Therefore, when rent inflation is excessive, the 20 % permissible new rent premium over the reference rent applies to a greater reference rent after the retrofit. Thus, high rent inflation makes the retrofit more profitable for the landlord as, starting from a larger base, the dampening effect of the new rent limit is more lenient. This effect only applies when rent inflation considerably exceeds the general inflation.

6.4 Summary of sensitivity analysis

The sensitivity analysis reveals that of the four allocation systems, the rent-independent modernization apportionment (RIMA) offers a retrofit incentive independent of nearly every exogenous variable. This robustness is, arguably, excessive: it is hard to argue that the landlord should always receive the same profits from a retrofit, no matter its cost efficiency. The modernization surcharge (MS) and the consumption-based partially inclusive rent system (CB) suffer from high unpredictability in their distributional effect, in addition to not providing sufficient retrofit investments in the base scenario. On the one hand, it seems fair to allocate increasing net costs and benefits of a retrofit somewhat between landlords and tenants when the exogenous variables change. On the other hand, their complicated interaction with the reference rent makes it difficult to estimate how far they both help in reaching whichever goal the legislator aims for in terms of retrofit activity and distributional effects. The demand-based partially inclusive rent system avoids both pitfalls at the cost of tenants. It gives greater retrofit incentives when the retrofit is more cost-efficient while being robust to changes in the rental market conditions that do not affect the retrofit's profitability. The only surprising effect is that tenants generally benefit from rising energy prices of the new heating system and falling prices for fossil fuels.

7 Conclusions and Policy Implications

The German residential building stock experiences insufficient retrofit activity to meet the climate protection goals. One of the reasons lies in the privately unfavorable cost-benefit ratio of most energy efficiency retrofits. Another reason is the landlord-tenant dilemma, which befalls the rental sector that is extraordinarily large in Germany compared to the EU average. The primary landlord-tenant dilemma arises from tenancy law regulating rent levels in ongoing tenancies. In contrast, the secondary landlord-tenant dilemma follows from an undervaluation of energy efficiency in the new rental market. Tenancy law can employ various allocation systems for retrofit and energy costs between landlord and tenant to alleviate the primary dilemma.

We developed a simulation model to test the effects of four allocation systems on landlords and tenants: the current modernization surcharge, a consumption-based partially inclusive rent system, a demand-based partially inclusive rent system, and a rent-independent modernization apportionment. We used concrete exemplary buildings and retrofit options paired with a coherent energy price scenario over the next twenty years to examine whether the retrofit performs better or worse than maintaining a business-as-usual scenario for the project in total as well as for landlords and tenants separately, assuming that each allocation system was already matured.

Our analysis revealed that most retrofit projects are unprofitable considering the entire building. This implies that if tenancy law's goal is to induce retrofits by offering profits for landlords, then this must occur at tenants' costs. We found that neither the current modernization surcharge nor the consumption-based partially inclusive rent system reliably offers profitability for retrofitting landlords. On the other hand, the demand-based partially inclusive rent system and the rent-independent modernization apportionment often make retrofits financially viable for landlords at tenants' costs. A sensitivity analysis reveals that the latter two's effects are independent of general tenancy law and local rent markets. The retrofit incentive in the demand-based partially inclusive rent system scales with project profitability, whereas the rent-independent modernization apportionment does not, requiring detailed and nuanced policy design.

Based on our analysis, we recommend two mutually exclusive policy options. The rent-independent modernization apportionment is suitable for a command-and-control policy approach. As it offers reliable returns for the investing landlord, regardless of the retrofit's effect, it requires detailed stipulations about which retrofits qualify and whether or not subsidies must be applied to benefit the tenant. However, given the landlord's reliable income perspective, the policy could be used with regulatory law that mandates the landlord to perform the socially desired retrofit. This, of course, then raises the question about the tenants' increasing costs of living.

The demand-based partially inclusive rent system is suitable for a more voluntary approach as it only incentivizes retrofits that cost-efficiently reduce at least the costs of the building's technical energy demand, barring considerations of the tenants' consumption behavior. This places the financial costs of the so-called rebound effect onto the tenant, who likely chooses less frugal energy consumption behavior in the retrofitted apartment. To implement this policy, widely available demand-based energy performance certificates are required, which, in the intermediate time, must be rolled out in any way to fulfill the recast EU Energy Performance of Buildings Directive (EPBD). Furthermore, the implementation requires adaptations of the Heating Costs Ordinance, introducing the demand cost levy from the tenant to the landlord and the demand cost reimbursement in the opposite direction. This allocation system also raises questions about the tenants' increasing living costs.

8 Appendix

Table 5: Detailed overview of the buildings and retrofit projects analyzed. All costs in €$_{2023}$, annual costs increase over time by the inflation index. Data kindly provided by ITG Dresden and FIW München.

	Variable	SFH	MFH-6	MFH-8	MFH-16	MFH-32
Size	Usable surface [m²]	150	473	474	1,407	2,022
	Habitable surface [m²]	125	394	395	1,173	1,685
	Number of dwellings	1	6	8	16	32
Business-as-usual	Energy demand per usable surface [kWh/m²/a] and Energy performance rating	311 – H	173 – F	171 – F	157 – E	149 – E
	Share electricity of energy demand	1%	1%	1%	1%	1%
	Share gas of energy demand	0%	99%	99%	99%	0%
	Share district heating of energy demand	0%	0%	0%	0%	99%
	Share oil of energy demand	99%	0%	0%	0%	0%
	Annual maintenance costs [€/a]	2,232.50	3,249.00	3,876.75	8,731.50	11,628.00
	Annual operational costs [€/a]	375.00	495.00	495.00	600.00	590.00

Retrofit 1	Energy demand per usable surface [kWh/m²/a] and Energy performance rating	168 – F	102 – D	54 – B	147 – E	145 – E
	Share electricity of energy demand	38%	29%	100%	0%	0%
	Share gas of energy demand	0%	71%	0%	0%	0%
	Share district heating of energy demand	0%	0%	0%	100%	100%
	Share oil of energy demand	62%	0%	0%	0%	0%
	Annual maintenance costs [€/a]	2,211.00	3,357.00	3,985.00	8,561.00	11,440.50
	Annual operational costs [€/a]	525.00	680.00	410.00	455.00	590.00
	Investment costs heating system [€]	29,200.00	40,000.00	64,000.00	39,200.00	36,800.00
	Of which eligible for subsidies [€]	18,300.00	32,300.00	64,000.00	34,100.00	36,800.00
	Subsidy quota heating system	25%	25%	35%	40%	30%
	Investment costs windows [€]	0.00	0.00	0.00	0.00	0.00
	Of which eligible for subsidies [€]	0.00	0.00	0.00	0.00	0.00
	Subsidy quota windows	0%	0%	0%	0%	0%
	Investment costs envelope [€]	0.00	0.00	0.00	0.00	0.00
	Of which eligible for subsidies [€]	0.00	0.00	0.00	0.00	0.00
	Subsidy quota envelope	0%	0%	0%	0%	0%
	Investment costs eligible for modernization surcharge [€]	9,725.0066	19,425.00	29,100.00	6,260.00	0.00
Retrofit 2	Energy demand per usable surface [kWh/m²/a] and Energy performance rating	66 – B	49 – A	132 – E	97 – C	91 – C
	Share electricity of energy demand	100%	100%	0%	0%	0%
	Share gas of energy demand	0%	0%	0%	0%	0%
	Share district heating of energy demand	0%	0%	100%	100%	100%
	Share oil of energy demand	0%	0%	0%	0%	0%
	Annual maintenance costs [€/a]	1,904.00	2,905.50	3,631.50	6,990.00	9,327.00
	Annual operational costs [€/a]	215.00	410.00	360.00	455.00	590.00
	Investment costs heating system [€]	35,800.00	48,500.00	23,400.00	35,400.00	33,500.00
	Of which eligible for subsidies [€]	35,800.00	48,500.00	21,800.00	32,200.00	33,500.00
	Subsidy quota heating system	35%	35%	40%	40%	30%
	Investment costs windows [€]	20,700.00	69,400.00	66,600.00	169,600.00	227,600.00
	Of which eligible for subsidies [€]	20,700.00	69,400.00	66.600.00	169,600.00	227,600.00
	Subsidy quota windows	15%	15%	15%	15%	15%
	Investment costs envelope [€]	35,200.00	16,300.00	0.00	202,800.00	272,400.00
	Of which eligible for subsidies [€]	35,200.00	16,300.00	0.00	202,800.00	272,400.00
	Subsidy quota envelope	15%	15%	0%	15%	15%
	Investment costs eligible for modernization surcharge [€]	39,115.00	66,160.00	38,810.00	208,040.00	275,000.00
Retrofit 3	Energy demand per usable surface [kWh/m²/a] and Energy performance rating	37 – A	33 – A	31 – F	23 – A+	71 – B
	Share electricity of energy demand	100%	100%	100%	100%	0%
	Share gas of energy demand	0%	0%	0%	0%	0%
	Share district heating of energy demand	0%	0%	0%	0%	100%
	Share oil of energy demand	0%	0%	0%	0%	0%
	Annual maintenance costs [€/a]	1,490.00	2,290.00	2,711.00	6,012.00	7,656.00

	Annual operational costs [€/a]	215.00	410.00	410.00	505.00	590.00
	Investment costs heating system [€]	36,100.00	50,300.00	50,500.00	90,700.00	68,200.00
	Of which eligible for subsidies [€]	36,100.00	50,300.00	50,500.00	90,700.00	68,200.00
	Subsidy quota heating system	35%	35%	15%	35%	30%
	Investment costs windows [€]	20,700.00	69,400.00	66,600.00	169,600.00	227,600.00
	Of which eligible for subsidies [€]	20,700.00	69,400.00	66,600.00	169,600.00	227,600.00
	Subsidy quota windows	15%	15%	15%	15%	15%
	Investment costs envelope [€]	99,100.00	124,400.00	170,500.00	375,100.00	436,800.00
	Of which eligible for subsidies [€]	99,100.00	124,400.00	170,500.00	375,100.00	436,800.00
	Subsidy quota envelope	15%	15%	15%	15%	15%
	Investment costs eligible for modernization surcharge [€]	83,425.00	126,785.00	150,730.00	339,240.00	397,060.00

Table 6: Inflation and energy price estimates used in the base scenario. Coherent price scenario kindly provided by ITG Dresden and FIW München.

Variable (VAT included)	Unit	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042
Inflation	Index	1.00	1.03	1.05	1.08	1.10	1.12	1.14	1.16	1.19	1.21	1.24	1.26	1.28	1.31	1.34	1.36	1.39	1.41	1.44	1.47
Carbon price	€/T	35.70	41.65	53.55	77.35	95.20	113.05	130.90	136.85	157.08	177.31	197.54	217.77	238.00	261.80	285.60	309.40	333.20	357.00	357.00	357.00
Electricity price for heat pumps	€/kWh	0.29	0.33	0.30	0.30	0.28	0.27	0.27	0.27	0.27	0.27	0.27	0.28	0.29	0.30	0.31	0.32	0.33	0.33	0.33	0.33
Carbon price for electricity	€/kWh	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Gas price	€/kWh	0.18	0.16	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.10	0.10	0.10	0.10	0.10	0.10	0.11	0.11	0.11	0.11	0.12
Carbon price for gas	€/kWh	0.01	0.01	0.01	0.02	0.02	0.03	0.03	0.03	0.04	0.04	0.05	0.05	0.06	0.06	0.07	0.08	0.08	0.09	0.09	0.09
Oil price	€/kWh	0.08	0.09	0.09	0.09	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.11	0.11	0.11	0.11	0.11	0.12	0.12	0.12	0.12
Carbon price for oil	€/kWh	0.01	0.01	0.01	0.02	0.03	0.03	0.03	0.04	0.04	0.05	0.05	0.06	0.06	0.07	0.08	0.08	0.09	0.09	0.09	0.09
District heating price	€/kWh	0.16	0.15	0.13	0.14	0.14	0.14	0.15	0.15	0.15	0.15	0.16	0.16	0.16	0.17	0.17	0.18	0.18	0.19	0.19	0.20
Carbon price for district heating	€/kWh	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 7: Minimum, mean, and maximum effect of variable changes on average discounted retrofit profitability across five buildings and three retrofits in €$_{2023}$/m²/month per allocation system. MS refers to the modernization surcharge system, CB to the consumption-based partially inclusive rent system, DB to the demand-based partially inclusive rent system, and RIMA to the rent-independent modernization apportionment. L corresponds to the landlord, and T to the tenant. Minimum effect at bottom of each cell, mean effect in the middle, and maximum effect on top.

	Minimum, mean, and maximum effect of variable changes on average discounted retrofit profitability across five buildings and three retrofits in €$_{2023}$/m²/month per allocation system				MS		CB		DB		RIMA	
	Variable	**Min**	**Max**	**Project**	**L**	**T**	**L**	**T**	**L**	**T**	**L**	**T**
Increasing retrofit's profitability	Subsidy	0 % of base case	200 % of base case	2.47 0.81 0.07	2.47 0.47 0.02	0.82 0.34 0.00	2.47 0.81 0.07	0.00 0.00 0.00	2.47 0.81 0.07	0.00 0.00 0.00	0.00 0.00 0.00	2.47 0.81 0.07
	Carbon, natural gas, oil price	+ 0.00 % p.a. from 2026	+ 5.00 % p.a. from 2026	0.88 0.55 0.00	0.18 0.10 0.00	0.70 0.45 0.00	0.48 0.30 0.00	0.40 0.25 0.00	1.39 0.76 0.00	0.00 -0.21 -0.51	0.02 0.00 0.00	0.88 0.55 0.00
	Average energy consumption relative to technical demand	50 % of BBSR-estimate	150 %of BBSR-estimate	1.84 0.76 0.05	0.64 0.29 0.01	1.20 0.47 -0.13	1.04 0.50 0.02	0.88 0.26 0.02	0.37 0.18 0.01	1.47 0.58 0.04	0.00 0.00 0.00	1.84 0.76 0.05
Decreasing retrofit's profitability	Retrofit and maintenance costs	50 % of base case	150 % of base case	-0.67 -2.01 -4.65	-0.67 -1.47 -3.98	0.00 -0.54 -1.43	-0.66 -1.97 -4.59	-0.01 -0.05 -0.25	-0.65 -1.94 -4.54	-0.02 -0.07 -0.29	0.56 -0.27 -1.47	-0.11 -1.74 -5.21
	Interest rate	0.50 % p.a.	5.50 % p.a.	-0.03 -0.69 -2.13	-0.03 -0.69 -2.13	0.00 0.00 0.00	-0.03 -0.69 -2.13	0.00 0.00 0.00	-0.03 -0.69 -2.13	0.00 0.00 0.00	0.00 0.00 0.00	-0.03 -0.69 -2.13
	Electricity, district heating price	+ 0.00 % p.a. from 2026	+ 5.00 % p.a. from 2026	0.33 -0.36 -0.75	0.05 -0.04 -0.10	0.28 -0.32 -0.69	0.18 -0.20 -0.41	0.15 -0.16 -0.34	0.46 -0.41 -0.84	0.17 0.05 -0.13	0.00 0.00 -0.01	0.33 -0.36 -0.75
Rental market characteristics with no effect on retrofit's profitability	Initial rent	3 €/m²/month	20 €/m²/month	0.00 0.00 0.00	0.00 -0.28 -0.97	0.97 0.28 0.00	0.00 -0.15 -0.41	0.41 0.15 0.00	0.00 -0.02 -0.04	0.04 0.02 0.00	0.00 0.00 0.00	0.00 0.00 0.00
	Rent inflation compared to general inflation	95 %	105 %	0.00 0.00 0.00	0.00 -0.71 -1.72	1.72 0.71 0.00	0.27 -0.44 -0.98	0.98 0.44 -0.27	0.33 0.15 -0.11	0.11 -0.15 -0.33	0.01 0.00 0.00	0.00 0.00 -0.01
	Rent limit new tenancies	0 % premium permissible	10 % premium permissible	0.00 0.00 0.00	0.00 -0.64 -1.17	1.17 0.64 0.00	0.00 -0.34 -0.86	0.86 0.34 0.00	0.18 0.01 -0.05	0.05 -0.01 -0.18	0.00 0.00 0.00	0.00 0.00 0.00
	Rent limit for rent increases according to reference rent	+ 0 % every 3 years permissible	+ 10 % every 3 years permissible	0.00 0.00 0.00	-0.01 -0.75 -1.25	1.25 0.75 0.01	-0.03 -0.35 -0.99	0.99 0.35 0.03	0.30 0.08 0.01	-0.01 -0.08 -0.30	0.00 0.00 0.00	0.00 0.00 0.00
	Undervaluation initial rent	50 % of market rent	100 % of market rent	0.00 0.00 0.00	1.16 0.45 0.00	0.00 -0.45 -1.16	0.52 0.22 -0.03	0.03 -0.22 -0.52	0.03 -0.02 -0.02	0.02 0.02 -0.03	0.00 0.00 0.00	0.00 0.00 0.00
	Valuation energy cost savings	0 %	100 %	0.00 0.00 0.00	0.71 0.31 0.00	-0.04 -0.31 -0.71	1.28 0.41 -0.01	0.01 -0.41 -1.28	1.57 0.72 0.04	-0.04 -0.72 -1.57	0.16 0.02 0.00	0.00 -0.02 -0.16

9 Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Open AI's Chat GPT 4.0 and Meta's Llama 3.1 8B Instruct in order to make the writing in the manuscript more concise. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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