Egal wie Titel schlussendlich im Detail: Brauchen wir „equitable" & optimal im Titel.. Ich würde optimal streichen und in Equitable so lassen oder statt optimal/equitable

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Equitable decarbonization of ~~the~~ heat supply ~~of~~ in rented residential buildings: Optimal subsid~~ization~~ ~~strategy~~ ~~under allocating the costs of inaction~~

allocation between landlord and tenants

multi-apartment

Sebastian Zwickl-Bernhard[a,*], Hans Auer[a], Antonia Golab[a]

[a] *Energy Economics Group (EEG), Technische Universität Wien, Gusshausstrasse 25-29/E370-3, 1040 Wien, Austria*

heat system change

Abstract

To be added.

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Keywords: Equitab~~le~~, decarbonization, residential ~~buildings~~ heat supply, subsidization, ~~costs of inaction~~ landlord, tenants

evt. streichen

Equitable decarbonization of .....: Subsidy allocation .....

oder: Decarbonization of ....: Equitable subsidy allocation ....

*Corresponding author

Email address: `zwickl@eeg.tuwien.ac.at` (Sebastian Zwickl-Bernhard)

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 ~~received by~~ to the landlord	EUR
$\Omega_{y,m}$	Subsidy payment ~~received by~~ to a tenant in y and m	EUR
$d_{y,m}$	Total heat demand per tenant/unit in y and m	kWh
$q_{y,m}$	Heat demand supplied by the ~~sustainable~~ new heating system alternative in y and m	kWh
π	n capacity of the ~~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 of an agent (governance, landlord, tenant)	%
$d_{y,m}$	Total heat demand per unit in y and m	kWh
α_m	Load factor (ratio total and peak demand) in m	1
c_{alt}	Investment costs of the heat system alternative	EUR/kW
c_{con}	Construction costs of the heat system alternative per unit	EUR
$\bar{r}$	Initial rent price	EUR/m^2
ρ	Upper limit of the biannual rent charge adjustment	%
a	Rented area per tenant/unit	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

(for one dwelling/unit)

adaptation of

1. Introduction

The recently published "Fit for 55" package [1] by the European Commission outlines the pathway until 2030 to reduce greenhouse gas emissions by 55 % compared to 1990 in the Europe Union (EU). With an eye on the therein described energy policy recommendations, undisputedly, massive efforts across sectors are necessary to enable a sustainable transformation of the energy system (see also in [2]). At the same time, 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. There are at least three reasons for this: (i) High shares of fossil fuels in the provision of heat service needs (but also the cold service needs as well), (ii) Inefficient ways of delivering the heat demand caused by low standards in terms of building stock quality and heat generation technologies, (iii) Complex building ownership structures and the fact that many people do not live in a property but in rented apartments or dwellings.

In fact, buildings are responsible 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]. To increase this rate, most scientific literature findings suggest federal financial incentives since renovation measures do not achieve economic viability under current market environments in the EU (see, e.g., Fina et al. [5], Weber and Wolff [6], and Kumbaroğlu and Madlener [7]).

We have already seen in the last decades how federal financial incentives have led to massive market penetration of renewable energy technologies. For example, solar photovoltaic (PV) has flooded the electricity markets driven by public monetary subsidies such as feed-in tariff programs [8]. In addition, significant cost reductions were found due to efficiency improvements and economies of scale [9]. In principle, there are good reasons to think that one can learn from the diffusion pathway of solar PV and related experiences. Nevertheless, two aspects are crucial in this context that has received too little attention in the past. First that the public monetary diffusion of renewable energy has to be accompanied by measures ensuring energy efficiency. Recently, Poponi et al. [10] conducted a subsidization cost analysis of renewable energy deployment in Italy. Studying the diffusion of solar PV, they concluded that public monetary support strategies are a cost-ineffective policy instrument if energy efficiency investments are ignored. And second, that the support needs to be socially balanced in terms of society with and without private ownership, which is essential for many renewable technology investments, not only 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 rented 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 key role in the analysis as this is a generally crucial relationship since typically, a 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 price but without ownership, not able to invest in sustainable heat supply measures independently.

Against this background, the core objective of this work is to determine a cost-optimal and socially balanced subsidization strategy for a multi-apartment building to trigger a sustainable heat supply. The governance incentivizes the replacement of the initial natural gas-based heating system toward a sustainable alternative along with building renovation measures to increase efficiency and reduce heat demand by monetary support to the landlord and the tenants. Federal subsidy payments can be direct payments in the form of an investment grant for the landlord or a subsidy payment 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 efficiency of the heat supply by passive retrofitting measures.

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 units or tenants respectively. The partially renovated building is located in an urban area and initially heated by individual gas heating systems at the unit'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 [11]. The reviews from Sousa et al. [12] and Koirala et al. [13] go into even more depth with resepect to peer-to-peer energy sharing and energy communities. Also the authors' literature review of the paper in [14] 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 discloses 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. [15] 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. [16] 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. [17] 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. [18]. 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. [19] 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. [20] 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. [21] 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., [20] and [21]) and/or because to compensate non-existing networks in the future. Popovski et al. [18] 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. [22] 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. [23] provide an extensive literature and state-of-the-art analysis of retrofitting focusing on existing buildings. Vieites et al. [24] elaborate in this context of European initiatives improving the energy efficiency in existing and old (historic) buildings. Recently, Weinberger et al. [25] 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. [27]. 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 [26].

[1]In some works, restorative and cosmopolitan justice are also mentioned in this context. See, exemplarily in [26].

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 [28]. Besides that, Lacey-Barnacle et al. [29] focus in their study on energy justice in developing countries. Coming back to this paper's content and spatial scope, Mundaca et al. [30] 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. [31] showing that energy justice and transitions framework can be combined and achieved simultaneously. However, Hiteva and Soacool [32] 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. [33] 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 [34] 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. [35] 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 [36]. In this context, Greene [37] 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. [38] provide a fundamental review paper investigating a wide range of policy options that can support the deployment of renewable heat technologies. Masini and Menichetti [39] 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. [40] 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 [42]. 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. [41] 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 [43]. 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 [44]. Østergaard et al. [45] 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. [46] 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. [47] 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. [45] 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 [48]. Kindström and Ottosson [49] 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 [50] 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 [51] investigates business models for residential retrofit in the United Kingdom and the European Union. Fina et al. [52] 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 literature review, the scientific contribution and the novelties of this paper can be summarized as follows:

- An equitable and socially balanced heating system change with accompanied passive retrofitting measures of a rented multi-apartment old building is modeled. Thereby, special attention is paid to the representative ownership structure of the building, which means that the sustainable investment decision into a heating system alternative is in the building owner's (landlord) hands – and the tenants depend on it. The governance through monetary and regulative support incentivizes the local heat system transformation. In particular, the financial interest of both the landlord and the tenants is considered in the subsidization and plays a crucial role in the governance's optimal strategy. In this context, optimality accounts for the social balance of financial subsidy between the owner and the renters. Therefore, it implicitly emphasizes the importance of the high-efficient provision of residential heat service needs and the necessity of heat demand reduction and building efficiency improvements.

- The developed analytical framework determines a cost-optimal and socially balanced governance's subsidization strategy for the decarbonization of the heat demand at the building level. That includes, among others, the profit-oriented behavior of the landlord and the tenants, as well as the abovementioned financial support parity among both sides. Especially the proposed optimization model allows a detailed quantitative analysis of justice in a low-carbon residential building and heating sector with an eye on the complex ownership structure within buildings. Moreover, this work focuses on the trade-offs between different agents in the energy transition, particularly the government's role in triggering private sustainable investment decisions and social balance with an eye on the costs of inaction (opportunity costs) and increasing carbon pricing.

- Different sensitivity analyses are conducted determining a main focus of this paper. These give insights to the allocation of the costs of inaction among the governance, the landlord, and the tenants can be seen as one of the main novelties. Moreover, the importance of building stock quality in the context of federal subsidy payments is comprehensively discussed. Both analyses represent substantial innovations in the field of research for decarbonizing the existing rented building stock with owner-renter relations. In this context, the obtained insights can help build a more reliable understanding of a sustainable future urban society that does not live in ownership but in highly efficient supplied rented apartments. Even more, this work may also contribute to rapidly increasing the renovation rate of old buildings, often seen as a key for a sustainable decarbonized residential building sector.

The tenants, for their part, can be financially supported directly by the governance through.....

After into comprises

3. Materials and methods

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

is presented

, and followed by

3.1. Introduction ~~and~~ model ~~overview~~

into the

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

Governance. The governance's main policy 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~~.

paid

for the landlord

and/or adjusted....

Landlord. The landlord is the owner of the multi-apartment building, 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).

The tenant

Tenant. The tenant rents a dwelling/unit 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

its

wegen dem gantzen Gender He/she his/her wiederholung ... besser willingness to realize a ~~low-emission~~ sustainable alternative. ~~Especially in the case of~~ In connection with .... the existing heating system, ~~its~~ the tenant's costs are directly subject to a higher pricing due to the consideration 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~~ permission 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.

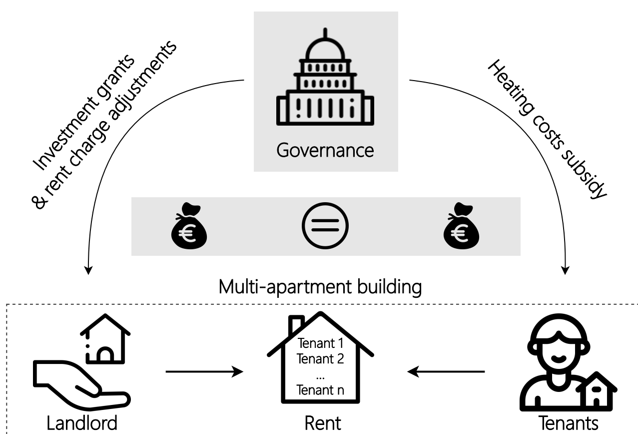

Figure 1: Sketch of the model illustrating the iterrelations between the governance, landlord, and tenants. Financial support from the governance is socially balanced at the multi-apartment building.

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 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

[4]This corresponds to the maximization of the governance's net present value.
[5]It is assumed that the multi-apartment building consists of n equal tenants/units.

do adapt one unit.

to the corresponding peak demand. Equation 4 defines the landlord's overnight investment costs (ζ)

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

where c_{alt} is the specific investment costs of the heating system alternative and c_{con} the construction costs ~~of all~~ 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 ($\lambda_{y,m}$)

$$\lambda_{y,m} = a \cdot n \cdot r_{y,m} \quad : \forall y, m \tag{6}$$

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 0

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

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 spendin case of implementing

ings (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}) ~~resulting~~ 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 ing costs subsidy payments and Equation 13 a 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 s by the landlord only every two years and Equation 15 and 16 set a n 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~~ work is applied to a typical multi-apartment building in an urban area. In particular, a partially renovated and natural gas-~~based~~ fired heat~~ed~~ ing system in an old building in Vienna, Austria, is investigated. In 2020, ~~there were over~~ more than 440 000 natural gas-based heated dwellings existed in Vienna, Austria (48.5 % of the total building stock) [53]. Nevertheless, this case study is representative for the European multi-apartment building stock in densely populated areas, as similar proportions of natural gas fired heating systems exist in the residential 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 unit is equal. Each dwelling is rented by a tenant and heated by a individual natural gas-based heating system. The decarbonization of the existing heating systems can be realized by two different options, namely, a connection to the district heating network ~~and a~~ or an installation of a air-sourced heat pump[7]. It is assumed, that only one of the two ~~options~~ technology alternatives 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.

---

[6]For example, there are more than 600 000 natural gas-based ~~heat~~ systems covering residential heat demand in dwellings in Berlin, Germany, in 2020 [54].

[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~~ work and is not further examined.

of the

with the tailor-made model presented above.

Input settings of

3.3.2. Scenarios

Four different quantitative scenarios are studied ~~in this work~~. Three of them ~~are~~ have been 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 target. Below, we ~~qualitatively describe~~ the three openENTRANCE scenarios used in this work and refer for ~~further information~~ to the studies in [55] and [56]. For the reader with a particular interest in the openENTRANCE scenarios, we refer to the work in [57], in which the underlying storylines outlining the narrative frames of the quantitative scenarios can be found.

assuming to those

briefly summarise

a distilled description

The *Directed Transition* (DT) scenario 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). ~~A deep~~ decarbonization of the European electricity and heating sector ~~is achieved~~ in 2040.

do

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to achieve the ambitious 1.5°C target

the

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results in a deep

in this work

"The fact that in the DT scenario the ...

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 ~~participation~~ 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~~

do

to foster its accelerated roll-out.

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

are

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supported

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clean

to reflect the strong policy-driven character of implementing an alternative sustainable heating system.

Thus the SC scenario assumes deep....

zation of the without to

decarboni~~zed~~ energy system ~~since~~ no fundamental breakthroughs of new ~~clean-~~ , novel technologies ~~are in sight~~. Therefore, the multi-apartment building implements an air-source heat pump as sustainable heating system alternative. ~~The~~ A 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.~~ in the SC scenario by 2040.

increase from

achieves deep

The *Gradual Development* (GD) scenario ~~reaches~~ aims at achieving a global temperature increase of 2.0 °C ~~and the corresponding climate target.~~ In general, ~~it is a very~~ this describes a more 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~~ the GD 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.

reduced

limited

less promising

in this work.

In addition to the three openENTRANCE scenarios, the so-called "Low CO_2 price development" (LD) 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 CO_2 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. Table 1 summarizes the scenario~~s~~ settings and the corresponding heating system alternative ~~implemented~~.

Stimmt das? macht ihr die beiden Analysen für GD oder meinst du, dass GD bei Analysen vom „Narrativ" zulassen würde?

transition for

of the ingredients of the remaining openENTRANCE scenarios:

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 (LD)	none	✓	✓

Table 1: Four different scenarios 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.

in this work and corresponding

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. Note that the landlord's interest rate i_l implicitly considers change of tenants and the associated temporary empty dwelling state. Further empirical settings can be found in Appendix A.

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)

3.4. Validation of the model

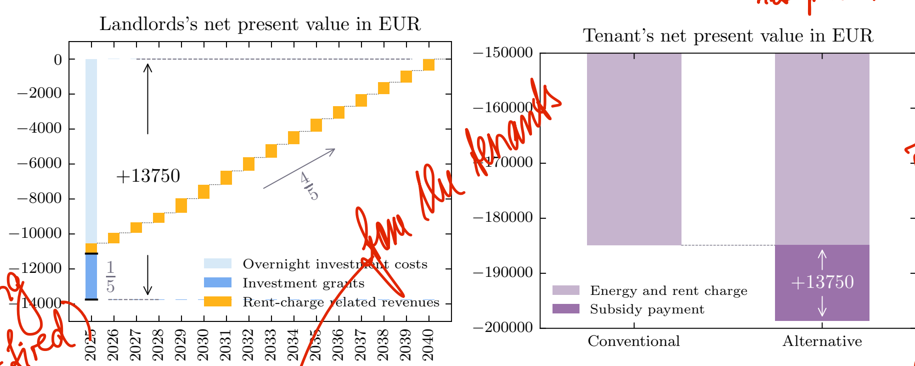
This section aims to test the presented model and its functionalities. However, a model validation using existing empirical data can not be applied in this case.

Switching to — *as an alternative heating system* — *a* — *world examples.* — *n*

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 house ~~when 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 C. Figure 2 shows the landlord~~'s~~ (a) and tenant~~'s~~ (b) ~~net present value~~.

In this simple verification example it ....

net present value of the financial support for both



(a) Development of landlord's net present value

(b) Comparison of tenant's net present value

existing (e.g. gas-fired) — *from the tenants* — *due to* — *directly from governance* — *adjusted*

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.

Until 2040,

Both agents receive equal financial support with a total of 13 750 EUR. One fifth 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).

Thus the total

Hier 1 Satz was es dem Steuerzahler in Summe mehr kostet (d.h. governance schüttet ja Steuergeld aus): 13750€ oder mehr

3.5. Open-source programming environment and data format

The developed optimization model is implemented in Python 3.8.12 using the modeling framework Pyomo version 5.7.3 [58]. It is solved with the solver Gurobi

of cash flows — *the* — *energy and rent charges*

for exchanging the heating system — *(e.g. gas-fired)*

Ändern:
4.2 → 4.1
4.3 → 4.2
4.1 → 4.3
4.4 → 4.4

quantified in this work is conducted in Section 4.3.

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 [59]. 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.

A comparison of

elaborates

quantitative

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 ~~and thus on the heat alternatives in the ambitious scenarios. Especially, the 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.

focuses

where the model indicates feasible solutions for a retrofitted building with lower heat demand only.

varying

governance's total subsidies

(compared to the default settings)

~~4.1. Objective value and results comparison~~ 3

~~Table 3 shows~~ a comparison of the ~~obtained objective values~~ for district heating (DH) ~~and~~ heat pump implementation in the different scenarios.

is conducted

~~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 ~~(presented in detail and discussed in~~ Section 4.3). Only the low CO_2 price development provides a solution for the heat pump but with a significantly

see discussion already in ...

scenario

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

Governance's total subsidies in the different scenarios

or total subsidies

In this section

for the different settings of the building quality.

Table 3 and Figure 3 present the quantitative results of this comparison. In summary, the following interesting observations are made:

hier dann 3 Bullet points

Bullet point 1
— " — 2
— " — 3

governance's total subsidies

Governance's total subsidies

~~Objective value~~	District heating (DH)			Heat pump (HP)		
	DT	GD	LD	SC	GD	LD
	(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 3: Comparison of ~~objective value results~~ for the different heating system alternatives and scenarios (explanations of shortcuts in Table 1)

total governance's subsidies

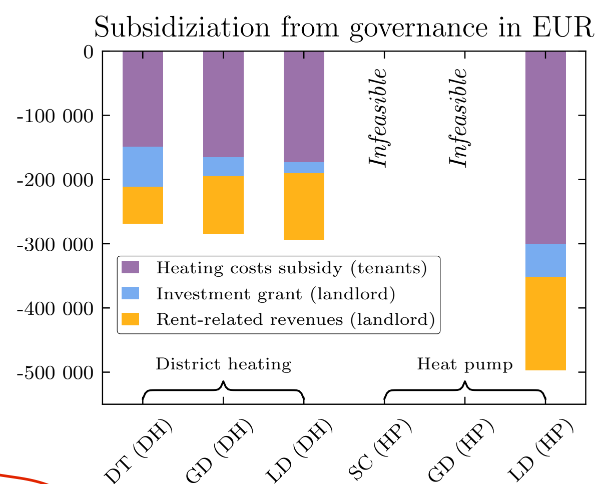
lowest subsidy

subsidy (+82.6%)

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).

When comparing Table 3 and Figure 3 it is important to note

hier neuer Absatz



governance's

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

following up Table 1 in Section 3.3.2,

4.1. *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

of cash flows in general, and revenues in particular,

weiß nicht, ob das alles ganz richtige Ausdrücke ist pays off for the landlord by 2040.

due to

Figure 4 (...

presents the different items

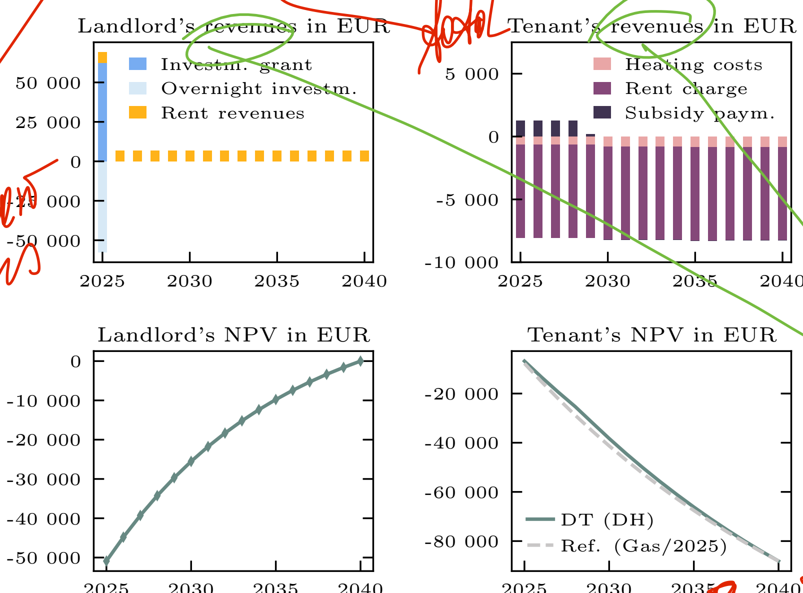
2040. ~~The subfigure at the~~ top left ~~shows the revenues~~ of the landlord consisting of the overnight investment costs (light blue), investment grant (blue), and rent-related revenues (yellow). Note that latter represent the additional rent-related revenues ~~based on the modernization of the building 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 corresponding tenant's ~~revenues~~ (top) and total net present value (bottom) until 2040.

Figure 4(...

of its cost flows over time.

Figures 4 (top right, bottom right)

cash flow items



find also revenues over "cash flows"?

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 receives 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

related

prices

of

matches with the

in 2040

gas-based heat system parameters,

open ENTRANCE

aspect

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Figure 4(...

also

Figure 4(....

which requires an explanation.

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.

price

used in this work

Es fehlt hier noch 1 Satz, daß alles halb so schlimm...

4.~~3~~2. *Heat pump and building ~~heat~~ quality in the Societal Commitment scenario*

~~The following results base on the findings of the results comparison between scenarios in Section 4.1. In particular~~, the focus is put on the impact of different building renovation levels, ~~and~~ the ~~corresponding~~ impact on the feasibility of the model. ~~The results are explicitly not presented in the same way as in the previous Section 4.2 for the *Directed Transition* scenario. On the one hand, such a presentation could not provide any further significant findings, and on the other hand, the scenarios have already been compared in detail in the first section. Instead, this section goes into more detail and shows reasons for the infeasibility of the heat pump option. As no solution for the *Societal Commitment* scenario can be yield due to the high demand, assumptions on building renovation which lower the heat demand level are introduced and tested for different degrees.~~ Figure 5 shows the results of the heat pump ~~option~~ in the *Societal Commitment* scenario for four different heat demand levels in detail. 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~~

Interestingly, the model indicates for the heat pump implementation in the Societal Commitment scenario an infeasible solution. The reason for that is, among others, the high heating demand used in the default input settings. Therefore, in the following ...

wenn es auch andere Gründe gibt bzw. geben könnte, hier aufzählen. Sonst den Teil des Satzes einfach weglassen.

associated heating demand decrease, and finally the....

implementation

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the following

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building quality (and thus...

default

In Figure 5 (top left) the corresponding settings of the specific heat load (describing building quality) are indicated.

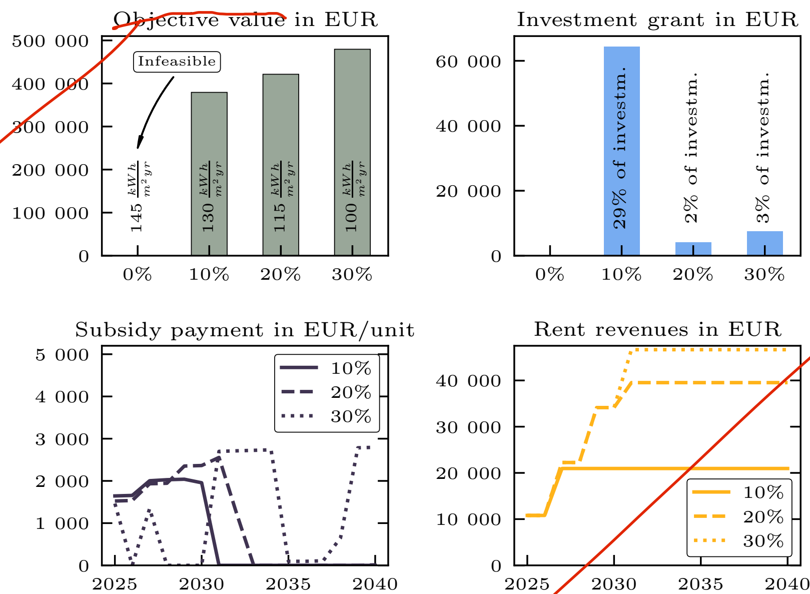


Figure 5: Comparison of the heat pump option in the *Societal Commitment* scenario for different renovation levels. Top left: governance's ~~objective value~~, top right: landlord's investment grant, bottom left: tenant's subsidy payment per unit, bottom right: landlord's rent-related revenues in total

associated

hier wieder Absatz

~~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

building of the retrofitting measures

Bei Tausenderstelle entweder Beistrich oder Abstand 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~~. sufficient.

1 Satz dazu, warum 2026, 28-30, 36-37 nix, sonst schon....

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.~~

This section examines the costs of inaction by sticking to the initial gas-based heating system. In detail, this means that (i.e., opportunity costs) CO_2 prices, due to increasing CO_2 prices to be expected, have to be allocated to the different parties/agents (or a single one): governance, landlord, and tenant.

Table 4 provides an overview of the different cases ~~that cover different allocation assumptions~~. CO_2 costs

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 D.

on the allocation of the opportunity cost (i.e. CO_2 costs of inaction) compared to the alternative on district heating implementation in the Gradual Development scenario.

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

Table 4: 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. The metric used is the relative change of the objective value (i.e. governance's total subsidies)

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

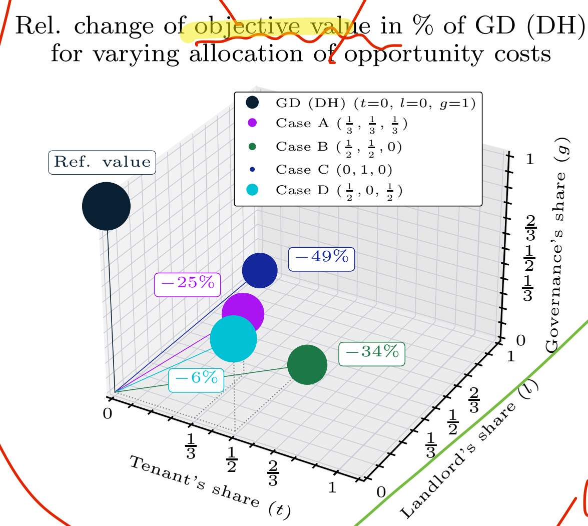
gleich direkt anknüpfen, Satz anschließen

setups

CO_2-related

presents the results of the modifications here in this section evtl. so belassen oder auch governance's total subs. dies schreiben, überlass' ich dir ....

CO2-related



An dieser Stelle musst du 2 Sätze noch schreiben, was das Vorzeichen jetzt bedeutet, d.h.: "bedeutet, dass CO2 vermeiden des Problems und Zahlen der opportunity cost um x% weniger total subsidies bedeutet als das Problem zu lösen und zu CO2 ... oder umgekehrt?

Figure 6: Comparison of the objective value for varying allocation of CO2-related 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).

unklar

in Figure 6. — neuer Absatz

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.

hardly / does / is the financial / of / which / cannot / necessarily has / total subsidy / necessary to create an investment incentive, and the fact that the financial...

Figure 7 shows the objective value for 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. 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

Eventually, / in Figure 7. / (black; Fig. 6) / (dark blue, Fig. 6) / ve

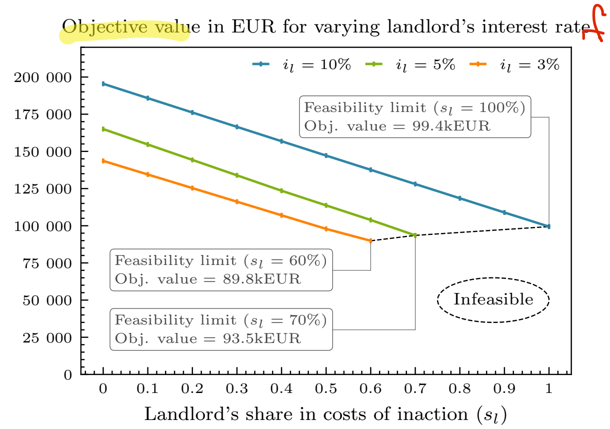


Figure 7: Comparison of the objective value for varying landlord's interest rate and share in costs of inaction

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, 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~~ e.g. 10% for $i_l = 10\%$, ~~feasibility limit is~~ 70 % for $i_l = 5$ %, and 60 % for $i_l = 3$ %) ~~respectively~~.

5. Conclusions and ~~recommendations~~ outlook

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 the application of the developed modeling framework to 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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6 APEN
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Appendix A. Data

Table A.1 shows specific emissions, energy prices, and further technical assumptions. The values correspond to the initial input parameters in 2025 in our analysis. Furthermore, it is assumed that the specific emissions of electricity and district heating decrease linearly between 2025 and the corresponding decarbonization target year of the scenario (2040 in the *Directed Transition* and *Societal Commitment* scenario as well as 2050 in the *Gradual Development scenario*). The energy price development of electricity, natural gas, and district heating is in line with the assumptions in [5]. According to this, the (retail) electricity price increases by 2.37 % and the district heating price by 5 % per year. Additionally, the CO_2 price increases the energy price according to the specific emissions per year. Table A.2 shows the CO_2 price development in the different scenarios.

Variable	Unit	Value	Ref.
Specific emissions|Electricity	kgCO_2/kWh	0.130	[60]
Specific emissions|District heating	kgCO_2/kWh	0.132	[61]
Specific emissions|Natural gas	kgCO_2/kWh	0.220	[60]
Price|District heating	EUR/kWh	0.047	[62]
Price|Natural gas	EUR/kWh	0.050	[63]
Price|Electricity	EUR/kWh	0.200	[64]
Coefficient of performance (average)	1	2.35	[65]

Table A.1: Relevant economic parameters and further empirical settings for Austria in 2020

Scenario	2020	2025 – 30	2030 – 35	2035 – 40
Directed Transition	30	196	357	510
Societal Commitment	30	62	137	273
Gradual Development	30	83	128	183
Low Development	30	60	70	80

Table A.2: CO_2 price development

(EUR/tCO_2)

Appendix B. Passive building retrofitting measures

We consider passive retrofitting measures in a very simplified way in this study and focus here only on the insulation of ~~outer wall~~ and wall to neighboring buildings. The economic and technical assumptions are oriented to the study from Fina et al. in [52]. Moreover, we assume the following relationships between the specific heat demand and the heat pump's (average) coefficient of performance (COP): 130 kWh/m^2 (COP= 2.5), 115 kWh/m^2 (3.0), 100 kWh/m^2 (3.5).

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Appendix C. Empirical settings of the ~~small~~ case example

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 C.3: ~~Small~~ case example's parameters and assumptions

Appendix D. Mathematical formulation for varying allocation of the costs of inaction

This work considers the CO_2 price related costs as the costs of inaction and opportunity costs (OC) respectively. Hence, Equation D.1 describes the costs of inaction per year y and month m

$$OC_{y,m} = \gamma_{init} \cdot p_y^{CO_2} \cdot d_{y,m} \tag{D.1}$$

where γ_{init} is the specific emissions of the initial heating system (i.e., natural gas) and $p_y^{CO_2}$ the CO_2 price in year y and month m. Exemplarily, Equation D.3 shows the landlord's net present value in total when a part of the total OC is allocated to the landlord's net present value

$$OC_l = \sum_y \sum_m s_l \cdot \frac{OC_{y,m}}{(1+i_l)^y} \tag{D.2}$$

where s_l is the share in the costs of inaction borne by the landlord. Consequently, Equation 7 is modified as follows by considering the landlord's costs of inaction.

$$-OC_l = -\zeta + \sum_y \sum_m \frac{1}{(1+i_l)^y} \cdot \lambda_{y,m} \tag{D.3}$$

A similar logic is developed in the modification of the tenant's net present value. Therfore, the tenant's share of the costs of inaction (OC_t) are considered in Equation 11. Most importantly, the tenant's OCs influence the initial spendings that are assumed to be the limit in the sustainable heating system alternative (see Equation D.4).

$$K_{alt} = K_{init} - OC_t \tag{D.4}$$

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