Equitable decarbonization of the heat supply of rented residential buildings: Optimal subsidization strategy under allocating the costs of inaction

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Abstract

Keywords:

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Nomenclature

Type	Description	Unit
Set and index		
$y \in \mathcal{Y} = \{1, \ldots, Y\}$	Years, index by y	
$m \in \mathcal{M} = \{1, \ldots, M\}$	Months, index by m	
Decision variables		
Ψ	Investment grant paid to the landlord	EUR
$\Omega_{y,m}$	Heating costs subsidy payment for a single tenant in y and m	EUR
$d_{y,m}$	Total heat demand per dwelling	kWh
$q_{y,m}$	Heat demand supplied by the heating system alternative	kWh
π	Newly installed heating system alternative capacity	kW
$r_{y,m}$	Rent charge adjustment in y and m	EUR/m^2
Relevant parameters		
n	Number of tenants within the multi-apartment building	1
i	Interest rate	%
$q_{load,y,m}$	Total heat demand in y and m	kWh
α_m	Monthly load factor (ratio between total and peak heat demand) in m	1
c_{alt}	Specific heating system alternative investment costs	EUR/kW
c_{con}	Heating system alternative construction costs	EUR
$\bar{r}$	Initial rent price	EUR/m^2
ρ	Upper bound of the biannual rent charge adjustment	%
a	Rented area per tenant/dwelling	m^2
$p_{init,y}$	Energy price fueling the initial heating system	EUR/kWh
$p_{alt,y,m}$	Energy price fueling the heating system alternative	EUR/kWh

1. Introduction

The recently published "Fit for 55" package [1] by the European Commission outlines the path until 2030 to reduce greenhouse gas emissions by 55 % compared to 1990 in the Europe Union (EU). Undisputedly, massive efforts across sectors are necessary to enable a sustainable transformation of the energy system [2]. Simultaneously, there is a need for energy justice complying with the manner of "no one left behind" [3]. Against this background, the residential building sector calls for particular attention. With an eye on the residential building's heat demand, there are at least three reasons for this: Firstly, the high shares of fossil fuels in the provision of heat service needs (but also the cold service needs as well). Secondly, the often very inefficient way of delivering the heat demand is caused by low standards in terms of building stock quality and heat generation technology. And thirdly, the complex ownership structure and the fact that many people do not live in a property but in rented apartments or dwellings.

In fact, buildings are responible for 40 % of EU energy consumption and 36 % of the greenhouse gas emissions. Moreover, the European Commission states that 75 % of EU's buildings are energy efficient. The essential factor to improve these indicators is building retrofitting. Passive renovation measures can already make a significant contribution, as 35 % of EU's buildings are older than 50 years. However, this alone will not bring the European building stock to deep decarbonization. Rather, it is necessary to increase the current renovation rate of 1 %/year [4]. Thus, the share of passive (e.g., insulation improvements) alongside active renovation (e.g., heating system change) measures needs to be increased rapidly to be compliant with European climate plans such as the abovementioned Fit for 55 package. Indeed, European decarbonization scenarios assume a much higher renovation rate up to 3 % in order to achieve climate neutrality [2]. In order to filling this gap, most of scientific literature findings suggest federal financial incentives since renovation measures do not achive economic viability under current the current market environments in the EU (see, e.g., Fina et al. [5]).

We have already seen in the last decades how federal financial incentives have led to a massive market penetration of renewable energy technologies. For example, solar photovoltaic has literally flooded the electricity markets driven by public monetary subsidies such as feed-in tariff programms. In addition, significant cost reduction were found due to efficiency improvements and economies of scale [6]. There is much to suggest that we can learn from the diffusion pathway of solar photovoltaics and related experiences. Nevertheless, two aspects are important in this context that have received too little attention in the past. First, that the public monetary diffusion of renewable energy have to be accompanied by measures ensuring the energy efficiency. To given an example here. Recently, Poponi et al. [7] conducted a subsidisation cost analysis of renewable energy deployment in Italy. Studying the diffusion of solar photovoltaics, they concluded that public monetary support strategies are a cost-ineffective policy instrument if energy efficiency investments are ignored. And second, that the support is socially balanced in terms of society with and without private ownership, which is essential for many renewable technology investments in the heating sector.

The scope of this paper aims at exploring one ”hot potato” of a sustainable society future, namely, the decarbonization of the residential building sector in terms of heating system change and passive retrofitting measures. A focus lies on multi-apartment buildings in urban areas that are often heated by natural gas-based heating systems. Moreover, the frequently occurring ownership structure within the building with a single landlord (building owner) and numerous tenants plays a crucial role in the analysis. The building's landlord is the decision-maker in terms of potential (active and passive) retrofitting measures but is not influenced by an increasing CO_2, as the key determining parameter of deep decarbonization strategies in its decision process yet. On the contrary, the tenants are impacted significantly by the CO_2 but without ownership not able to invest into sustainable heat supply measures.

Against this background, the core objective of this work is to determine a cost-optimal and socially balanced governance's subsidization strategy for a multi-apartment building leading to building renovation measures to reduce and decarbonize heat supply. Federal subsidy payments can be direct payments in the form of an investment grant for the owner or a heating cost subsidy for the tenant. Besides, the owner can also be indirectly financially supported by allowing a rent adjustment as the building is refurbished. Social balance is defined at the building level from a monetary perspective using the net present value of the governance's subsidy payments for the building's owner and the tenants. This is also associated with a significant increase in the provision of heat service needs by (i) a heating system change from a fossil-fuel-based technology to a sustainable alternative and (ii) passive retrofitting measures (e.g., insulation improvements). Latter is comprehensively investigated within a sensitivity analysis using the CO_2 price-related energy cost allocation between the landlord ant the tenants as a parameter.

The method applied is the development of a linear optimization model. Thereby, the objective function is to minimize the governance's net present value. The landlord's and tenants' strategy to minimize total costs in considered by tailor-made adapted constraints in the modeling framework. The generalized formulation of the model allows to investigate different building types and categorizes (e.g., size and number of tenants, building's efficiency, initial rent price, etc.) that can be helpful to represent different building stocks.

The numerical example analyzed is a multi-apartment old building with a single owner and 30 dwellings or tenants respectively. The partially renovated building is located in an urban area and initially heated by individual gas heating systems at the dwelling's level. The decarbonization of the heat supply can be achieved by two different options, namely, a connection to the district heating network or an implementation of an air-sourced heat pump system.

The paper is organized as follows. Section 2 summarizes the current state-of-the-art in research and outlines the present study's own contribution beyond the existing literature. Section 3 presents the materials and methods developed in this work including the mathematical formulation of the model, scenario and numerical example description and model validation. Section 4 presents the results of this work, including sensitivity analyses of key determining parameters. Section 5 discusses the results, concludes the work, and outlines possible future research.

2. State-of-the-art and progress beyond

This section aims to provide an overview of relevant scientific contributions with respect to this paper's scope. Explicitly not part of the literature review is the already widely discussed topic of sharing renewable energy generation and related peer-to-peer innovations in the light of energy communities. A general study comprehensively dealing with the sharing economy is provided by Codagnone and Martens [8]. The reviews from Sousa et al. [9] and Koirala et al. [10] go into even more depth and with resepect to peer-to-peer energy sharing and energy communities. Also the authors' literature review of this paper in [11] provides a comprehensive review of energy sharing on the local level.

Against this background, the focus here lies on three different dimensions without claiming to be absolutely complete in each case. The first dimension is the decarbonization of heating and cooling systems from a system analysis perspective and is described in Section 2.1. The second dimension deals with the increasingly importance of justice in the energy system transition and is presented in Section 2.2. The third dimension is dedicated to the trade-offs analysis of investment decisions into renewable energy technologies including realted contracting business cases and is discussed in Section 2.3. The choice of these focal points, as well as the explicit exclusion of the mentioned topics, are deliberately chosen in order to reflect the DNA of the analysis.

2.1. Decarbonizing the provision of heating service needs

The insights obtained from various scientific studies allow us to see the big picture of a decarbonized heating and cooling sector. A fundamental change of the energy carrier mix, alongside a significant efficiency increase, is necessary for a sustainable heating and cooling service need supply. For example, Connolly et al. [12] provide in their study such a strategy and present a decarbonization roadmap for the European heating sector. They propose a new sustainable heat strategy that is based on changes on the demand-side and supply-side. In addition to significant heat savings, integrating sustainable heat sources into centralized heat networks (or district heating networks) and electrifying heat supply (e.g., heat pump) are suggested to achieve a low-carbon heating sector. Seyboth et al. [13] focus in their study on supportive energy policy recommendations to enhance the deployment of renewable energy heating and cooling technologies. In particular, this means the integration of renewable sources such as solar, geothermal, and biomass into heating and cooling systems.

In general, the sustainable heat source or heat generation technology that is ultimately implemented/used at the end-user levels depends on a number of factors. Among these, geographical and spatial characteristics (e.g., availability of heat network infrastructure, building construction features, outdoor temperature, etc.), in particular, play a crucial role. Su et al. [14] deal in their study with optimal sustainable heating system alternatives with a special focus on local geographical features of the application site. Their results show that there might not be a one-fits-all solution if decarbonizing local heating systems. However, certain trends are very much emerging in their findings, which can also be confirmed by further case studies. Renewable-fed district heating networks have significant potential to supply heat demand in urban areas. This is exemplarily also shown by the results of Popovski et al. [15]. They state that from a socio-economic perspective, district heating networks with excess heat are the most favorable supply option in densely populated areas. Lake et al. [16] present a comprehensive review of district heating and cooling systems. They analyze among others the economic feasibility and system identification based on primary energy sources of centralized heating and cooling networks. Rama et al. [17] study the optimal combination of different sustainable heating alternatives.In particular, they show how heat pumps and solarthermal can assist district heating networks. There exist also other alternatives. Sopha et al. [18] focus in their study on the potential of wood-pellet in Norway, a country with high shares of district heating-based heat supply. They use an agent-based model to identify energy policy options supporting the uptake of such sustainable heating systems. The authors conclude that a stable financial support (i.e., stable wood-pellet price) has the highest impact on the transition of wood-pellet. We refer to Section 2.3 in this context for a detailed discussion of financial incentives for renewable energy technologies in the heating sector.

In any case, there is a need for sustainable alternatives to district heating. Either to complement existing district heating networks in a high-efficient way (e.g., [17] and [18]) and/or because to compensate non-existing networks in the future. Popovski et al. [15] identify the electrification of the heat supply using heat pumps with photovoltaics as the most cost-competitive alternative from a socio-economic perspective. Leibowicz et al. [19] also show end-use electrification as an optimal strategy for the decarbonization of the heating sector. However, the authors state that the electrification using heat pumps for example only makes sense in combination with building thermal efficiency improvements.

In order to emphasize the importance of building renovation measures, we dedicate this concluding paragraph the corresponding literature. In particular, we select papers focusing on the impact of different retorfitting measures on sustainable heating system alternatives. However, we do not differentiate here in detail between different types of retrofitting measures (e.g., purely passive, passive, active, etc.) and refer in this context to the comprehensive literature review of Fina et al. in [5]. Ma et al. [20] provide an extensive literature and state-of-the-art analysis of retrofitting focusing on existing buildings. Vieites et al. [21] elaborate in this context of European initiatives improving the energy efficiency in existing and old (historic) buildings. Recently, Weinberger et al. [22] investigate the impact of retrofitting on district heating networks. Fina et al. [5] put their focus on the profitability of retrofitting of multi-apartment buildings with special consideration of different heating systems. They thoroughly study the implementation of the combination of building-attached/integrated photovoltaics supporting sustainable heating systems. Their results show how (passive) retrofitting measures result in a reduction of the required installed heating system capacity. However, the energy cost reduction achieved from higher building standards are not able to compensate the initial passive renovation investment costs. They conclude that latter significantly depend on the development of the CO_2 price and the assumptions of end-user investment grants as well as subsidies. We again take up these findings associated with financial support in Section 2.3

2.2. Justice in energy systems: fair and socially balanced sustainable energy transition

The issue of justice in energy systems is addressed in various studies. According to them, a key part of achieving climate targets is to ensure that no one is left behind in the climate action. More generally, the three energy justice tenets are distributive, recognition, and procedural[1]. Recently, these are comprehensively discussed and reviewed by Pellegrini et al. [24]. Considering this work's scope, we put our focus on procedural justice, as it represents measures that reduce potential barriers to new clean energy investments [23].

[1]In some works, restorative and cosmopolitan justice are also mentioned in this context. See, exemplarily in [23].

Generally speaking, dealing with just sustainable energy systems is a monumental task and seems to be very challenging to be generalized. However, studies focusing on certain local regions are likely to be the most promising approach. Recently, van Bommel and Höffken conducted a review study focusing on energy justice at the European community level [25]. Besides that, Lacey-Barnacle et al. [26] focus in their study on energy justice in developing countries. Coming back to this paper's content and spatial scope, Mundaca et al. [27] propose two local European case studies in Germany and Denmark investigating local energy transition from an energy justice perspective. Their findings are in line with those from Jenkins et al. [28] showing that energy justice and transitions framework can be combined and achieved simultaneously. However, Hiteva and Soacool [29] conclude from a business model perspective that energy justice may be realized through market principles but not through the market alone. We continue discussing this point in Section 2.3 when dealing with necessary (financial) incentives that foster the sustainable energy transition.

Recently, Hanke et al. [30] investigate renewable energy communities and their capability to deliver energy justice. They explore insights from 71 European cases and highlight the necessity of distributing affordable energy to vulnerable households. Furthermore, it is necessary to focus in this regard on low-income households. Exemplarily, Xu and Chen [31] propose on the basis of their generated results that low-income households need tailored assistance to ensure energy justice. In particular, they demonstrate that low-income households are renters and thus have fewer energy efficiency appliances. Sovacool et al. [32] heat in the same direction and discuss the special difficulties for households without the capital for sustainable energy investments and for those that do not own their own home such as renters. Moreover, renters also often have higher residential heating energy use intensity, an energy efficiency proxy [33]. In this context, Greene [34] discussed the so-called "efficiency gap" or "energy paradox". He showed that consumers have a bias leading to undervaluation of future energy savings in relation to their expected value. The main reasons are a combination of two aspects, namely, an uncertainty regarding the net value of future fuel savings and the loss aversion of typical consumers. Filling the above-mentioned efficiency gap is crucial in order to achieve both the energy transition and energy justice. Sovacool et al. [3] show that unfolding the energy transition result in deeper injustices investigating four different low-carbon transitions.

2.3. Overnight investments versus net present value

In particular, this concluding section is about looking at different renewable energy promotion instruments focusing on the heating sector. However, in some places, we refer to literature that deals in detail with the electricity sector. We consider this to be useful for the reader, to show the parallels and differences between the two sectors through comparison. Connor et al. [35] provide a fundamental review paper investigating a wide range of policy options that can support the deployment of renewable heat technologies. Masini and Menichetti [36] state that despite numerous energy policies implemented to promote renewable energy technologies, the penetration of these remains below expectations. They identify as one main key a lack of appropriate financing investment incentives. Public (financial) incentives are often seen as the most appropriate and efficient measures to fill this gap. Reuter et al. [37] compare different policy instruments, ranging from feed-in tariffs to investment subsidies, tax credits, portfolio requirements, and certificate systems. While focusing on companies and their willingness for renewable energy technology investments in the electricity sector, they conclude that feed-in tariffs are an effective means promoting these investments[2]. Similar results also can be found in the study from Couture and Gagnon [39]. Nevertheless, the two latter studies only investigate the deployment of renewable energy technologies in the electricity sector and not in the heating sector.

[2]Zhou et al. [38] provide a study dealing with the effectiveness of public financial incentives. The authors define effectiveness/efficiency as the amount of intervention (e.g., taxes collected, subsidies paid, etc.) to achieve a policy goal. Here, it is essentially the electricity sector that is being studied.

Building on these literature findings, however, it is of particular importance to differentiate between renewable energy technology investments from companies and private end-customers and households. In contrast to companies, private households are incentivized more effectively by investment grants to invest in renewable energy technologies [40]. This distinction and targeted adjustment of public financial incentives are important since private investment is a key driver of the diffusion of renewable energy technologies [41]. Østergaard et al. [42] investigate the investment costs of households to prepare existing buildings for high-efficient and sustainable heating systems. Their results show that customer investments require financial incentives and are required to be motivated economically[3]. In this context, the role of an increasing CO_2 price should also be interpreted with particular circumspection. Although, in general, the literature sees carbon pricing as the most important measure speeding up the sustainable energy system transition (see, for example, Nägeli et al. [43] focusing on the impact of carbon pricing on the residential building sector). However, this does not solve the inherent problem of differential ownership in the residential sector (i.e., landlords and tenants/renters). It is, therefore, only logical that Hecher et al. [44] focus in their work on the decision-making processes regarding sustainable heating system investments of homeowners. Therefore, there is a gap in the literature dedicated precisely to a heating system change in the residential sector, not neglecting the different ownerships.

We conclude this section with the topic of energy and heat contracting business models and explicitly aim to give only a small overview, as contracting business models themselves are not part of the paper's main scope. A comparative review of municipal energy business models in different countries is given by Brinker

[3]In particular, Østergaard et al. [42] show that the investment into an expansion of an existing low-temperature district heating network can be seen significantly differently. For example, a heat supply company achieves economic viability with the investment considering the potential of newly supplied heat demand in the area. However, it is not guaranteed that new consumers aim to be connected to the network since their investment profitability is highly uncertain due to high connection costs and low heat energy price savings.

and Satchwell [45]. Kindström and Ottosson [46] analyze local and regional energy companies offering energy services and conclude that most many of these are experiencing difficulties on the market. One reason is, as Fine et al. state, that the contracting framework itself decreases the economic viability since the contractor business companies (third party) aim to gain profit (i.e., contractor's interest rate). Suhonen and Okkonen [47] conduct an analysis of energy service companies in the residential heating sector and show a wide-ranging set of barriers of such business models. Moreover, the results of their Finnish case study reveal that this kind of contracting business model is unattractive and not profitable. Brown [48] investigates business models for residential retrofit in the United Kingdom and the European Union. Fina et al. [49] study the profitability of contracting business cases for shared photovoltaic generation and renovation measures in a residential multi-apartment building. Their results indicate that the profitability of (passive) building renovation measures significantly depends on the carbon price. However, the difficulties of high carbon prices are already addressed above and in the novelties of this work in the next section. Furthermore, Fina et al. focus explicitly in their study on building owners and neglect different ownership relationships.

2.4. Progress beyond state-of-the-art

Based on the abovementioned literature review, the scientific contribution and the novelties of this paper can be summarized as follows:

- A sustainable heating system change with a focus on the efficient provision of heat service needs at the multi-apartment building is carried out, emphasizing the ownership structure of the building and related financial interests of the building owner and the different tenants/renters. In particular, this addresses one of the hot potatoes of deep decarbonization strategies, namely, the residential heating sector with tenants who cannot change the heating system on their own due to missing ownership, and therefore extra attention need. The sustainable heating system alternative is financially incentivized by a federal subsidy strategy considering monetary justice between the landlord and the tenants.

- The developed analytical framework determines a cost-optimal and socially balanced subsidization strategy from the governance incentivzing a just heating system decarbonization at the building level. Especially, the optimization model allows a quantitative analysis of justice in low-carbon residential heating sector including the agent's specific monetary interests and the ownership structure within a building. Thus, this work focus on the trade-off analysis between the governance, landlord and tenants.
- The sensitivity analysis of sharing carbon-related energy costs between the building owner and tenants on the one hand, and linking the governance's strategy directly to building retrofitting measures, on the other hand, represent substantial innovations in the field of research for decarbonizing the existing building stock with landlord and tenants relations. The obtained insights can help build a more reliable understanding of decarbonizing the existing (rented) building stock. Even more, this work may contribute to rapidly increasing the renovation rate, often seen as a key for a high-efficient and decarbonized residential sector.

3. Materials and methods

Interest rate des Landlords corresponds zum Mieterwechsel

This section explains the methodology and the optimization model developed in this work. The section starts with an introduction and overview of the model in Section 3.1, followed by a detailed description of the mathematical formulation in Section 3.2. The case study and scenario description is given in Section 3.3. The model validation is described in Section 3.4 and the open-source programming environment in Section 3.5

3.1. Introduction and model overview

This section provides an comprehensive overview of the proposed model. In general, three agents with the following characteristics are considered:

Governance. The governance's main objective is to decarbonizing the residential heating sector. Therefore, the intention is to trigger a heating system change to a sustainable alternative on the multi-apartment building level by financial support for both landlord and tenants. The avowed aim is to find a cost-minimal and socially balanced solution. The financial support can be realized by an investment grant (paid directly from the governance) or rent-charge-related revenues (from the tenants and refunded by the governance) for the landlord and heating costs subsidy payments for the tenants.

Landlord. is the owner of the multi-apartment building and provides the heating system for the tenants, and is profit-oriented. Thus, a heating system change toward a sustainable alternative only is realized in case of the economic viability of the investment. In this context, the landlord can achieve profitability of the alternative heating system by receiving an investment grant (to reduce the overnight investment costs from the governance) and a rent-charge-related revenue cash flow (from the tenants).

Tenant. rents a dwelling within the multi-apartment building from the landlord and has rent-related and energy-related spendings. He cannot change the heating system on his authority but depends on the landlord's willingness to realize a low-emission sustainable alternative. Especially in the case of the existing heating system, its costs are directly subject to a higher pricing of CO_2 emissions. Nevertheless, the tenant aims to limit total costs in case of a heating system change at the level of the initial condition.

Figure 1 shows a sketch illustrating the interrelations between the governance, the landlord, and the tenants. The governance can support the landlord financially by investment grants and by the allowance of rent charge adjustments. At the same time, tenants are supported by a heating costs subsidy payment. The gray bar in the middle indicates that these financial benefits need to be socially balanced and overcome the differences in ownership within the multi-apartment building. The rent or rent charge adjustment is the direct financial exchange between the landlord and the tenant.

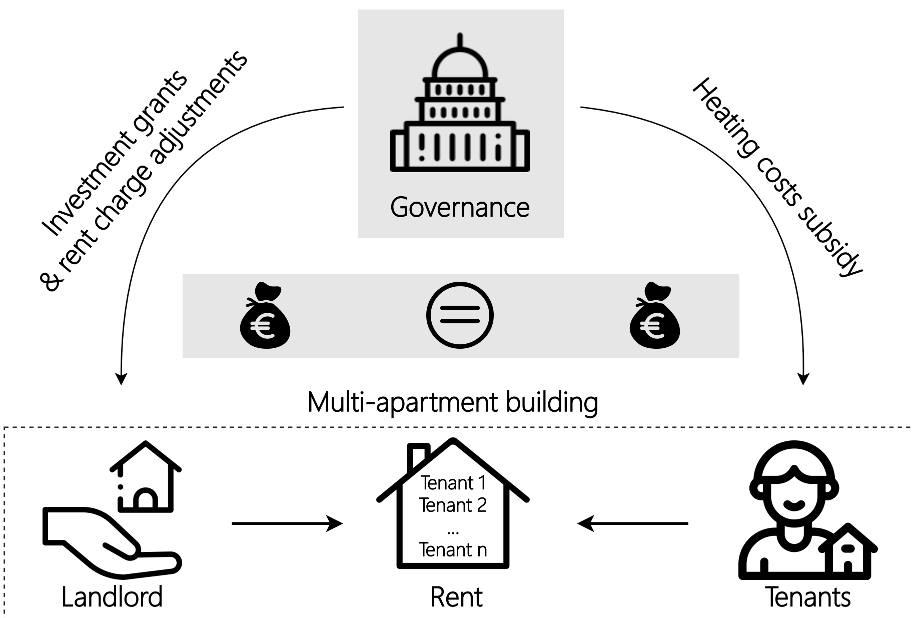


Figure 1: Sketch of the model illustrating the iterrelations between the governance, landlord, and tenants. Financial support from the governance is socially balanced at the multi-apartment building.

3.2. Mathematical formulation of the model

This section explains the mathematical formulation of the optimization model in detail. First, the objective function is defined. Then, a detailed explanation of the model's constraints is given.

3.2.1. Model's objective function

The objective function of the model is to minimize governance's total costs, including investment grants and subsidy payments[4]. Therefore, the objective

[4]This corresponds to the maximization of the governance's net present value.

function can be written as follows:

$$\min_{x} \Psi + \sum_{y} \sum_{m} \frac{n}{(1+i_g)^y} \cdot \Omega_{y,m} \tag{1}$$

where Ψ is the investment grant paid to the landlord and $\Omega_{y,m}$ the heating costs subsidy payment paid to a single tenant in year y and month m. In addition, n is the number of tenants[5] and i_g the governance's interest rate. The model's decision variables are included in the decision variable vector x. We refer to the nomenclature at the beginning of the paper containing a list of all decision variables.

3.2.2. Model's constraints

Equation 2 describes the load satisfaction of the total heat demand within the multi-apartment building using the alternative heating system in each time step (year and month)

$$n \cdot d_{y,m} \leq q_{y,m} \quad : \forall y, m \tag{2}$$

where $d_{y,m}$ is the total heat demand of a tenant's dwelling and $q_{y,m}$ the heat demand covered by the alternative heating system in y and m. Building on this, Equation 3 defines the minimum required newly installed capacity of the heating system alternative

$$\alpha_m \cdot q_{y,m} \leq \pi \quad : \forall y, m \tag{3}$$

where α_m is the load factor transforming the monthly amount of heat demand to the corresponding peak demand. Equation 4 defines the landlord's overnight investment costs (ζ)

$$\zeta = \pi \cdot c_{alt} + n \cdot c_{con} - \Psi \tag{4}$$

[5]It is assumed that the multi-apartment building consists of n equal tenants.

where c_{alt} is the specific investment costs of the heating system alternative and c_{con} the construction costs of an dwelling. Equation 5 defines the upper bound for the investment grant

$$\Psi \leq \hat{d} \cdot c_{alt} + n \cdot c_{con} \tag{5}$$

where $\hat{d}$ is the peak value of the heat demand. Equation 6 defines the rent-related revenues of the landlord ($\lambda_{y,m}$)

$$\lambda_{y,m} = a \cdot n \cdot (\bar{r} + r_{y,m}) \quad : \forall y, m \tag{6}$$

where $\bar{r}$ is the initial rent price, $r_{y,m}$ the rent charge adjustment associated with the heating system change in y and m and a the area of a tenant's dwelling. Equation 7 sets the landlord's net present value of the alternative heating system investment equal to zero

$$-\zeta + \sum_{y} \sum_{m} \frac{1}{(1 + i_l)^y} \cdot \lambda_{y,m} = 0 \tag{7}$$

where i_l is the landlord's interest rate. Equation 8 defines the initial annual spendings of all tenants (κ_y) using the existing heating system

$$\kappa_y = n \cdot (\bar{r} \cdot a + \sum_{m} q_{load,y,m} \cdot p_{init,y,m}) \quad : y = y_0 \tag{8}$$

where $p_{init,y,m}$ is the price of the conventional fuel initially supplying the heat demand in y and m. Building on this, Equation 9 sets the tenants' total spendings (K_{init})

$$K_{init} = -\sum_{y} \frac{1}{(1 + i_t)^y} \cdot \kappa_{y_0} \tag{9}$$

where σ_{y_0} represents the initial tenants' spendings from Equation 8 above and i_t the tenant's interest rate. Equation 10 defines the total spendings of all tenants

(K_{alt}) realizing the sustainable heating system alternative

$$K_{alt} = -\sum_{y}\sum_{m} \frac{n}{(1+i_t)^y} \left(a \cdot (\bar{r} + r_{y,m}) + q_{y,m} \cdot p_{alt,y,m} - \Omega_{y,m}\right) \tag{10}$$

and Equation 11 defines constant remaining spendings (i.e., economic viability) for the tenants in case of the heating system change.

$$K_{alt} = K_{init} \tag{11}$$

Equation 12 defines constant heat costs subsidy payments and Equation 13 constant total rent price for a tenant in y.

$$\Omega_{y,m} = \Omega_{y,m-1} \quad : y \tag{12}$$

$$\bar{r} + r_{y,m} = \bar{r} + r_{y,m-1} \quad : y \tag{13}$$

Equation 14 allows rent charge adjustment by the landlord only every two years and Equation 15 and 16 set a upper bound to the rent charge adjustment

$$\bar{r} + r_{y,m} = \bar{r} + r_{y-1,m} \quad : \forall y \backslash \{y_0\}, m \text{ if } y \bmod 2 = 0 \tag{14}$$

$$\bar{r} + r_{y,m} \leq \rho \cdot \bar{r} \quad : \forall y \in y_0 \tag{15}$$

$$\bar{r} + r_{y,m} \leq \rho \cdot (\bar{r} + r_{y-1,m}) \quad : \forall y \backslash \{y_0\} \tag{16}$$

by introducing ρ, as the rent charge adjustment upper bound. Equation 17 defines the financial support parity between the landlord and all tenants at the multi-apartment building level from the governance's perspective

$$\underbrace{\Psi + n \cdot \sum_{y}\sum_{m} \frac{r_{y,m}}{(1+i_g)^y}}_{\text{landlord's financial support}} = \underbrace{n \cdot \sum_{y}\sum_{m} \frac{\Omega_{y,m}}{(1+i_g)^y}}_{\text{tenants' financial support}} \tag{17}$$

3.3. Definition of the case study, scenarios and empirical settings

3.3.1. Multi-apartment building

The model proposed in this paper is applied to a typical multi-apartment building in an urban area. In particular, a partially renovated and natural gas-based heated old building in Vienna, Austria is investigated. In 2020, there were over 440 000 natural gas-based heated dwellings in Vienna, Austria (48.5 % of the total building stock) [50]. Nevertheless, this case study is representative for the European building stock in densely populated areas, as similar proportions of natural gas heating systems exist in the heating sector there as well[6].

It is assumed that the multi-apartment building (incl. all dwellings) are privately owned by the landlord. The number of dwellings is 30, whereby the area and rent price for each is equal. Each dwelling is rented by a tenant and heated by a individual natural gas-based heating system. The decarbonization of the heating systems can be realized by two different options, namely, a connection to the district heating network and a installation of a air-sourced heat pump[7]. It is assumed, that only of the two options is realized for all the dwellings. We refer to the empirical scaling and data in Section 3.3.3 for a detailed quantitative description of the multi-apartment building.

3.3.2. Scenarios

Four different quantitative scenarios are studied in this work. Three of them are developed in the Horizon 2020 research project openENTRANCE (`https://openentrance.eu/`) and describe a future European energy system development under achieving the 1.5 °C or 2.0 °C climate target. These scenarios are called *Directed Transition*, *Societal Commitment*, and *Gradual Development* scenario[8]. The first two scenarios consider the remaining CO_2 budget of the 1.5 °C climate

[6] For example, there are more than 600 000 natural gas-based heat dwellings in Berlin, Germany in 2020 [51].

[7] In general, it is assumed that the heat pump can be installed in the basement of the building. Nevertheless, the installation on the rooftop may also be considered. However, this explicit distinction is out of the scope of this paper and is not further examined.

[8] The openENTRANCE scenario *Techno-Friendly* is not part of this work.

target. Below, we qualitatively describe the three openENTRANCE scenarios used in this work and refer for further information to the studies in [52] and [53]. For the reader with a particular interest in the openENTRANCE scenarios, we refer to the work in [54], in which the underlying storylines outlining the narrative frames of the quantitative scenarios can be found.

The *Directed Transition* (DT) scenarios leads to limiting the global temperature increase well below 1.5 °C. This is achieved by a breakthrough of new sustainable technologies triggered through strong policy incentives. The markets themselves do not push this development and only deliver insufficient financial impulse for the clean energy transition. Besides, society is also too passive in supporting the penetration of renewable energy sources. Thus, it is assumed that multi-apartment building is connected to the district heating network. The CO2 price is between 196 EUR/tCO_2 (in 2025) and 680 EUR/tCO_2 (in 2040). Deep decarbonization of the European electricity and heating sector is achieved in 2040.

The *Societal Commitment* (SC) scenario also leads to limiting the global temperature increase well below 1.5 °C. In contrast to the previous scenario, decentralization of the energy system and participatory as well as societal acceptance of energy transition pushes the sustainable development. In addition, currently existing technologies significantly driven by policy incentives contribute to a decarbonized energy system since no fundamental breakthroughs of new clean technologies are in sight. Therefore, the multi-apartment building implements an air-source heat pump as sustainable heating system alternative. The CO2 price in this scenario is between 62 EUR/tCO_2 (in 2025) and 497 EUR/tCO_2 (in 2040). Deep decarbonization of the European electricity and heating sector is achieved in 2040.

The *Gradual Development* (GD) scenario reaches a global temperature increase of 2.0 °C and the corresponding climate target. In general, it is a very conservative expression of an European energy system future. This scenario includes a little of each sustainable development consisting of limited policy incentives, social acceptance, and technological advances. Both heating system alternatives (district heating connection and air-sourced heat pump installation) are examined. The CO2 price in this scenario is between 83 EUR/tCO_2 (in 2025) and 261 EUR/tCO_2 (in 2040). Deep decarbonization of the European electricity and heating sector is achieved in 2050.

In addition to the three openENTRANCE scenarios, the so-called "Low CO_2 price development" (LP) scenario is examined. This scenario neglects any remaining European CO_2 budget and misses both the 1.5 °C and 2.0 °C climate target. Thus, decarbonizing the electricity and heating sector develops only sluggishly. Therefore, neither the CO_2 price nor the specific emissions of electricity and district heating significantly significantly changed compared to today's values. Again, both heating system alternatives are studied. The CO2 price in this scenario is between 60 EUR/tCO_2 (in 2025) and 90 EUR/tCO_2 (in 2040). No target year achieving deep decarbonization of the European electricity and heating sector is set.

Scenario	Climat target	Heat pump (HP)	District heating (DH)
Directed Transition (DT)	1.5 C	-	✓
Societal Commitment (SC)	1.5 C	✓	-
Gradual Development (GD)	2.0 C	✓	✓
Low CO_2 price (LP)	none	✓	✓

Table 1: Four different scenarios are studied, including three ambitious deep decarbonization scenarios, developed in the Horizon 2020 project openENTRANCE and a low CO_2 price development scenario. The scenario specific heating system alternative is marked by the check.

Table 1 summarizes the scenarios and the corresponding heating system alternative implemented.

3.3.3. Empircial settings

Table 2 contains the empirical settings of the multi-apartment building including the agent's specific interest rates and further economic parameters.

Variable	Unit	Value
Number of tenants	-	30
Governance's interest rate	%	3
Landlord's interest rate	%	10
Tenant's interest rate	%	5
Heat demand (per dwelling)	kWh	8620
Peak heat demand (per dwelling)	kW	5
Heat pump|Investment costs	EUR/kW	1000
Heat pump|Construction costs (per dwelling)	EUR	1000
District heating|Investment costs	EUR/kW	320
District heating|Construction costs (per dwelling)	EUR	2000
Initial rent price	EUR/m^2	10
Maximum rent charge adjustment (ρ)	%	10
Rented area (per dwelling)	m^2	60

Table 2: Data assumptions of the multi-apartment building and its agents (landlord, tenants, and governance)

Table 3 contains the data with a temporal development (e.g., CO_2 price, specific emissions of the district heating supply, etc.).

Scenario	Variable	Unit	2020	2025 − 30	2030 − 35	2035 − 40
DT	CO_2 price	EUR/tCO_2	30	196	357	510
SC	CO_2 price	EUR/tCO_2	30	62	137	273
GD	CO_2 price	EUR/tCO_2	30	83	128	183
LP	CO_2 price	EUR/tCO_2	30	60	70	80

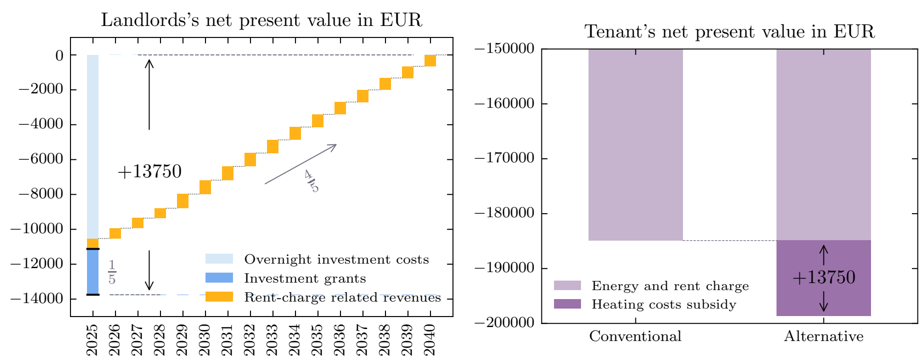
Table 3: Empirical settings of the data with a temporal development between 2020 and 2040

Further empirical settings can be found in Appendix A.

3.4. Validation of the model

This section aims to test the presented model and its functionalities. However, a model validation using existing empirical data can not be applied in this case.

There is simply a lack of comparable data from real cases. Therefore, a small illustrative case study is chosen to demonstrate the main functionalities and to verify the model. We assume a single landlord and tenant in a representative single-family household implementing a heat pump. It is assumed that the landlord's and tenant's interest rate is equal (3 %). A detailed description of the empirical settings can be found in Appendix B. Figure 2 shows the landlord's (a) and tenant's (b) net present value.



(a) Development of landlord's net present value

(b) Comparison of tenant's net present value

Figure 2: Landlord's and tenant's net present value and equal financial support. The landlord reaches a net present value equal to zero in 2040 resulting from an investment grant and rent-charge related revenues. The tenant's net present value remains constant compared to the conventional heating system resulting from heating costs subsidy payments.

Both agents receive equal financial support with a total of 13 750 EUR. One finfth of the landlord's support is paid as an investment grant and four-fifths as rent-charge related revenues. The tenant receives a heating costs subsidy. The level of financial support results exactly in (i) a landlord's net present value equal to zero within the time horizon of 15 years (see Figure 2a) and (ii) a constant remaining net present value of tenant compared to the conventional (existing) heating system (including the initial rent charge) (see Figure 2b).

3.5. Open-source programming environment and data format

The developed optimization model is implemented in Python using the modeling framework Pyomo [55]. It is solved with the solver Gurobi version 9.0.3. We use for data analysis the common data format template developed by the Integrated Assessment Modeling Consortium (IAMC) using the open-source Python package pyam [56]. Note that all materials used in this study are disclosed as part of the publication at GitHub [9]. We refer to the repository for the codebase, data collection, and further information.

[9]https://github.com/sebastianzwickl

4. Results and sensitivity analysis

This section presents the most relevant results of the proposed case study. Section 4.1 compares the results of the district heating or heat-pump-based heat supply in the different scenarios. Section 4.2 puts the focus on the district heating option results in the *Directed Transition* scenario and Section 4.3 on the implementation of a heat pump system in the *Societal Commitment* scenario. Latter highlights the impact of passive retrofitting measures on the feasibility of the model when implementing a heat pump in the old building and subsidization strategy and presents a sensitivity analysis regarding the total heat demand of the building as a parameter. Finally, Section 4.4 presents the results in the case of a CO_2 pricing cost allocation between the landlord as the building's owner and the tenants.

4.1. Objective value and results comparison

Table 4 shows a comparison of the obtained objective values for district heating (DH) and heat pump implementation in the different scenarios.

	District heating (DH)			Heat pump (HP)		
	DT	GD	LD	SC	GD	LD
Objective value	(1.5 °C)	(2.0 °C)	(-)	(1.5 °C)	(2.0 °C)	(-)
Absolute in thous. EUR	211.4	195.5	190.1	*infeasible*	*infeasible*	351.5
Rel. change in % of LD (DH)	11.2	2.6	-			82.6

Table 4: Comparison of objective value results for the different heating system alternatives and scenarios

In particular, two important aspects can be obtained while studying this table. The values across the three district heating cases are relatively stable and are within 11.2 %. In addition, the heat pump implementation in the two decarbonization scenarios *Societal Commitment* and *Gradual Development* is infeasible. In this context, only the low CO_2 price development provides a solution for the heat pump but with a significantly higher value compared to the scenario with the lowest value (+82.6 % compared with the lowest value).

Figure 3 shows the subsidization from the governance for the different technologies and scenarios. Note that the landlord's rent-related revenues (orange bar) are an implicit subsidy. Hence, the objective values from above are equal to the sum of the tenants' heating costs subsidy (purple bar) and the landlord's investment grant (blue bar).

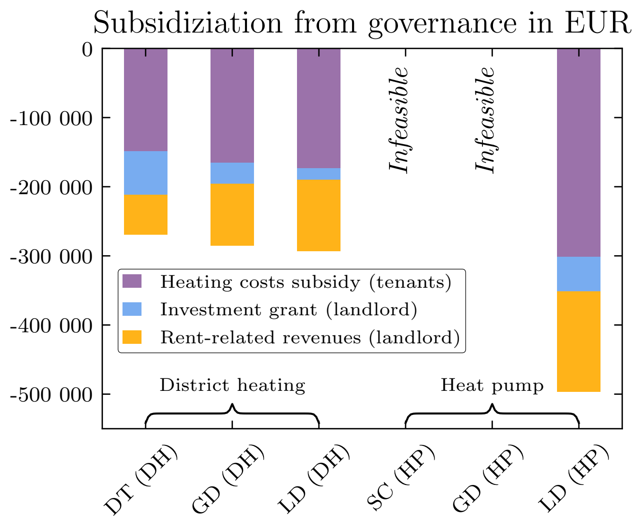


Figure 3: Comparison of subsidiziation from the governance for the landlord and the tenants for district heating (DH) and heat pump (HP) implementation in the different scenarios

4.2. District heating in the Directed Transition scenario

This section presents the results of the district heating implementation in the *Directed Transition* scenario in detail. Figure 4 shows the revenues and net present value of the landlord and a single tenant within the time horizon 2025 to 2040. The subfigure at the top left shows the revenues of the landlord consisting of the overnight investment costs (light blue), investment grant (blue), and rent-related revenues (yellow). Note that later represent the additional rent-related revenues based on the modernization of the building regarding the newly installed sustainable heating system alternative. The subfigure at the bottom left shows the development of the landlord's net present value. Thereby, it is shown that the investment achieves a net present value equal to zero at the end of the time horizon in 2040. The two subfigures to the right illustrate the tenant's revenues (top) and net present value (bottom).

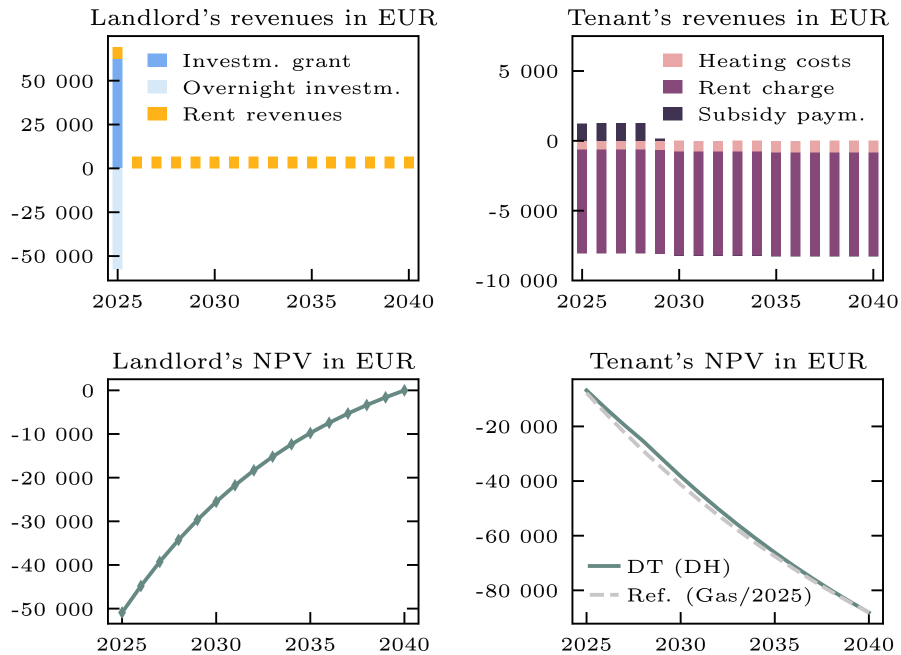


Figure 4: Development of the landlord's and tenant's economic viability of the district heating option in the *Directed Transition* scenario. Top left: landlord's revenues, bottom left: landlord's net present value (NPV), top right: tenant's revenues, bottom right: tenant's net present value

The tenant gets subsidy payments from the governance between 2025 and 2030. Thus, the tenant's net present value achieves the same value as in the reference case. The reference case considers constant remaining rent- and heat-related costs for the tenant based on the initial rent, gas, and CO_2 as in 2025. In the years 2025 to 2029, the subsidy payments exceed the heating costs of the tenant. Note that the tenant already pays a higher rent charge to the landlord within the same period (see the yellow bars in the top left subfigure). Most importantly, the tenant's reference net present value ("Ref. (Gas/2025)" marked by the gray dashed line in the bottom right subfigure) shows a crucial issue of the results and analysis, respectively. Since "Ref. (Gas/2025)" is used as the initial tenant's spendings, the results take into account the fact that the total opportunity costs (hence, those costs that would be incurred by sticking to the initial gas-based heating system for the tenant due to a rising CO_2 price). Note that the decarbonization scenarios do consider both a significant increase of the CO_2 and a decrease of the specific emissions of the district heating and electricity fueling mix. A detailed discussion of the allocation of CO_2 price-related opportunity costs is shown in Section 4.4.

4.3. Heat pump in the Societal Commitment scenario

Figure 5 shows the results of the heat pump option in the *Societal Commitment* scenario in detail.

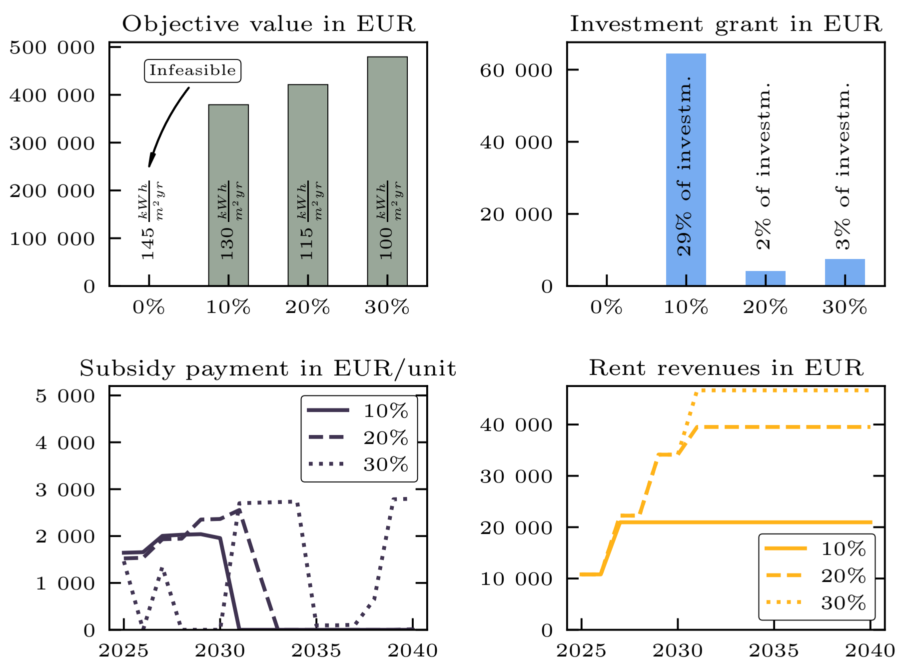


Figure 5: Comparison of the heat pump option in the *Societal Commitment* scenario for different renovation levels. Top left: governance's objective value, top right: landlord's investment grant, bottom left: tenant's subsidy payment per unit, bottom right: landlord's rent-related revenues in total

Since the initial condition of the old building in terms of total and peak heat demand leads to the infeasibility of the model, three additional renovation levels are presented. Latter correspond to a 10 %, 20 %, and 30 % reduction of both the total and peak heat demand. The initial condition of the old building is marked by 0 % as no reduction takes place. Most importantly, it can be seen that the building renovation increases the objective value (Fig. 5 top left). In case of a 10 % reduction of the heat demand, the landlord receives a significant investment grant be equivalent to 29 % of the landlord's total overnight investment costs (Fig. 5 top right). The tenant's subsidy payment takes place between 2025 and 2030 with a maximum of 2040 EUR (Fig. 5 bottom left). The rent charge adjustment and related revenues remain almost constant during the period (Fig. 5 bottom right). In case of a 20 % reduction of the heat demand, the landlord receives only a small investment grant related to the total overnight investment costs (around 2 %). The tenant's subsidy payment takes place between 2025 and 2032 with a maximum of approximately 2556 EUR. The landlord's rent-related revenues increase until 2031 and then remain constant. In case of a 30 % reduction of the heat demand, the landlord receives as before a small investment grant (3 % of total overnight investment costs). Instead, the landlord makes significant rent-related revenues (the highest among the three renovation levels). The tenant gets subsidy payments in most years, excluding 2026 and 2028 to 2030. The maximum is 2796 EUR in 2040. The lower heat energy-related costs as a result of the building renovation lead to higher rent charge payments. Hence, smaller investment grants supporting the landlord are needed.

4.4. Allocation of CO_2 pricing related costs between the governance, landlord and tenant

This section presents the results of district heating in the *Gradual Development* scenario for varying allocation of the opportunity costs among the governance, landlord, and tenants. In this context, the opportunity costs are defined as the costs of inaction and result from sticking to the initial natural gas-based heat system. Particularly, the CO_2 price related costs are allocated between the three parties/agents. Table 5 provides an overview of the different cases which cover different allocation assumptions. Exemplarily, "Case A (equally)" takes into account that the carbon price is shared equally among the governance, landlord, and tenants. Each of them bear one third of the costs. Note that the scenarios from Sec. 3.3.2 considered so far that the the total costs of inaction are covered by the governance or public authority (see Equation 9 and 11). The mathematical formulation can be found in Appendix C.

Rel. allocation of the opportunity costs	Governance	Landlord	Tenants
Case A (equally)	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$
Case B (within the building)	0	$\frac{1}{2}$	$\frac{1}{2}$
Case C (provider-side)	0	1	0
Case D (consumer-side)	$\frac{1}{2}$	0	$\frac{1}{2}$
Scenarios from Sec. 3.3.2	1	0	0

Table 5: Allocation of the opportunity costs (costs of inaction) among the governance, the landlord, and tenants

Figure 6 shows the relative change of the objective value for varying allocation of the opportunity costs.

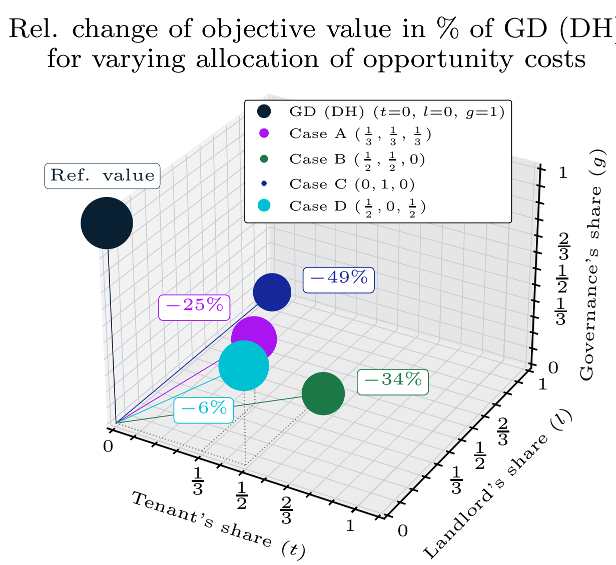


Figure 6: Comparison of the objective value for varying allocation of opportunity cost among the tenants (x-axis), the landlord (y-axis), and governance (z-axis) switching to district heating. The size of the points corresponds to the obj. function value in proportion to the *Gradual Development scenario* (percentage change in the boxes).

The objective value of the district heating option in the *Gradual Development* scenario (GD (DH)) is used as the reference value and marked by the black point in the upper left corner. Most importantly, the highest reduction is obtained in "Case C" where the landlord has to cover the costs of inaction (-49 % compared to the reference value). The second highest reduction is in "Case B". In this case, the opportunity costs are shared equally within the building among the landlord and tenants (-34 %). "Case A" reduces the objective value by 25 %. It is evident that an even allocation between the governance and the tenants ("Case D") do not lead to a reduction of the objective value. The main reason for this are monetary support for the landlord that is required to incentivize the investment and that the monetary support between the landlord and tenants is forced to have the same net present value.

Figure 7 shows the objective value foy varying landlord's interest rate. Note that these results are located in the YZ-plane spanned by the landlord's and governance's share in the costs of inaction in Figure 6.

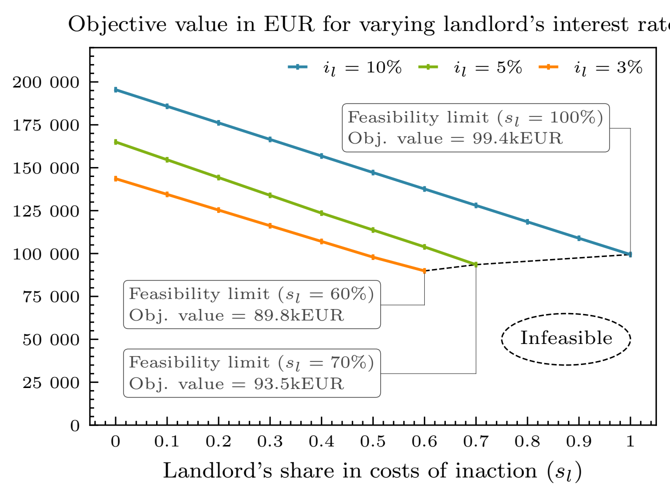


Figure 7: Comparison of the objective value for varying landlord's interest rate and share in costs of inaction

Particularly, "Ref. value" and and "Case B" specify the two endpoints of the blue line with $i_l = 10\,\%$. The varying landlord's interest rate has two important impacts. First, a decreasing interest rate reduces the objective value as revenues are discounted less (see Fig. 7 for a fixed landlord's share in costs of inaction, e.g., 0.2). Second, that as the interest rate decreases, a feasibility limit becomes apparent. This means, that the feasible maximum of the landlord's share in costs of inaction depends on the landlord's interest rate i_l. For example, the feasibility limit is 70 % for $i_l = 5\,\%$ and 60 % for $i_l = 3\,\%$ respectively.

5. Conclusions and recommendations

Rapid and equitable decarbonization of the building heat sector is an indispensable cornerstone in a sustainable society. Special attention is needed for the rented residential buildings sector since a sustainable investment decision is in the landlord's hands. Simultaneously, an expected increase in the CO_2 price primarily impacts the tenant's energy costs. This work studies cost-optimal federal subsidy payment strategies incentivizing sustainable heat change and retrofitting measures at the multi-apartment building level. We analyze the results of a partly renovated old building connecting to the district heating network and implementing an air-sourced heat pump system under several decarbonization storylines.

We found that a fair sustainable heat system change is possible but with massive federal subsidy payments. In particular, the building's owner investment grant and additional rent-related revenues based on the building modernization are crucial to trigger the profitability of the investment. At the same time, subsidy payments are required at the beginning of the investment period to limit the energy and rent-related spendings of the tenants. Furthermore, the results imply that the heat pump alternative is not competitive in supplying heat service needs in partly renovated old buildings. Either the subsidy payments are significantly higher than in the district heating case, or the equitable constraints of the model can not be satisfied. Building renovation and reducing heat demand lead to feasibility but with high total costs because passive retrofitting measures need to be incentivized.

Moreover, the results demonstrate that allocating the costs of inaction between the governance, the building owner, and the tenants is an important lever and can reduce the required subsidy payments. First and foremost, the biggest drop of the objective value (to nearly half) takes place when the costs of inaction are completely borne by the building owner. Also, a decrease in the landlord's interest rate reduces the total costs but limits the maximum share of the costs of inaction allocated to the landlord and implies a lower bound of the cost-minimized solution.

Future work may investigate a stronger coupling of active and passive renovation measures as a necessary condition for federal subsidy payments. This could bring further insights to decarbonization strategies with an eye on the heat demand and sustainable heat source alternatives in the residential building sector (i.e., climate neutrality in 2050). Besides, the tenant's set-up of the building could be improved. In particular, further work should include different types of tenants within the building (e.g., different willingness to pay). More generally, this study could be extended by introducing further technology options, such as solar photovoltaic, solar thermal, and heat and electricity storage systems.

Declaration of interests

None.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Data

Variable	Unit	Value
Specific emissions|Electricity	$kgCO_2/kWh$	0.130
Specific emissions|District heating	$kgCO_2/kWh$	0.130
Specific emissions|Natural gas	$kgCO_2/kWh$	0.220
Price|District heating	EUR/kWh	0.047
Price|Natural gas	EUR/kWh	0.05
Price|Electricity	EUR/kWh	0.2
Coefficient of performance (heat pump)	1	3

Table A.1: 2020's economic parameters and empirical settings

Appendix B. Empirical settings of the small case example

Hier beschreiben was die passive Retrofitting measures sind: Wall renovation

Appendix C. Varying allocation

Variable	Unit	Value
Heat pump investment costs	EUR/kW	1000
Construction costs	EUR	1000
Initial rent price	EUR/m^2	10
Rented area	m^2	100
Total heat demand	kWh	22 000
Peak heat demand	kW	13
CO_2 price (2025-2034)	EUR/tCO_2	50
CO_2 price (2035-2040)	EUR/tCO_2	100
Natural gas price	EUR/kWh	0.05
Electricty price	EUR/kWh	0.2
Specific emissions|Electricity	kgCO_2/kWh	0.130

Table B.2: Small case example's parameters