PROCEEDINGS OF ECOS 2023 - THE 36TH INTERNATIONAL CONFERENCE ON
EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS
25-30 JUNE 2023, LAS PALMAS DE GRAN CANARIA, SPAIN

Landlord-Tenant Dilemma: How Does the Conflict Affect the Design of Building Energy Systems?

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Abstract:

To achieve the climate goals, the European Union needs to increase the renovation rate of buildings from 1 to 3 %. In owner-occupied buildings, financial incentives for renovation are motivated by energy cost savings. However, 30 % of all Europeans live in rented property, where conflicting stakeholder interests arise. Landlords are responsible for renovation decisions on the building envelope and the energy system as well as the corresponding investments. Tenants, for their part, face rising rents as investments are apportioned and only slightly benefit from falling utility costs. Literature calls this conflict the landlord-tenant dilemma. However, existing publications lack a precise quantification of the conflict, and little is known about the effects on technology choices and the heat transition. To address this gap, we incorporate the different perspectives of landlords and tenants in a model-based approach for optimized technology choice in form of a mixed-integer linear program. We compare optimal individual technology choices against the total cost optimum for renovations decisions. Additionally, we examine how changes in the regulatory framework affect the landlord's technology choice. Thereby, we consider the regulatory framework of Germany because of a comparatively low home ownership rate of 49 %. On this basis, we assess the technology choice of different stakeholders in terms of its impact on costs and emissions. Our study reveals that total costs and emissions are up to 29 % and 143 % higher for landlords deciding for rented houses compared to owner-occupied properties. Current approaches to solve the dilemma, such as tenant electricity and an energy-differentiated reference rent, could lead to the replacement of technical equipment and favor the development towards a climate-friendly energy system. However, the renovation of the building envelope is only partly considered in decisions of landlords, and operating costs are completely disregarded. As a result, tenants are the most burdened within the transition to a climate-neutral building stock.

Keywords:

Landlord-tenant dilemma; Renovation; Multi family houses; Optimization; MILP; Emissions; Costs.

1. Introduction

The building sector is responsible for 36 % of the greenhouse gas emissions in the European Union (EU) [1]. To achieve the set climate goals, e.g., a climate-neutral building stock by 2050, an increase of the renovation rate of buildings is required. While the European Commission is aiming for an increase in the renovation rate from an average of 1 % to 2 % [2], recent studies assume a minimum renovation rate of 3 % necessary to achieve the climate targets [3]. In addition to the renovation of the building envelope, a transformation of the building energy system is needed to defossilize the heating sector.

This transformation involves considerable costs for renovation measures, and the question of who pays for the heat transition arises. Especially in rented property, where 30 % of all Europeans live [4], conflicting stakeholder interests and the challenge of an appropriate cost distribution between the landlord (owner) and the tenant (user) arises. Landlords are responsible for the renovation decisions on the building envelope and the energy system, as well as the corresponding investment, but will not benefit from future energy cost savings. On the other side, tenants face raising rents and often only slightly decreased energy costs. This causes the so-called *landlord-tenant dilemma*, which involves two major challenges concerning the landlord's decisions:

1. Missing incentives to invest in renovation measures
2. No interest in renovation decisions that lower operating costs for tenants

Based on these issues, a third problem arises:

 https://doi.org/10.52202/069564-0175

3. Lack of emission reductions and incentive to reach the climate targets

To achieve the climate targets, it is therefore essential to resolve these challenges. This means incentivizing investment decisions by landlords that simultaneously contribute to a favorable solution for tenants and, furthermore, do not contradict the climate goals.

In comparison with other EU countries, Germany has the largest rental share in the residential building stock of 51 % [4]. In regard to the *landlord-tenant dilemma*, Germany has introduced a retrofitting fee (RF). This fee is supposed to refinance the investments in renovation measures by allocating a proportion of the investment to the tenants. However, the RF leads to further problems, as its determination is only cost-based and the profitability depends strongly on the development of market rents [5]. In addition, the cost-based calculation results in an increase in base rents (rent without energy costs) for which tenants are not necessarily compensated with reduced energy costs [6].

As a further step, Germany has introduced the Tenant Electricity (TEL) Act in practice, which is intended to simplify the sale of self-generated electricity from landlords to tenants. In addition, literature proposes different approaches to resolve this dilemma. A promising solution is an energy differentiated (ED) local reference rent (LRR) [6–8]. According to the German Civil Code (BGB) landlords in Germany have the right to increase the rent up to the LRR, irrespective of any renovation decision. Taking into account energy related attributes of buildings within an ED LRR could lead to renovation decisions that actually reduce energy demand and green house gas emissions and therefore, simultaneously costs.

Although this approach seems promising, most publications focus on qualitative studies on the *landlord-tenant dilemma* and its solutions and lack precise quantification of it. Therefore, little is known about the associated technology choices of landlords and the consequences for tenants. This further implies, literature has not yet investigated the specific impact of the dilemma on the heat transition. To address this gap, we develop a model-based approach in from of a mixed-integer linear program (MILP) to perform a holistic investigation of the conflict and the possible solutions by TEL and an ED LRR.

The developed optimization model is based on an existing MILP, that includes renovation measures of the building envelope and the building energy system [9]. As Germany is the country with the highest share of rented property in Europe, we extend the model by the respective legal framework of Germany for this study. Additionally, we incorporate the different perspectives of the stakeholders and compare individual technology choices with the total cost optimum and emissions of an owner-occupied building. With this framework, we close the current research gap by answering the following questions:

- How does the building owner's renovation decision differ between owner-occupied and rented buildings based on current regulations?
- Do TEL or an ED LRR solve the dilemma?
- What is the impact of the *landlord-tenant dilemma* on the heat transition?

2. State of the art

2.1. Landlord-tenant dilemma in literature

The *landlord-tenant dilemma* has been studied in various research disciplines, whereby economic, legal, and social science as well as engineering approaches can be identified. Table 1 provides an overview of the different research disciplines and their consideration of relevant aspects related to the *landlord-tenant dilemma*. The evaluation reveals three relevant aspects - building calculation, rental law and other legal framework. With regard to the building calculation, the literature overview denotes whether the studies consider renovations of the building envelope and the building energy system and the studies' level of detail in the building modeling. The area of rental law focuses on whether rent payments and the RF or the LRR and therein specifically ED features are considered. Furthermore, the overview lists whether requirements from the Building Energy Act (GEG), subsidies, CO_2 price allocation, feed-in tariffs and TEL are taken into account.

Studies from economics [7, 8, 10, 11] and legal science [6, 12, 13] focus on the current rental law and neglect a precise building calculation. The analyses from social science mostly show a detailed consideration of the stakeholder's willingness to pay and some individual aspects of rental law, but strong simplifications in other aspects [14–17]. Engineering approaches represent actual refurbishment options on the building envelope and building energy systems with varying degrees of accuracy in building modeling [18–20]. However, these models widely disregard the applicable rental law. In addition, all considered publications only occasionally address aspects of other related legal frameworks (e.g., GEG or CO_2 price allocation).

This literature review demonstrates that scientific publications so far mostly focuses on individual topics instead of combining all relevant aspects related to the *landlord-tenant dilemma*. For instance, Braeuer et al. [19] examine TEL in terms of its profitability for the landlord, but neglect rental payments. Henger et al. [5, 8] and Mellwig et al. [11] extensively address the rental law and further combine it with subsidies, but disregard

https://doi.org/10.52202/069564-0175

Table 1: *Landlord-tenant dilemma* in literature.

Considered in publication: ○ not, ◔ hardly, ◑ partly, ◕ almost, ● fully

			Building calculation			Rental law (BGB)				Other legal framework					
			Building envelope	Building energy system	Building modeling	Rent payments	Retrofitting fee (RT)	Local reference rent (LRR)	Energetic differentiation (ED)	Buildings Energy Act (GEG)	Subsidies	CO_2 price allocation	Feed-in tariffs	Tenant electricity (TEL)
Economic science	2022	Ahlrichs et al.	●	○	◑	◔	●	○	○	○	○	○	○	○
	2021	Henger et al.	○	○	○	●	●	●	●	○	●	◔	○	○
	2020	Henger et al.	○	○	○	●	●	●	●	○	●	◔	○	○
	2019	Mellwig et al.	◑	○	○	●	●	◑	○	○	●	○	○	○
	2016	Kossmann et al.	○	○	◔	●	●	●	●	○	○	○	○	○
Legal science	2019	Gaßner et al.	○	○	○	●	●	●	●	○	○	○	○	○
	2011	Neitzel et al.	◔	◔	○	●	●	●	●	○	○	○	○	○
	2009	Ekardt et al.	○	○	○	●	●	○	○	○	○	○	○	○
Social science	2022	Taruttis et al.	◕	◕	◑	●	◔	◔	●	○	○	◔	○	○
	2022	März et al.	◔	◔	○	●	○	○	●	○	○	○	○	○
	2021	Lang et al.	○	○	○	◑	○	○	◑	○	○	○	○	○
	2019	März	◔	◔	○	●	●	●	●	○	◑	○	○	○
Engineering	2022	Petkov et al.	●	●	◕	●	○	○	○	○	○	○	●	○
	2022	Braeuer et al.	○	●	◔	○	○	○	○	○	○	○	●	●
	2015	Steinbach	●	●	●	◔	●	○	○	○	○	○	◔	○

a specific examination of the building and some regulations (e.g. GEG and TEL). Since these topics are interdependent we close this gap by developing a comprehensive optimization model taking into account all mentioned aspects within this study.

2.2. Solutions to the landlord-tenant dilemma

In 2017, the TEL Act came into force in Germany with the aim of creating incentives for landlords to invest in systems for the self-generation of electricity. Moreover, the reviewed literature proposes a variety of further possible ways to resolve the *landlord-tenant dilemma* (see Tab. 2). The most frequently referenced solutions in literature are an adjustment of the current RF, an ED LRR, and the so-called one-third model.

For an adjusted RF, literature suggests an RF that is no longer solely dependent on the cost, but rather on energy savings. The aim is to prevent landlords from benefiting from increasing the costs of renovations. The ED LRR aims for a similar goal. A higher LRR for climate-friendly energy systems is intended to create incentives for renovation decisions that are favorable for all stakeholders and the climate targets. The one-third model was first presented by Mellwig et al. [11]. The model states that the costs of an energy-efficient renovation should be equally allocated between landlords, tenants, and the state.

Among the suggested solutions ED LRR is the only proposed solution that already has a legal basis in the context of the rental law in Germany. Moreover, current political efforts with a law to reform the rent index law indicate that LRRs will play a central role in the future. However, in the reviewed literature, ED LRRs have not been quantitatively addressed yet. Therefore, we contribute to literature by applying the developed optimization model to address the question on whether or not an ED LRR represents a possible solution to the *landlord-tenant dilemma*. Also, very few have examined the impact of TEL on the landlord's renovation decision [19]. Therefore, we combine both solutions to show their effects and dependencies.

Table 2: Overview of presented solutions for the landlord-tenant dilemma

Approach	Source
Adjustment of the retrofitting fee (RF)	[7], [8], [10], [13], [12], [17]
Energy differentiated local reference rent (ED LRR)	[7], [8], [6]
One-third model	[11], [8], [12], [17]
Energy and climate fund model	[5], [8]
Separate surcharge on cold rent	[6], [12]
Differentiation of subsidies by landlord type	[17]
Obligation to renovate	[17]

https://doi.org/10.52202/069564-0175

3. Method

3.1. Optimization framework

We extend an existing MILP for design and operational optimization of residential buildings. For a complete documentation of the initial model, we refer to Schütz [21]. Figure 1 presents all aspects of the extended MILP.

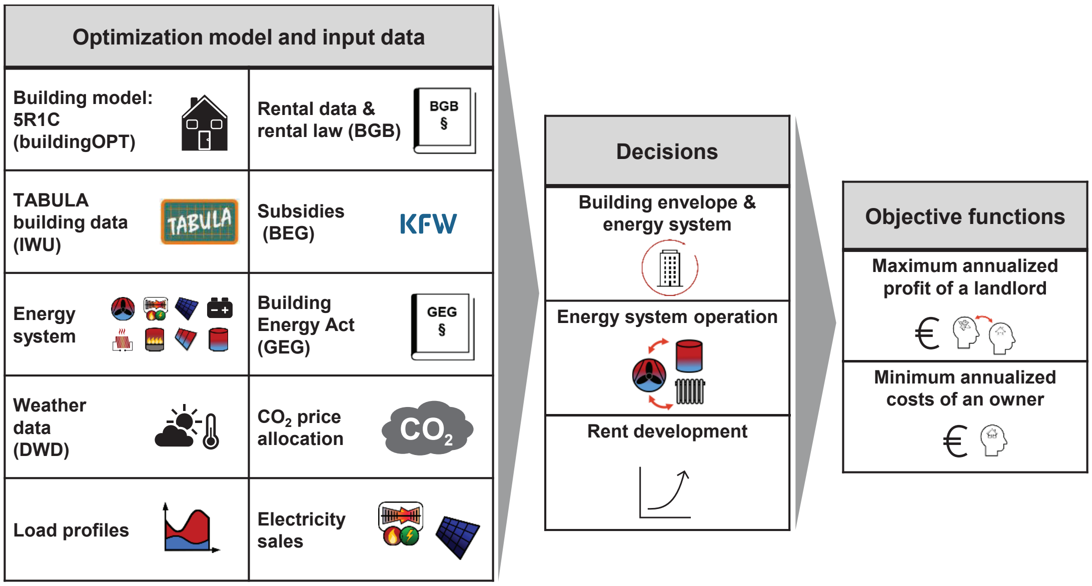

Figure 1: Overview of the optimization model and its decisions and objectives.

3.1.1. Objective functions

The objective of the model is to find a cost-optimal technology choice at the beginning of a specified time period from different perspectives. The annuity serves as economic metric [22]. Table 3 illustrates the relevant financial contributions for the respective stakeholders. Costs are marked with a minus sign (-), revenues with a plus sign (+) and no consequences with an empty field ( ). Investments, installation costs and subsidies are incurred at the beginning of the period under consideration. Maintenance costs, consumption costs, emission costs, metering costs, feed-in revenues, rental payments and TEL payments are incurred annually. A price-dynamic present value factor is determined to reflect price changes, except for rental payments. For the latter the cost for tenants for each year (y) are obtained by multiplying variable specific rental payments c_y^{rent} with the living area (A) and discounting it to the starting point by q. The annualized rental payments $c_{\text{ann}}^{\text{rent}}$ are then determined by applying the capital recovery factor (CRF) to the sum of yearly rent payments over the considered time period T (1).

$$c_{\text{ann}}^{\text{rent}} = \Big(\sum_{y \in (1,\ldots,N)} \frac{c_y^{\text{rent}} \cdot 12 \cdot \text{A}}{q^y} \Big) \cdot \text{CRF} \tag{1}$$

Table 3: Overview of the costs of the objective function

Category	Owner-occupied	Landlord	Tenant
Investment	-	-	
Installation	-	-	
Maintenance	-	-	
Consumption	-	-	-
Emissions	-	-	-
Metering	-		-
Feed-in/ self-consumption surcharges	+	+	
Subsidies	+	+	
Rent		+	-
TEL*		(+)	(-)

*only if TEL is applied

https://doi.org/10.52202/069564-0175

3.1.2. Decision variables

As a result of the optimization, the model decides on the cost-optimal combination of the building envelope and the energy system design and operation. Thereby, we consider various renovation measures, which can be combined in any way. For the facade, the roof and the windows four levels with increasing insulation standard can be selected independently. Regarding the energy system we consider boilers (BOI), combined heat and power engines (CHP), air source heat pumps (HP), electric heaters (EH), solar thermal collectors (STC), photovoltaics (PV), thermal energy storages (TES) and batteries (BAT). In case of optimized costs in a landlord-tenant relation, the MILP also determines how the rent can be increased according to regulations. For the rent development, the two rent increase mechanisms LRR and RF are available (see subsubsection 3.1.3.).

3.1.3. Optimization model and input data

Building and energy system

The building and energy system models are provided by the existing MILP. The thermal behavior of the building is described by a 5R1C model based on DIN EN ISO 13790 [23]. The 5R1C model summarizes the entire building into one thermal capacity and five thermal resistances. The whole building is modeled as one thermal zone with central heating. Building data for the initial building standard is taken from TABULA typologies [24]. To determine the size of the initial energy system, the standard heating load according to DIN EN 12831-1 is used with with a set indoor temperature of 20 °C.

To derive the external influences due to ambient heat and solar irradiation, local weather data from the Germany's National Meteorological Service are applied [25]. In this work, hourly resolved ambient temperatures and solar irradiances for average years are used. The method of Richardson et al. serves as a basis for the definition of electricity demand profiles [26]. Profiles for domestic hot water are retrieved by combining the presence profiles according to Richardson et al. with the domestic hot water profiles according to Beausoleil-Morrison [27]. In each case, the load profiles take into account that the peak demand grows degressively with the number of households, since a temporal distribution of the loads takes place.

Regulations and economic boundary conditions

With regard to the rental law, we implement regulations for rent increase, specifically the allowed rent increase mechanisms for the LRR according to § 558 BGB and for the RF according to § 559 BGB. The combination of both mechanisms is integrated based on a German Federal Court of Justice ruling [28]. For both mechanisms, we only consider existing tenants, as more extensive regulations apply to new tenants (e.g., rent control - see § 556d BGB). The RF allows the costs of renovation measures to be passed on to the tenant in the amount of 8 % of the investment. The LRR, which is determined every two years, is specified in rent indices and reflects the rent for comparable residential spaces. The landlord may increase the rent in accordance with the housing characteristics in particular location, size, type, features and quality.

The review of current literature reveals an ED LRR as one promising solution for the *landlord-tenant-dilemma*. To evaluate the impact, we implement an LRR with ED and without ED. The ED LRR in this work is based on the final energy demand for heating and domestic hot water as defined for the building energy pass (§§ 79-88 GEG). Other types of energy differentiation are possible and used in practice [29,30]. However, the final energy demand must be determined after renovation measures and allows for a standardized comparison of buildings. The binary variable x_{lev} indicates which LRR level (lev) has to be applied based on the achieved final energy demand $Q^{\text{fin}}_{\text{tot}}$ (4). Thereby, each energy quality level has a maximum final energy demand Q^{fin}_{lev} and only one energy level can be chosen (4). The corresponding LRR c^{lrr}_{y} is selected from the available LRRs $c^{\text{lrr}}_{y,lev}$ (3). The variable x^{switch}_{y} indicates whether the LRR is applied in the respective year if the RF was previously used. The switch is only possible once since the RF becomes part of the newly determined rent (5).

$$Q^{\text{fin}}_{\text{tot}} \leq \sum_{lev \in L} Q^{\text{fin}}_{lev} \cdot x_{lev} \tag{2}$$

$$c^{\text{lrr}}_{y} = \sum_{lev \in L} c^{\text{lrr}}_{y,lev} \cdot x_{lev} \quad \forall\, y \in (1, ..., T) \tag{3}$$

$$\sum_{lev \in L} x_{lev} \leq 1 \tag{4}$$

$$x^{\text{switch}}_{y} \leq x^{\text{switch}}_{y+1} \quad \forall\, y \in (1, ..., T-1) \tag{5}$$

For the allowed combination of the LRR and the RF, we distinguish whether a switch from the RF to the LRR has occurred using the big-M method with the binary x^{switch}_{y}. If the RF is applied, the base rent is the rent of the previous year c^{rent}_{0} (year 0 before the start of the period under consideration) or the initial LRR of the unrenovated state $c^{\text{lrr,init}}_{1,lev}$ and the RF is charged on top (6). Alternatively, the rent can be increased according to the LRR of the refurbished condition (7). The calculation of the RF c^{rf} is based on 8 % of the investment minus received subsidies.

 https://doi.org/10.52202/069564-0175

$$c_y^{\text{rent}} \leq c^{\text{rf}} + max(c_0^{\text{rent}}, c_{1,lev}^{\text{lrr,init}}) + M \cdot x_y^{\text{switch}} \quad \forall\, y \in (1, ..., T) \tag{6}$$

$$c_y^{\text{rent}} \leq x_y^{\text{lrr}} + M \cdot (1 - x_y^{\text{switch}}) \quad \forall\, y \in (1, ..., T) \tag{7}$$

For both rent increase mechanisms, independent capping limits must be respected. The capping limit for the LRR consists of a maximum percentage rent increase within three years (§ 558 Art. 3 BGB). The capping percentage $c_{\text{limit}}^{\text{lrr}}$ depends on the local housing market (8). The capping limit of the RF consists of an absolute rent increase value per m^2 (§ 559 Art. 3a BGB). The capping limit $c_{\text{limit}}^{\text{rf}}$ is dependent on the rent before the application of the RF (9) and is constrained by (10). By (11) and (12) we take into account the independence of both capping limits.

$$c_{\text{limit}}^{\text{lrr}} = \begin{cases} 0.15 & \text{if} \quad \text{tense market} \\ 0.20 & \text{if} \quad \text{no tense market} \end{cases} \tag{8}$$

$$c_{\text{limit}}^{\text{rf}} = \begin{cases} 2\,\frac{€}{\text{m}^2} & \text{if} \quad max(c_0^{\text{rent}}, c_{1,lev}^{\text{lrr,init}}) \leq 7\,\frac{€}{\text{m}^2} \\ 3\,\frac{€}{\text{m}^2} & \text{if} \quad max(c_0^{\text{rent}}, c_{1,lev}^{\text{lrr,init}}) > 7\,\frac{€}{\text{m}^2} \end{cases} \tag{9}$$

$$c^{\text{rf}} \leq c_{\text{limit}}^{\text{rf}} \tag{10}$$

$$c_y^{\text{rent}} \leq c^{\text{rf}} + c_{\text{limit}}^{\text{lrr}} \cdot c_{y-3}^{\text{rent}} + M \cdot x_y^{\text{switch}} \quad \forall\, y \in (1, ..., T) \tag{11}$$

$$c_y^{\text{rent}} \leq c_{\text{limit}}^{\text{lrr}} \cdot c_{y-3}^{\text{rent}} + M \cdot (1 - x_y^{\text{switch}}) \quad \forall\, y \in (1, ..., T) \tag{12}$$

For the modeling of the basic structure of the subsidies, we refer to the original model [21]. In this study, some new regulations are added and existing parameters are changed according to current standards. Thereby, we take into account current subsidies for efficient buildings from BEG in form of single measures and the overall building efficiency. The BEG single measures, among other measures, subsidizes the installation of HPs, STCs, TESs and the insulation of the facade, the roof and the windows. Regarding the overall building efficiency, BEG subsidizes the achievement of certain efficiency house levels based on specified values for the annual primary energy demand and the specific transmission heat loss. Further, GEG prescribes U-values for the facade, the roof and windows that must be achieved as a minimum in the case of renovations (§ 48 GEG). Alternatively, limit values for the annual primary energy demand and the specific transmission heat loss after renovation must be met (§ 50 GEG).

Since 2023 the CO_2 costs of fossil energy solutions are split between landlord and tenant based on a distribution scheme considering the specific emissions [31]. The higher the CO_2 emissions relative to the heated living space, the higher the landlord's share of the costs.

Owners can profit from the feed-in and the self-consumption of PV and CHP power. According to the Renewable Energy Sources Act (EEG), PV feed-in is remunerated for 20 years (§ 25 Art. 1 EEG) depending on the installed capacity (§ 48 Art. 2 EEG). CHP feed-in is regulated by the CHP Act (KWKG) and remunerated for 30,000 full load hours (§ 8 Art. 1 KWKG) depending on the installed capacity (§ 7 Art. 1 KWKG). The CHP remuneration includes the average price for base-load electricity (CHP-index) [32] in addition to the federal surcharges. For the self-consumption of PV power, we consider the option of a TEL between landlord and tenant. In this case, the German Energy Act (EnWG) states that the landlord acts as the electricity supplier for the tenant with a price cap of 90 % of the respective basic supply tariff (§ 42a Art. 4 EnWG). In addition, the federal tenant electricity surcharge is granted (§ 48a EEG). The CHP self-consumption is remunerated regardless of a tenant electricity contract (§ 7 Art.2/3 KWKG).

3.2. Use case

We apply the developed model for two typical multi family houses (MFHs) according to TABULA. Table 4 presents the specifications for both buildings, which mainly differ in the construction age and thus also in their energetic quality (e.g., heat demand and building envelope). The energy system of the initial building consist of a gas BOI with low efficiency (82 %) based on data from TABULA. Since Hamburg is considered a good example in Germany for the implementation of an ED LRR as described in 3.1.2., we choose Hamburg as the location for our study [33]. Here, LRR levels are determined by dividing the final energy demand into five levels (0-4). MFH D (MFH H) is classified into level 0 for a final energy demand above 167.7 kWh/m^2 (84.3 kWh/m^2) and in the highest level 4 for final energy demands below 121.0 kWh/m^2 (48.5 kWh/m^2). This results in an LRR dependent on the energetic level between 7.06 and 9.88 €/m^2 (6.30 and 10.30 €/m^2). Table 5 provides information about energy tariffs and assumptions about revenues from feed-in electricity. General economic parameters, e.g., for energy prices developments, and prices for all considered technologies are listed in the appendix A. For improved solving times, we apply a k-medoid clustering after Domínguez-Muñoz et al. [34] and solve the problem for four representative days with a MIP gap of 0.5 %.

Table 4: Use case: MFH D and MFH H from TABULA

	MFH D	MFH H
Construction period	1949-1957	1984-1994
Living area	575 m^2	707 m^2
Apartments	9	10
Annual heat demand	210 kWh/m^2	115 kWh/m^2
Nominal heat load	61 kW	43 kW

	MFH D	MFH H
BOI	74,2 kW	52,0 kW
TES	45,6 kWh	56,1 kWh
Facade (F)	1,2 W/(m^{2}K)	0,6 W/(m^{2}K)
Roof (R)	1,6 W/(m^{2}K)	0,4 W/(m^{2}K)
Window (W)	3,0 W/(m^{2}K)	3,0 W/(m^{2}K)

Table 5: Energy prices from the end of 2022 (Scenario 1) and predictions for 2030 (Scenario 2) [35] (left). Assumptions for feed-in of CHP and PV electricity (right).

Prices		Scenario 1	Scenario 2	Unit
Gas price		0.2004	0.125	€/kWh
El. price		0.4007	0.327	€/kWh
CO_2 price		0.03	0.105	€/kg
Revenue	MFH D	35240	33238	€/year
landlord*	MFH H	43181	42327	€/year
Cost	MFH D	69467	64240	€/year
tenant*	MFH H	70150	66735	€/year

*initial state

Revenues	Scenarios	Unit
CHP index feed-in	0.1928	€/kWh
CHP feed-in	0.044 - 0.016*	€/kWh
CHP self-consume	0.015 - 0.08*	€/kWh
PV feed-in	0.082-0.109*	€/kWh
PV self-consume	0.0167-0.0267*	€/kWh

*dependent on the installed power

4. Results

4.1. Effects of the landlord-tenant dilemma

In a first step, we analyze how the renovation decision of the building owner differs between owner-occupied and rented buildings. Therefore, we first consider the use case without any of the suggested solutions to the *landlord-tenant dilemma* (ED LRR or TEL). Figure 2 compares total annual costs and emissions of the initial state with the owner-occupied building and a landlord-tenant relation for MFH D (left) and MFH H (right). For comparability, only the costs that correspond to the owner-occupied building are shown (see Tab. 3), hence rent payments, although they are considered in the landlord's decision, are not illustrated. It becomes obvious that for both buildings the landlord's decision is worse than the decision in an owner-occupied building in terms of costs and emissions. For MFH D for example, the owner of an owner-occupied building chooses a HP in combination with an EH and a PV. Further, the decision leads to an increased insulation of the roof (R), which lowers the total energy demand by around 16.7 % compared to the initial state. In contrast, the landlord of a rented property chooses a hybrid system consisting of a BOI, a HP and an EH. Compared to the owner-occupied building this is not only more expensive when comparing total costs (+29 %) over the considered lifetime, but also causes higher emissions (+123 %). Instead of a hybrid system, the landlord of MFH H only chooses a BOI, which leads to increased costs (+22 %) and high emissions (+143 %) compared to the respective owner-occupied building.

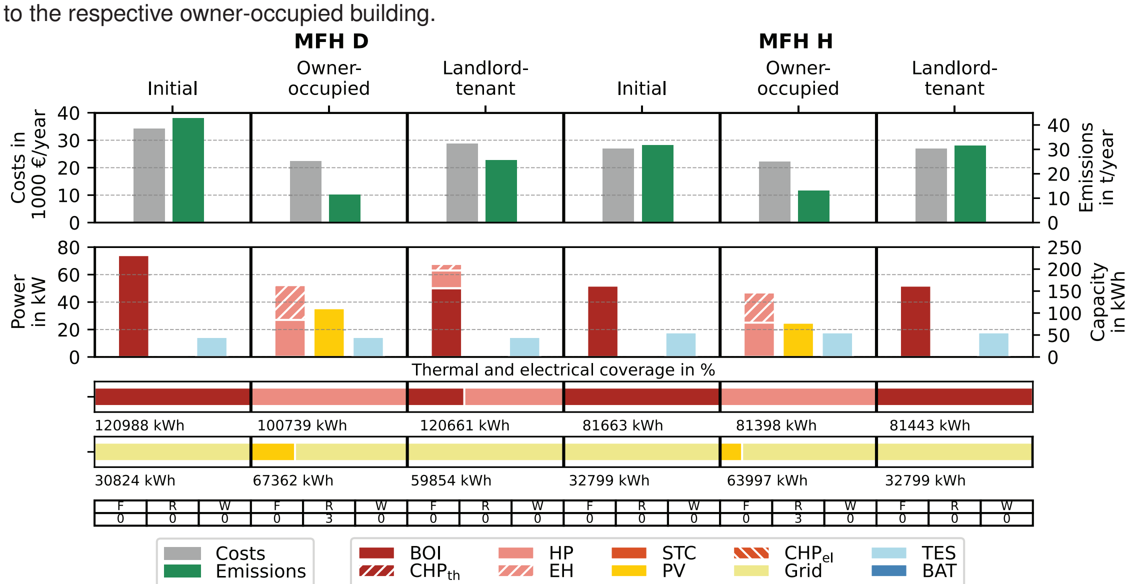

Figure 2: Renovation decisions for owner-occupied and rental buildings within price scenario 1.

https://doi.org/10.52202/069564-0175

Regarding the *landlord-tenant dilemma*, it can be concluded that although the landlord decides to replace the energy system, the favorable renovation of the roof is omitted for both considered use cases. This illustrates that there is no incentive for a landlord to invest in the building envelope and thus to decrease the energy demand (problem 1). Moreover, our results show that for both buildings the landlord decides on an energy system, which is not optimal in terms of total annual costs and emissions compared to the total cost optimum of an owner-occupied building (problem 2 and 3).

4.2. Solutions to the landlord-tenant dilemma

Based on the depiction of the *landlord-tenant dilemma*, we examine solutions proposed in the literature and, in some cases, already used in practice. Figure 3 shows the effect of an ED LRR without the application of TEL for two pricing scenarios for 2022 and 2030 (1 and 2). We find that in all scenarios with ED (w ED) compared to the scenarios without ED (w/o ED) an electrification of the energy system takes places by choosing an EH and/or an HP instead of a BOI or a CHP. This leads to decreased emissions, ranging from savings of only 1.6 % for MFH D to 51.9 % for MFH H in price scenario 1 (2022). Besides the different energy systems, in case of MFH H, the landlord also decides to renovate the roof to the highest energetic standard.

In terms of costs, the results show differences in revenues for the landlord and costs for the tenants compared to the respective initial status. Because of the ED, landlords can increase the rent more if a lower final energy demand is achieved. Thus, in scenarios with ED the landlord decides on renovation measures that lead to the highest level of energetic quality (level 4), enabling the highest rent increase. This results in higher revenues for the landlord, as well as higher cost for tenants, since the rent increase is not compensated for by lower energy costs, within all scenarios. Within price scenario 2 (2030), we can observe the highest increase in revenues for MFH D (+100.8 %) and in costs for MFH H (+54.3 %).

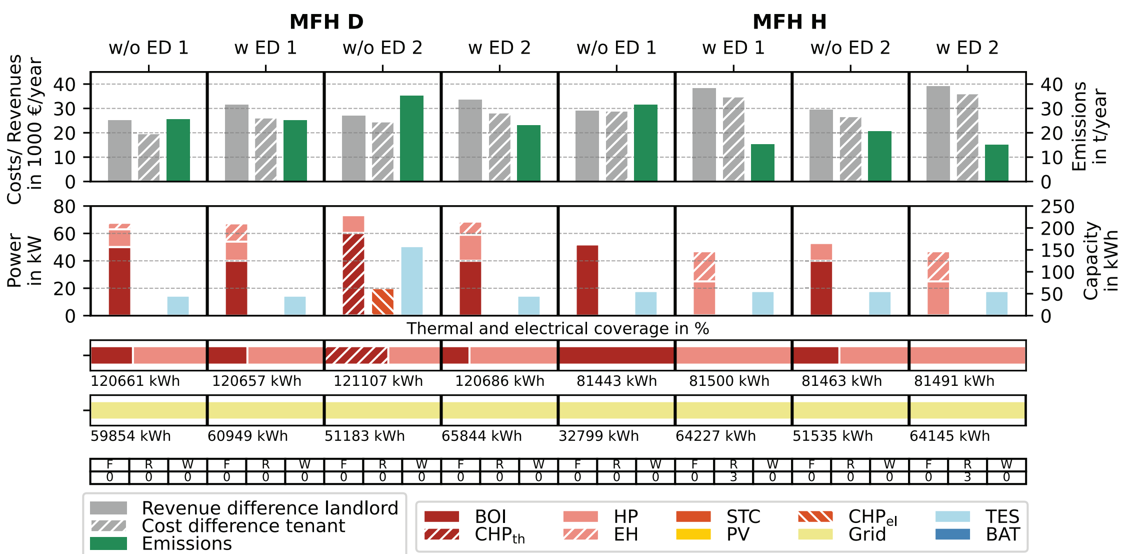

Figure 3: Renovation decisions in a landlord-tenant relation without (w/o) and with (w) ED LRR for price scenarios 1 and 2 (without TEL).

Regarding the *landlord-tenant dilemma* we see a slight reduction in the severity of the first problem of missing incentives for investments of the landlord, e.g., partly renovation of the roof of MFH H. In addition, the landlord invests in climate-friendly technologies (problem 3). However, due to high electrification combined with only minor measures on the building envelope, this could lead to an overload in the power grid during peak loads in the future. Referring to the second level of the dilemma, the tenant is burdened with significantly higher costs. Thus we can even observe an intensification of the second problem.

Finally, Fig. 4 presents the combination of ED LRR with TEL. In contrast to Fig. 3, the results reveal that TEL leads to the investment in PV in all considered scenarios. However, in the scenarios without ED (w/o ED) the owner's decision leads to mainly fossil based technologies for the remaining energy system. The energy system of MFH D, besides a small HP, mainly consists of a CHP as the landlord is able to sell the produced electricity to the tenants. In the case of MFH H, the landlord solely chooses a BOI. Although all scenarios have a PV, compared to the results without TEL that leads to higher emissions of up to 40.8 % for MFH D in price scenario 1 (2022).

Combining TEL with ED LRR, again a defossilization of the energy system takes place. Compared to Fig. 3 the emissions in the scenarios with ED are only higher for MFH D in price scenario 2 (+3.1 %). For all other

https://doi.org/10.52202/069564-0175

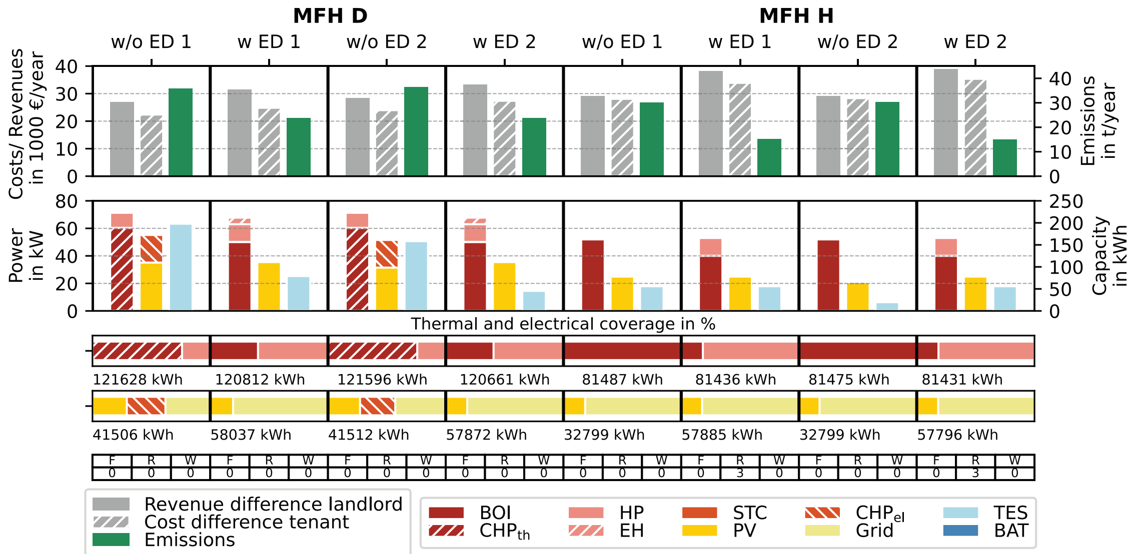

Figure 4: Renovation decisions in a landlord-tenant relation without (w/o) and with (w) ED LRR for price scenarios 1 and 2 (with TEL).

scenarios the combination of both solutions leads to favorable results in terms of emissions (up to 5.6 % for MFH D in price scenario 1) compared to the single approach of ED LRR. In terms of cost allocation, revenues for the landlord and costs for tenants are again significantly increased under the combined approach compared to the initial state. However, in comparison with the exclusive application of energy differentiated LRR, the landlord's revenues and the tenant's costs are slightly reduced (up to 0.3 % and 1.5 %).

Regarding the *landlord-tenant dilemma*, we find that TEL incentivizes the investment of landlords in PV. On the other hand, for the heating system, TEL rather favors CHP than a HP, which is consistent with the findings of Braeuer et al. [19]. In combination with the ED LRR, the decision of the landlord is again favorable for a more climate-friendly solution, adressing the first and the third problem of the dilemma. However, the second level of the conflict is only marginally improved, since the ED only considers the final energy demand, not the operating costs.

5. Discussion

In the optimization framework, we assume that the operation of the energy system is always optimal as we have a perfect foresight, allowing e.g., load shifts. That means that we likely underestimate operational costs in the MILP. This is particularly relevant for the operation of the HP in the owner-occupied building (see subsection 4.1.). Since the operation of the HP is highly dependent on the outdoor temperature and covers the entire heat demand within the considered period (see Fig. 2). This could mean that in practice the results are closer to each other and the second level of the landlord-tenant dilemma might be slightly less severe than presented. On the other hand, within the landlord-tenant relation, tenants are the ones burdened with operating costs. This means an underestimation of the operational cost, could also intensify the second level of the *landlord-tenant-dilemma*. Besides the operation of the energy system, in practice the heating behavior of the tenants might look different, too. For now, all apartments are assumed to be heated to 20 °C. Future studies should consider user behavior and related effects such as rebound and prebound effects as this could have a great impact on the results [36].

6. Conclusion

We extended a MILP for renovation decisions on the energy system and the building envelope to analyze the *landlord-tenant dilemma*. The dilemma consists of two levels. First, the landlord's missing incentives to invest in renovation measures, and second, increasing costs for tenants due to the landlord's decisions. To examine these two levels, we integrated the different perspectives and cost shares of landlords and tenants into the model and the objective function. The extension included the regulatory framework from Germany, in particular the rental law, but also, for example, the allocation of emission costs between landlords and tenants. Based on this, we implemented TEL and an ED LRR as possible solutions to the conflict. As a use case we chose two comparable typical buildings from the German city Hamburg with different construction ages.

The analysis without any of the proposed solutions confirmed both levels of the dilemma. The results showed

https://doi.org/10.52202/069564-0175

that for rented buildings the landlord's decisions are unfavorable in terms of total costs (29 %) and emissions (143 %) compared to an owner-occupied building. The application of TEL pushed investments in PV, but on the other hand, also led to a more fossil based heating system. In case of ED LRRs, we observed greater incentives of the landlord to invest in climate-friendly technology and, in some cases, in an advanced roof insulation. However, for both solutions, alone and combined, the *landlord-tenant dilemma* was only partially resolved for the first level. With regard to the second level, we found increasing costs for the tenants compared to the initial state for all considered scenarios. Thus, we deduce that the concept of ED LRRs needs to be extended and should not only be limited to the final energy demand.

In order to transfer these results further, additional building types and influences of different boundary conditions (e.g. location, price developments) should be investigated in the future. Furthermore, the operation of the energy system and user behavior should be modeled more precisely.

Appendix A Economical assumptions

Table A.1: General economical parameters and price developments [35]

General parameters		Price development	Scenario 1	Scenario 2
Observation period	20	Yearly el. price change	0.969	0.981
Interest rate	0.035	Yearly gas price change	0.960	0.992
Yearly inflation	1.02	Yearly CO_2 price change	1.08	1.02

Table A.2: Economical parameters for devices from manufacturer sheets and [37]

Device	Power/ Capacity	Investment Costs	Installation Cost	OM Cost
BOI	15 - 240 kW	2,158 - 13,516 €	5,000 €	3 %
HP	6 - 27 kW	7,800 - 18,315 €	1,530 €	2.5 %
CHP	2.5 - 293 kW	15,293 - 199,363 €	5,800 €	5 %
STC	continuous	245.22 €/m^2	6,500 €	1.5 %
PV	continuous	900 €/kWp	250 €/kWp	1 %
TES	0,116 - 7.3 m^3	756 - 6,973 €	500 €	0 %
BAT	5.5 - 66.24 kWh	7,638 - 47,785 €	2,500 €	0 %
EH	continuous	245 + 19 €/kW	2,000 €	0 %
Fasade	4 insulation levels	2.8484 €/(cm)	98.1968 €	0 %
Window	4 u-value levels	-226.8908 €/(W/m^2K)	736.18 €	0 %
Roof	4 insulation levels	4.1645 €/(cm)	105.5533 €	0 %

Nomenclature

Abbreviations

BAT Battery

BGB German Civil Code

BOI Boiler

CHP Combined heat and power engines

EEG Renewable Energy Sources Act

ED Energy differentiated

EH Electric heater

EM single measures

EnWG German Energy Act

EU European Union

GEG Building Energy Act

HP Air source heat pump

KWKG Combined Heat and Power Act

LRR local reference rent

MILP Mixed-integer linear program

PV Photovoltaic

RF retrofitting fee

STC Solar thermal collectors

TEL Tenant electricity

TES Thermal energy storage

WG Overall building efficiency

Variables

c_{ann}^{rent} annualized rent per month and m²

C_y^{rent} annual rent

c_y^{lrr} LRR per year

$c_{y,lev}^{lrr}$ LRR per year and level

c_{limit}^{lrr} LRR capping limit

c^{rf} RF

c_{limit}^{rf} RF capping limit

q interest rate

Q_{tot}^{fin} final energy demand

Q_{lev}^{fin} final energy demand of respective level

x_y^{switch} binary to switch between RF and LRR

x_y^{lrr} binary variable for the LRR level

x_{lev} binary variable for the energetic level

References

[1] European Commission. In focus: Energy efficiency in buildings. Brussels; 2020.

[2] European Commission. A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives. Brussels; 2020.

[3] Buildings Performance Institute Europe. On the way to a climate-neutral Europe – Contributions from the building sector to a strengthened 2030 climate target; 2020.

[4] Eurostat. Verteilung der Bevölkerung nach Wohnbesitzverhältnissen, Haushaltstyp und Einkommensgruppe - EU-SILC Erhebung; 2022. [accessed 15.3.2023]. Available from: https://ec.europa.eu/eurostat/databrowser/view/ilc_lvho02/default/table.

[5] Henger R, Krotova A. Auflösung des Klimaschutz-Wohnkosten-Dilemmas? Förderung energetischer Modernisierungen mit dem Energie- und Klimafonds. Cologne; 2020.

[6] Neitzel M, Dylewski C, Pelz C. Wege aus dem Vermieter-Mieter-Dilemma: Konzeptstudie. Bochum; 2011.

[7] Kossmann B, von Wangenheim G, Gill B. Wege aus dem Vermieter-Mieter-Dilemma bei der energetischen Modernisierung: Einsparabhängige statt kostenabhängige Refinanzierung; 2016.

[8] Henger R, Köhler B, Braungardt S, Meyer R. Potsdam-Institut für Klimafolgenforschung, editor. Wer zahlt für den Klimaschutz im Gebäudesektor? Reformoptionen der Modernisierungsumlage. Potsdam; 2021.

[9] Schütz T, Schiffer L, Harb H, Fuchs M, Müller D. Optimal design of energy conversion units and envelopes for residential building retrofits using a comprehensive MILP model. Applied Energy. 2017;185:1-15.

[10] Ahlrichs J, Rockstuhl S. Estimating fair rent increases after building retrofits: A max-min fairness approach. Energy Policy. 2022;164:112923.

[11] Mellwig P, Pehnt M. Sozialer Klimaschutz in Mietwohnungen: Kurzgutachten zur sozialen und klimagerechten Aufteilung der Kosten bei energetischer Modernisierung im Wohnungsbestand. Heidelberg; 2019.

[12] Gaßner H, Viezens L, Bechstedt A. Faire Kostenverteilung bei energetischer Modernisierung – rechtliche Rahmenbedingungen einer Umwandlung der Modernisierungsumlage gemäß § 559 BGB in ein sozial gerechtes und ökologisches Instrument. Berlin; 2019.

[13] Ekardt F, Heitmann C. Energetische Sanierung im Altbestand und das EEWärmeG: Kann das Investor-Nutzer-Dilemma ökologisch-sozial aufgelöst werden? Recht der Energiewirtschaft; 2009.

[14] Taruttis L, Weber C. Inefficient markets for energy efficiency - Empirical evidence from the German rental housing market. SSRN Electronic Journal. 2022.

[15] März S, Stelk I, Stelzer F. Are tenants willing to pay for energy efficiency? Evidence from a small-scale spatial analysis in Germany. Energy Policy. 2022;161:112753.

[16] Lang M, Lane R, Zhao K, Tham S, Woolfe K, Raven R. Systematic review: Landlords' willingness to retrofit energy efficiency improvements. Journal of Cleaner Production. 2021;303:127041.

[17] März S. Warum sollte ich meine Mietimmobilie energetisch sanieren? Analyse und Multi-Level-Governance quartiersbezogener und individueller Rahmenbedingungen zur Steigerung der energetischen Sanierungstätigkeit privater Kleinvermieter. DuEPublico: Duisburg-Essen Publications online, University of Duisburg-Essen, Germany; 2019.

https://doi.org/10.52202/069564-0175

[18] Petkov I, Mavromatidis G, Knoeri C, Allan J, Hoffmann VH. MANGOret: An optimization framework for the long-term investment planning of building multi-energy system and envelope retrofits. Applied Energy. 2022;314:118901.

[19] Braeuer F, Kleinebrahm M, Naber E, Scheller F, McKenna R. Optimal system design for energy communities in multi-family buildings: the case of the German Tenant Electricity Law. Applied Energy. 2022;305:117884.

[20] Steinbach J. Modellbasierte Untersuchung von Politikinstrumenten zur Förderung erneuerbarer Energien und Energieeffizienz im Gebäudebereich [Dissertation]. Fraunhofer-Institut für System- und Innovationsforschung; 2015.

[21] Schütz T. Optimale Auslegung von Energiewandlungsmaschinen und Gebäudehüllen in Wohngebieten. RWTH Aachen University; 2018.

[22] Verein deutscher Ingenieure. VDI Richtlinie 2067 Blatt 1 - Wirtschaftlichkeit gebäudetechnischer Anlagen: Grundlagen und Kostenberechnung; 2012.

[23] DIN Deutsches Institut für Normung e V . DIN EN ISO 13790 Energieeffizienz von Gebäuden: Berechnung des Energiebedarfs für Heizung und Kühlung. Berlin: Beuth Verlag GmbH; 2008.

[24] Loga T, Stein B, Diefenbach N, Born R. Typology approach for building stock energy assessment, EPISCOPE - Energy performance indicator tracking schemes for the continous optimisation of refurbishment processes in European housing stocks. 2nd ed. Darmstadt: IWU; 2015.

[25] Koppe, Christina. Deutscher Wetterdienst, editor. Klimaberatungsmodul. Offenbach; 2022. Available from: https://kunden.dwd.de/obt/.

[26] Richardson I, Thomson M, Infield D, Clifford C. Domestic electricity use: A high-resolution energy demand model. Energy and Buildings. 2010;42(10):1878-87.

[27] Beausoleil-Morrison I. The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (COGEN-SIM). Hertfordshire; 2013.

[28] Bundesgerichtshof. Urteil des VIII. Zivilsenats vom 16.12.2020;. [accessed 15.3.2023]. Available from: https://juris.bundesgerichtshof.de/cgi-bin/rechtsprechung/document.py?Gericht=bgh&Art=en&az=VIII%20ZR%20367/18&nr=113751.

[29] Knissel J, v Malottki, Christian, Alles R. Bundesinstitut für Bau-, Stadt- und Raumforschung (BBSR) im Bundesamt für Bauwesen und Raumordnung (BBR), editor. Integration energetischer Differenzierungsmerkmale in Mietspiegel; 2010.

[30] Bundesministerium für Verkehr, Bau und Stadtentwicklung. Bundesministerium für Verkehr, Bau und Stadtentwicklung, editor. Hinweise zur Integration der energetischen Beschaffenheit und Ausstattung von Wohnraum in Mietspiegeln; 2013.

[31] Bundesregierung. Entwurf eines Gesetzes zur Aufteilung der Kohlendioxidkosten: CO2KostAufG;. [accessed: 15.3.2022]. Available from: https://www.bmwk.de/Redaktion/DE/Downloads/Gesetz/20220525-entwurf-eines-gesetzes-kohlendioxidkosten.pdf?__blob=publicationFile&v=8.

[32] European Energy Exchange AG. KWK Index; 2023. [accessed: 15.3.2023]. Available from: https://www.eex.com/de/marktdaten/strom/indizes.

[33] Freie und Hansestadt Hamburg Behörde für Stadtentwicklung und Wohnen. Hamburger Mietenspiegel 2021. Hamburg; 2021. [accessed: 15.3.2023]. Available from: https://www.hamburg.de/mietenspiegel/.

[34] Domínguez-Muñoz F, Cejudo-López JM, Carrillo-Andrés A, Gallardo-Salazar M. Selection of typical demand days for CHP optimization. Energy and Buildings. 2011;43:3036-43.

[35] vbw – Vereinigung der Bayerischen Wirtschaft e V , Prognos AG Berlin. Strompreisprognose. München; 2022.

[36] Osterhage T. Messdatengestützte Analyse und Interpretation sanierungsbedingter Effizienzsteigerungen im Wohnungsbau [Dissertation]. Technische Universität Dortmund; 2018.

[37] Figgener J, Haberschusz D, Zumühlen S, Sauer DU. Speichermonitoring BW - Abschlussbereicht - RWTH Aachen Institut für Stromrichtertechnik und Elektrische Antriebe. 2021.