

Equitable decarbonization of heat supply in rented residential multi-apartment buildings: Optimal subsidy allocation between landlord and tenants

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Abstract

The core objective of this work is demonstrate an equitable decarbonization of heat supply in rented residential multi-apartment buildings. We develop a modeling framework determining a socially balanced financial governance's support strategy between the building owner (landlord) and the tenants. We analyze results of a partly renovated old building switching either to the district heating network or implementing a heat pump system under several decarbonization storylines. We find that an equitable switch to a sustainable heat system is possible but with massive public subsidy payments. Particularly, the landlord's investment grant and additional rent-related revenues based on the building renovation are crucial to trigger the profitability of investments. Simultaneously, subsidy payments to the tenants are required at the beginning of the investment period to limit the energy and rent-related spending. Results show that the heat pump alternative is not competitive in supplying heat demand. Allocating the costs of inaction (sticking to the existing gas-based heating system and paying increasing CO₂ costs) between the governance, landlord, and tenants turns out as an important lever as required subsidy payments can be reduced significantly.

Keywords: Equitability, decarbonization, residential, heat supply, subsidization, heat system change, *landlord, tenants*

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Nomenclature

Type	Description	Unit
Set and index		
$y \in \mathcal{Y} = \{1, \dots, Y\}$	Years, index by y	
$m \in \mathcal{M} = \{1, \dots, M\}$	Months, index by m	
Decision variables		
Ψ	Investment grant to the landlord	EUR
$\Omega_{y,m}$	Subsidy payment 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 new heating system alternative in y and m	kWh
π	Capacity of the new heating system alternative	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 (for adaption of one dwelling/unit) 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

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 [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 (and increasingly cold services as well), (ii) inefficient ways of delivering the heat demand caused by low standards of both building stock and heating devices, (iii) complex building ownership structures and the landlord/tenants nexus in rented apartments or dwellings.

In fact, buildings are responsible for 40 % of EU energy consumption and 36 % of the greenhouse gas emissions in 2021. Moreover, the European Commission states that 75 % of EU's buildings are energy inefficient. 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, retrofitting alone will not be sufficient for a deep decarbonization of the European building stock. Instead, it is necessary to increase the current renovation rate of 1%/year [4]. Thus, the share of passive (e.g., building insulation) 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 % per year 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 already led to massive market penetration of renewable energy technologies. For example, in recent years 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 achieved due to efficiency improvements and economies of scale [9]. In principle, there are good reasons to think that we can learn from the diffusion pathway of solar PV and related experiences. Nevertheless, two aspects are crucial in this context that have 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 and thus energy savings. Recently, Poponi et al. [10] conducted a subsidization cost analysis of solar PV in Italy where they concluded that public monetary support strategies are cost-ineffective policy instruments if energy efficiency investments are ignored. And secondly, that the support must be socially balanced in a society with and without private ownership. In the energy transition process, this is essential for both renewable generation and demand sector.

The scope of this paper aims at exploring how to deal with one of the "hot potatos" on the road to a sustainable society: namely, to trigger investments for deep decarbonization of the rented residential building sector in terms of heating system change and passive retrofitting. The focus is put 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. Typically, a building's landlord is the investment decision-maker in terms of potential (active and passive) ~~energy efficiency~~ measures but is not affected its decision process by an increasing CO₂ price as the most significant determining parameter.

deep decarbonization. On the contrary, the tenants are at the mercy of the future CO₂ development and have no decision-making power to counteract it, e.g., by changing the heating system.

Against this background, the core objective of this work is to set up a cost-optimal and socially balanced subsidization strategy for a multi-apartment building to trigger investments in a sustainable heat supply. A public authority (governance) incentivizes the replacement of the initial natural gas-based heating system toward a sustainable alternative along with building renovation measures (accompanied by reduced heat demand) by monetary support to the landlord and the tenants. Monetary support can be direct payments in the form of an investment grant for the landlord or a subsidy payment for the tenant. Besides, the owner (i.e., landlord) can also be indirectly financially supported by allowing a rent adjustment as the building is ~~unfinished~~. Social balance is defined at the building level from a monetary perspective using the net present value of the governance's total payments for the building's owner and the tenants.

retrofitted

The method applied is the development of a linear optimization model. Thereby, the objective function is to minimize the governance's net present value of financial support over time. The landlord's and tenants' strategy to minimize the individual total costs is considered by tailor-made 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 efficiency, initial rent price, etc.). This can be helpful to analyse different building stocks.

The numerical example examined is an old multi-apartment building with a single owner (landlord) and 30 units (tenants). The partially renovated building is located in an urban area (Vienna, Austria) 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 investment options, namely, a connection to

the district heating network or an implementation of an air-sourced heat pump system on building level.

The paper is organized as follows. Section 2 summarizes the current state-of-the-art in literature and outlines the own contribution of this work beyond existing research. Section 3 presents the materials and methods developed in this work including the mathematical formulation of the model, scenarios, description of numerical example ~~and validation~~ 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. The focus here lies on three different dimensions. The first dimension covers the decarbonization of heating and cooling systems from a system analysis perspective (see Section 2.1). The second dimension deals with the increasingly importance of justice in the energy system transition (see Section 2.2). The third dimension is dedicated to the trade-off analysis of investment decisions into renewable energy technologies including contracting business cases (see Section 2.3). The choice of these focal points are deliberately chosen in order to reflect the DNA of the analysis. Intentionally not part of the literature review (out of scope of this paper's analysis) is the already widely discussed topic of sharing renewable energy generation and related peer-to-peer innovations in the light of energy communities¹.

¹A 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 respect 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. The recently published review papers Cabeza et al. [15] and Zhang et al. [16] collect a variety of contributions focusing on similar topics acknowledged above.

2.1. Decarbonizing heating and cooling service needs

The insights obtained from various scientific studies discloses the big picture of a decarbonized heating and cooling sector which requires a fundamental change of the energy carrier mix, alongside a significant energy efficiency increase. For example, Connolly et al. [17] present a corresponding decarbonization roadmap for the European heating sector. Their sustainable heat strategy proposes changes on both demand-side and supply-side. In addition to significant heat savings, the utilization of renewable energy sources in centralized heat (or district heating) networks and the electrification of heat supply (e.g., heat pump) are proposed to achieve a low-carbon heat sector. Seyboth et al. [18] focus in their study on supportive energy policy recommendations to enhance the deployment of renewable energy heating and cooling technologies. In particular, this means integrating of renewable sources such as solar, geothermal, and biomass heating and cooling systems.

In general, the sustainable heat source or heat technology that is ultimately 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.) play a crucial role. In this context, Su et al. [19] focus on local geographical features of the application site. They conclude that there might not be a one-fits-all solution when decarbonizing local heating systems. However, certain trends are very much emerging in their findings, which can also be confirmed by further studies, e.g., that renewable-fed district heating networks have significant potential to supply heat demand in urban areas. Exemplarily this is shown by Popovski et al. [20]. Lake et al. [21] present a comprehensive review of district heating and cooling systems with special consideration of the economic feasibility based on primary energy sources. Rama et al. [22] study the optimal combination of different sustainable heating alternatives. In particular, they show how heat pumps and solarthermal can assist district heating networks. Sopha et al. [23] focus in their study on the potential of wood-pellet

and

in Norway ~~country with high shares of district heating-based heat supply.~~

The authors conclude that a stable financial support (i.e., stable wood-pellet price) has the highest impact on the transition of wood-pellet. A ~~continuation of the discussion on financial incentives for renewable energy technologies in the heating sector is conducted in Section 2.3.~~

follow-up

In any case, there are local circumstances where district heating does not fit. Sustainable alternatives must be sought, either to complement existing district heating networks in a high-efficient way (e.g., [22] and [23]) and/or to compensate non-existing networks. Popovski et al. [20] 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. [24] also show end-use electrification as an optimal strategy for the decarbonization of the heating sector. However, the authors state that the electrification of the heat sector is only meaningful in combination with ~~building thermal efficiency improve-~~ *ment*. Particularly, Kamel et al. review solar systems and their integration with heat pumps [25].

Overall retrofitting

In order to emphasize the importance of building renovation in combination with heating system exchange, this paragraph is dedicated to the corresponding literature. In general, we do not differentiate ~~here in detail~~ between different types of retrofitting measures (e.g., purely passive, passive, active) and refer in this context to the comprehensive literature review of Fina et al. in [5]. Ma et al. [26] provide an extensive literature and state-of-the-art analysis of retrofitting focusing on existing buildings. Vieites et al. [27] elaborate in this context ~~of~~ European initiatives improving the energy efficiency in existing and old (historic) buildings. Recently, Weinberger et al. [28] investigate the impact of retrofitting on district heating network design. 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 sustain-

able heating systems. Their results show how (passive) retrofitting measures result in a reduction of both optimal installed heating system and solar PV capacity. However, the energy cost reduction achieved from higher building standards are not sufficient to compensate the initial passive renovation investment costs. They conclude that economic viability significantly depends on the development of the CO₂ price and end-user investment grants for building renovation.

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

The aspect 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 distributional, recognition, and procedural². Recently, they are comprehensively discussed and reviewed by Pellegrini et al. [30]. 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 [29].

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 areas 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 [31]. Besides that, Lacey-Barnacle et al. [32] elaborate on energy justice in developing countries. Coming back to this paper's content and spatial scope, Mundaca et al. [33] present two local European case studies in Germany and Denmark assessing local energy transition from an energy justice perspective. Their findings are in line with those from Jenkins et al. [34] showing that energy justice and transition frameworks can be combined and achieved simultaneously. However, Hiteva and Soacool [35] conclude from a business model perspective that energy justice may be

²In some works, restorative and cosmopolitan justice are also mentioned in this context, see, exemplarily in [29].

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.

Motoring?

Recently, Hanke et al. [36] have investigated 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 [37] propose on the basis of their 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 less energy efficient appliances. Sovacool et al. [38] point in the same direction and discuss the difficulties for households who lack the capital for sustainable energy investments and predominantly tenants and not owners of their homes. Moreover, renters also often have higher residential heating energy consumption, an energy efficiency ~~lack~~ [39]. In this context, Greene [40] discussed the so-called “efficiency gap” or “energy paradox”, ~~showing~~ that consumers have a bias ~~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 abovementioned 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.

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2.3. Energy policy instruments

In particular, the following section is about different renewable energy policy instruments supporting ~~all~~ 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 similarities and differences between the two sectors. Connor et al. [41] provide a fundamental review paper investigating a

(public)

wide range of policy options that can support the deployment of renewable heat technologies. Masini and Menichetti [42] 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 seen as the most appropriate measures to fill this gap.~~ Reuter et al. [43] compare different policy instruments, ranging from feed-in tariffs, ~~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 investments³. Similar results also can be found in the study from Couture and Gagnon [45]. Nevertheless, the two latter studies only investigate the deployment of renewable energy technologies in the electricity sector and not in the heating sector.

Building on these literature findings, however, it is of particular importance to differentiate between renewable energy technology investments from companies and private households. In contrast to companies, private households are incentivized more effectively by investment grants to invest in renewable energy technologies [46]. This distinction and targeted adjustment of public financial incentives is important since private investments are key drivers of the diffusion of renewable energy technologies [47]. Østergaard et al. [48] conclude that the investment costs of households to ~~adapt~~ existing buildings for high-efficient and sustainable heating systems to be designated economically⁴. In this context,

³Zhou et al. [44] 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. However, ~~especially~~ in the electricity sector.

⁴In particular, Østergaard et al. [48] 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.

the role of an increasing CO₂ 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. [49] 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, obvious that Hecher et al. [50] focus in their work on the decision-making processes ~~regarding~~ sustainable heating system investments of homeowners. The ownership structure is often neglected in the literature and insufficiently considered.

Eventually, energy and heat contracting business models tangent this work's scope. However, we explicitly aim to give only a small overview, as contracting business models themselves do not constitute the core of the analysis in this paper. A comparative review of municipal energy business models in different countries is given by Brinker and Satchwell [51]. Kindström and Ottosson [52] as well as Fine et al. [53] conclude little optimistic that the contracting framework itself decreases the economic viability since the contractor business companies (third party) aim to gain profit. Suhonen and Okkonen [54] conduct an analysis of energy service companies in the residential heating sector and show a wide-ranging set of barriers ~~of such business models~~ responsible for non-profitability of contracting business models. Brown [55] investigates business models for residential retrofit in the United Kingdom and the European Union.

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 change ~~of~~ towards a currently gas-based towards a sustainable alternative heating system ~~in~~ a rented multi-apartment old building is modeled considering the complex ownership structure and relations between landlord and tenant to "take action".

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Exchange in the multi-apartment
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- First and foremost, the governance's claim is that the ~~heat system transformation~~ takes place. ~~Particularly~~ the governance incentivizes the sustainable investment through monetary and regulative support for both the landlord and tenants, while ~~considering their~~ individual financial interests. The governance's optimal financial support strategy plays a crucial role where optimality is defined with respect to the high-efficient provision of the residential heat service needs, heat demand reduction, and building efficiency improvements.

- economically*
- 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 ~~the~~ low-carbon residential buildings 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 ~~investment~~ investment and social balance with an eye on the costs of inaction (opportunity costs) and increasing carbon prices.

House

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critically
- Different sensitivity analyses play a key role in this paper. ~~Understanding~~ allocation of the costs of inaction among the governance, the landlord, and the tenants can be seen as one of the main novelties of this work. Moreover, the importance of building stock renovation in the context of public subsidy payments is comprehensively discussed. In this context, ~~what~~ ~~insights~~ ~~can~~ help build a more reliable understanding of a sustainable future urban society that ~~does~~ not live in ownership but in highly efficient ~~stock~~ rented apartments.

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3. Materials and methods

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

3.1. Introduction into the model

In general, three agents are considered in the model with the following characteristics:

Governance. The governance's main objective is to decarbonizing the residential heating sector. Therefore, the policy 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 for the landlord can be realized by an investment grant (paid directly from the governance) and/or adjusted rent-charge-related revenues (paid from the tenants). The tenants, for their part, can be financially supported directly by the governance through heating costs subsidy payments.

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).

An

Tenant. The tenant rents a dwelling/unit within the multi-apartment building from the landlord and has rent-related and energy-related spendings. The tenant cannot change the heating system on its authority but depends on the landlord's willingness to ~~have~~ a sustainable alternative. In connection with the existing heating system, the tenant's costs are ~~already subject to a higher pricing due to the consideration of CO₂ 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 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.

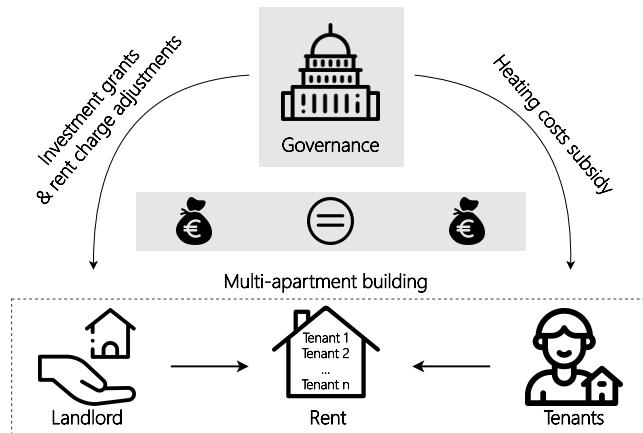


Figure 1: Sketch of the model illustrating the interrelations between the governance, landlord, and tenants. Financial support from the governance is socially balanced at the multi-apartment building.

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 payments⁵. Therefore, the objective function can be written as follows:

$$\min_x \left(\Psi + \sum_y \sum_m \frac{n}{(1+i_g)^y} \cdot \Omega_{y,m} \right) \quad (1)$$

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 tenants⁶ 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)

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

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

⁵This corresponds to the maximization of the governance's net present value.

⁶It is assumed that the multi-apartment building consists of n equal tenants/units.

heating system alternative

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

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)

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

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

$$\Psi \leq \hat{d} \cdot c_{alt} + n \cdot c_{con} \quad (5)$$

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

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

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

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

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

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

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})

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

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}) in case of implementing the sustainable heating system alternative.

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

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

$$K_{alt} = K_{init} \quad (11)$$

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

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

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

Equation 14 allows rent charge adjustments by the landlord only every two years

and Equation 15 and 16 set an upper bound to the rent charge adjustment

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

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

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

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

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

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

3.3.1. Multi-apartment building

The model proposed in this work is applied to a typical multi-apartment building in an urban area. In particular, a partially renovated and natural gas-fired heating system in an old building in Vienna, Austria, is investigated. In 2020, more than 440 000 natural gas-based heated dwellings existed in Vienna, Austria (48.5 % of the total building stock) [56]. 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 well⁷.

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 individual natural gas-based heating system. The decarbonization of the

⁷For example, there are more than 600 000 natural gas-based systems covering residential heat demand in dwellings in Berlin, Germany, in 2020 [57].

existing heating systems can be realized by two different options, namely, a connection to the district heating network or the installation of a air-sourced heat pump⁸. It is assumed, that only one of the two 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.

3.3.2. Scenarios

Four different quantitative scenarios are studied with the tailor-made model presented above. Input ~~parameters~~ settings of three of them have been developed in the Horizon 2020 research project openENTRANCE (<https://openentrance.eu/>) and describe a future European energy system development assuming to achieve the 1.5 °C or 2.0 °C climate target. These three scenarios are called *Directed Transition*, *Societal Commitment*, and *Gradual Development* scenario⁹. The first two scenarios consider the remaining CO₂ budget of the 1.5 °C climate target. Below, we briefly summarize the three openENTRANCE scenarios used in this work and refer for a detailed description to the studies in [58] and [59]. For the reader with a particular interest in the openENTRANCE scenarios, we refer to the work in [60], in which the underlying storylines outlining the narrative frames of the quantitative scenarios can be found.

The *Directed Transition* (DT) scenario leads to limiting the global temperature increase to 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 sufficiently and deliver weak financial impulses for the clean energy transition only. Besides, society is also too passive in supporting to achieve the ambitious 1.5 °C target. Thus, in this work it is assumed that the multi-apartment building is connected to the district heating network ~~and~~ to

⁸In 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 work and is not further examined.

⁹The openENTRANCE scenario *Techno-Friendly* is not part of this work.

reflect the strong policy driven character of implementing an alternative sustainable heating system. The fact that in the DT scenario the CO₂ price raises from 196 EUR/tCO₂ (in 2025) to 680 EUR/tCO₂ (in 2040) results in a 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 to 1.5 °C. In contrast to the previous scenario, decentralization of the energy system and active participation as well as societal acceptance of energy transition pushes the sustainable development. In addition, currently existing clean technologies are significantly supported by policy incentives to foster its accelerated roll-out. Thus, the SC scenario assumes deep decarbonization of the energy system without fundamental breakthroughs of new novel technologies. Therefore, the multi-apartment building implements an air-sourced heat pump as sustainable heating system alternative. A CO₂ price increase from 62 EUR/tCO₂ (in 2025) to 497 EUR/tCO₂ (in 2040) achieves deep decarbonization of the European electricity and heating sector in the SC scenario by 2040.

The *Gradual Development* (GD) scenario aims at achieving a global temperature increase of 2.0 °C. In general, this describes a more conservative expression of an European energy system transition. This scenario includes a little of each of the ingredients of the remaining openENTRANCE scenarios: reduced policy incentives, limited social acceptance, and less promising technological advances. Both heating system alternatives (district heating connection and air-sourced heat pump installation) are examined in this work. The CO₂ price in the GD scenario is between 83 EUR/tCO₂ (in 2025) and 261 EUR/tCO₂ (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 CO₂

price development” (LD) scenario is examined. This scenario neglects any remaining European CO₂ 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 CO₂ price nor the specific emissions of electricity and district heating significantly change compared to today’s values. Again, both heating system alternatives are studied. The CO₂ price in this scenario is between 60 EUR/tCO₂ (in 2025) and 90 EUR/tCO₂ (in 2040). No target year for achieving deep decarbonization of the European electricity and heating sector is set. Table 1 summarizes the scenario settings and the corresponding heating system alternatives.

Scenario	Climat target	Heat pump (HP)	District heating (DH)
<i>Directed Transition</i> (DT)	1.5 C	-	✓
<i>Societal Commitment</i> (SC)	1.5 C	✓	-
<i>Gradual Development</i> (GD)	2.0 C	✓	✓
Low CO ₂ price (LD)	none	✓	✓

Table 1: Four different scenarios studied in this work and corresponding scenario specific heating system alternative (marked by the check)

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.

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 world examples. Therefore, an illustrative case study is chosen to demonstrate the main functionalities and to verify the model. We assume a single landlord and a tenant in a representative

natural

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

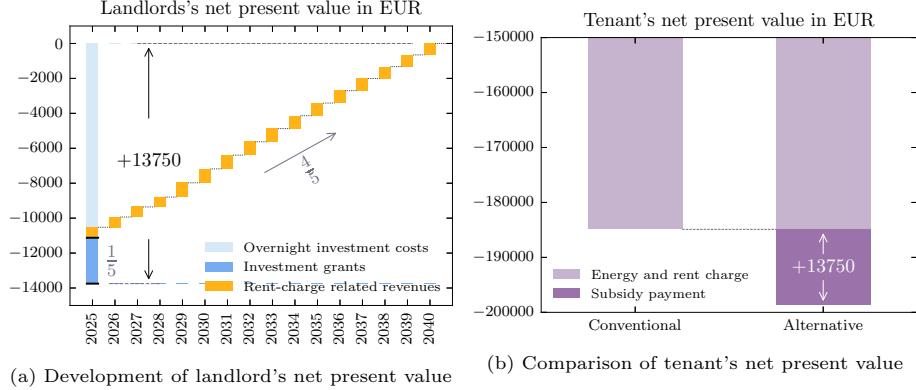
Table 2: Data assumptions of the multi-apartment building and its agents (landlord, tenants, and governance)

single-family house switching to a heat pump. In this simple verification example 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 net present value of the financial support for both landlord (a) and tenant (b).

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 directly and four-fifths as rent-charge related revenues from the tenants from governance. The tenant receives a heating costs subsidy. In sum, the governance pays 16 500 EUR. Thus the total level of financial support for exchanging the heating system results exactly in (i) a landlord's net present value of cash flows equal to zero within the time horizon of 15 years (see Figure 2a) and (ii) a constant remaining net present value of the tenant's energy and rent charges compared to the existing (e.g., gas-fired) heating system (see Figure 2b).

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 [61]. It is solved with the solver Gurobi



(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 adjusted rent-charge related revenues. The tenant's net present value remains constant compared to the existing (e.g., gas-fired) heating system due to heating costs subsidy payments.

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 [62]. Note that all materials used in this study are disclosed as part of the publication at GitHub¹⁰. We refer to the repository for the codebase, data collection, and further information.

4. Results and sensitivity analysis

This section presents the most relevant quantitative results of the proposed case study. Section 4.1 elaborates on the district heating option in the *Directed Transition* scenario. Section 4.2 focuses on the implementation of a heat pump system in the *Societal Commitment* scenario where the model indicates feasible solutions for a retrofitted building with lower heat demand only (compared to the default settings). A comparison of the results of the district heating ~~and~~ heat-pump-based heat supply in the different scenarios quantified in this work is conducted in Section 4.3. Finally, Section 4.4 presents the results in case of varying CO₂ pricing cost allocation between the landlord as the building ~~and~~

¹⁰<https://github.com/sebastianzwickl>

owner and the tenants.

4.1. District heating in the *Directed Transition* scenario

Following up Table 2 in Section 3.3.3, this section presents the results of the district heating implementation in the *Directed Transition* scenario in detail.

Figure 3 shows the net present value of cash flows in general, and revenues in particular, of the landlord and a single tenant within the time horizon 2025 to 2040. Figure 3 (top left) presents the different items 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 due to newly installed sustainable heating system. Figure 3 (bottom left) shows the development of the landlord's net present value of its cashflow over time. Thereby, it is shown that the investment pays off for the landlord by 2040. The two Figures 3 (top right, bottom right) illustrate the corresponding tenant's cash flow items (top) and total net present value (bottom) until 2040.

The tenant receives subsidy payments from the governance between 2025 and 2030. Thus, the tenant's net present value in 2040 matches with the value as in the reference case. The reference case considers constant remaining rent-related and heat-related costs for the tenant based on the initial rent, gas-based heat system parameters, and CO₂ prices as of 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 Figure 3 top left). Most importantly, the tenant's reference net present value ("Ref. (Gas/2025)"; gray dashed line in the Figure 3 bottom right) shows a crucial aspect of the results and assumptions of the analysis which requires an explanation. Since "Ref. (Gas/2025)" is used as the initial tenant's spendings, the results also take into account the total opportunity costs (i.e., those costs that would be incurred by sticking to the initial gas-based heating system for the tenant due to a rising CO₂ price). Note that the openENTRANCE decarbonization scenarios used in this work do consider both

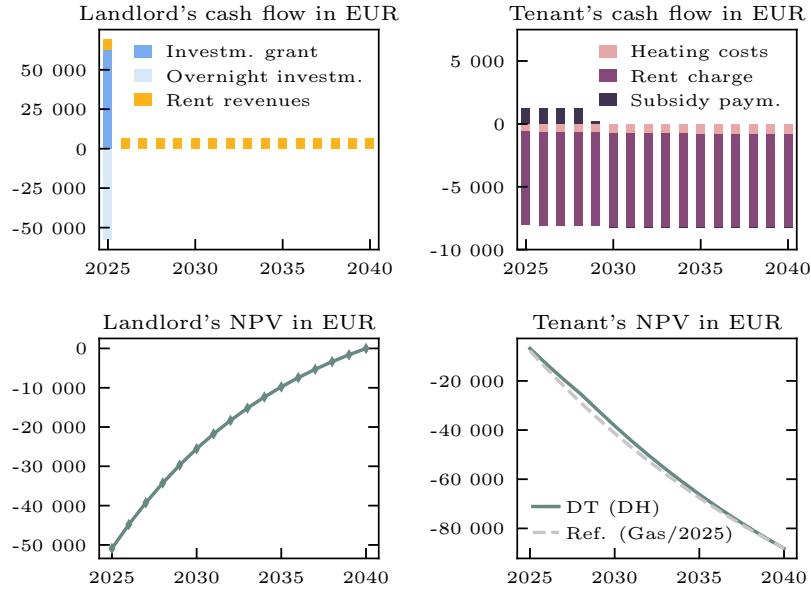


Figure 3: Development of the landlord's and tenant's economic viability of the district heating option in the *Directed Transition* scenario. Top left: landlord's cash flows, bottom left: landlord's net present value, top right: tenant's cash flows, bottom right: tenant's net present value

a significant increase of the CO₂ price and a decrease of the specific emissions of the district heating and electricity fueling mix. The quantitative results indicate that the heating system change in this scenario is achieved with manageable total governance's subsidies. However, a detailed discussion of the allocation of CO₂ price-related opportunity costs is ~~shown~~ conducted in Section 4.4.

4.2. Heat pump and building stock quality in the Societal Commitment scenario

Interestingly, the model indicates for the heat pump implementation in the *Societal Commitment* scenario an infeasible solution. The reason for that is, among others (investment costs of the air-sourced heat pump and the electricity price) the high heating demand used in the default input settings. Therefore, in the following the focus is put on the impact of different building renovation levels, the associated heating demand decrease, and finally the impact on the feasibility of the model.

Figure 4 shows the results of the heat pump implementation in the *Societal Commitment* scenario for four different building quality (and thus heat demand levels) in detail. Since the initial setting of the default building in terms of total and peak heat demand leads to the infeasibility of the model, the following three additional renovation levels are studied: 10 %, 20 %, and 30 % reduction of both the total and peak heat demand. In Figure 4 (top left) the corresponding settings of the specific heat load (describing building quality) are indicated.

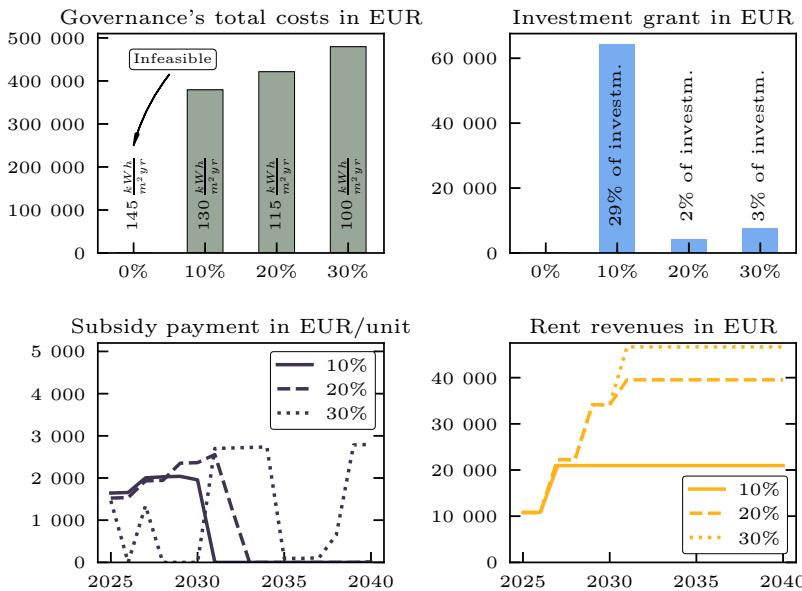


Figure 4: Comparison of the heat pump option in the *Societal Commitment* scenario for different renovation levels. Top left: governance's objective value, top right: landlord's investment grant, bottom left: tenant's subsidy payment per unit, bottom right: landlord's rent-related revenues in total

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 of the building retrofitting measures (Fig. 4 top right). The associated tenant's subsidy payment takes place between 2025 and 2030 with a maximum of 2040 EUR (Fig. 4 bottom left). The rent charge adjustment and related revenues remain almost constant during the period (Fig. 4 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 (2%). The tenant's subsidy payment takes place between 2025 and 2032 with a maximum of 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%). 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 (mainly as a result of the matching of the CO₂ price and the specific CO₂ emissions of the fueling energy mix). 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 sufficient.

4.3. Governance's total subsidies in the different scenarios

In this section, a comparison of the governance's total subsidies for district heating (DH) or heat pump (HP) implementation in the different scenarios is conducted. Table 3 and Figure 5 present the quantitative result of this comparison. In summary, the following interesting observations are made:

- The total subsidies across the three district heating cases are relatively stable and are within 11.2 %.
- The heat pump implementation in the two decarbonization scenarios *Societal Commitment* and *Gradual Development* is infeasible for the default setting of the building quality (see discussion already in Section 4.2).
- Only the low CO₂ price development scenario provides a solution for the heat pump but with a significantly higher subsidy +82.6 % compared to the lowest subsidy scenario.

When comparing Table 3 and Figure 5 it is important to note that the landlord's rent-related revenues (orange bar) are an "implicit" subsidy. Hence, the total governance's subsidies are equal to the sum of the tenants' heating costs subsidy (purple bar) and the landlord's investment grant (blue bar).

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	District heating (DH)			Heat pump (HP)		
	DT (1.5°C)	GD (2.0°C)	LD (-)	SC (1.5°C)	GD (2.0°C)	LD (-)
Governance's total subsidies						
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 governance's total subsidies for the different heating system alternatives and scenarios (explanations of shortcuts in Table 1)

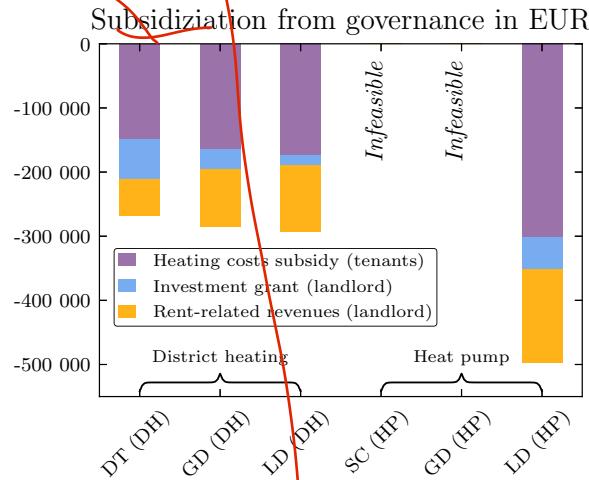


Figure 5: Comparison of governance's subsidization from the governance for the landlord and the tenants for district heating (DH) and heat pump (HP) implementation in the different scenarios

4.4. Allocation of CO₂ pricing related costs between the governance, landlord and tenant

This section examines the costs of inaction by sticking to the initial gas-based heating system. In detail, this means the CO₂ costs (i.e., opportunity costs) to be expected due to increasing CO₂ prices 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 on the allocation of the opportunity cost (i.e., CO₂ costs of inaction) compared to the alternative on district heating implementation in the *Gradual Development* scenario. Exemplarily, "Case A (equally)" takes into account that the CO₂ costs are shared equally among the

governance, landlord, and tenants. Each of them bear one third of the costs. Note that the scenario setups from Section 3.3.2 considered so far that the ~~the~~ total costs of inaction are covered by the governance (see Equation 9 and 11). The mathematical formulation of the modifications here in this section can be found in Appendix D.

Rel. allocation of opportunity costs	Governance	Landlord	Tenants
Case A (equally)	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$
Case B (landlord & tenant)	0	$\frac{1}{2}$	$\frac{1}{2}$
Case C (landlord)	0	1	0
Case D (governance & tenant)	$\frac{1}{2}$	0	$\frac{1}{2}$
Scenarios from Sec. 3.3.2 (governance)	1	0	0

Table 4: Allocation of the CO₂-related opportunity costs (costs of inaction) among the governance, the landlord, and tenants

Figure 6 presents the results of the 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 in the upper left corner in Figure 6. The negative signs indicate that the consideration of the costs associated with the ~~marginal~~ extraction of the problem (i.e., CO₂ price related opportunity costs) results in a reduction of the necessary governance's total subsidies.

Most importantly, the highest total subsidy 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 total subsidy by 25 %. It is evident that an even allocation between the governance and the tenants ("Case D") hardly leads to a reduction of the objective value. The main reason for this is the financial support of the landlord, which is necessary to create an investment incentive, and the fact that the financial support between the landlord and tenants necessarily has the same net present value.

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Rel. change of objective value in % of GD (DH)
for varying allocation of CO₂-related opportunity costs

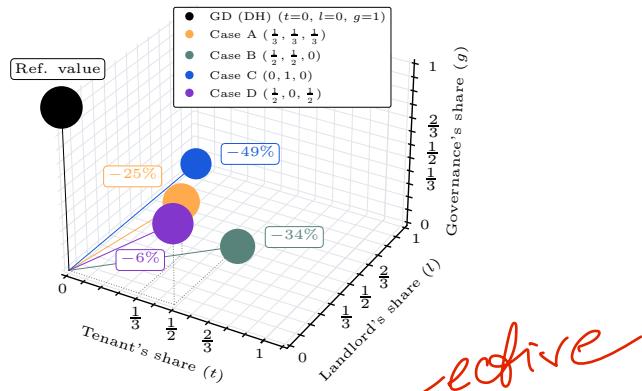


Figure 6: Comparison of the objective value for varying allocation of opportunity cost among the tenants (x-axis), the landlord (y-axis), and governance (z-axis) switching to district heating. The size of the points corresponds to the obj. function value in proportion to the *Gradual Development scenario*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

Eventually, Figure 7 shows the objective value for varying landlord's interest rates. 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" (black, Fig. 6) and "Case B" (dark blue, Fig. 6) specify the two endpoints of the blue line in Figure 7 with $i_l = 10\%$. The varying landlord's interest rates have 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, 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 (e.g., 100 % for $i_l = 10\%$, 70 % for $i_l = 5\%$ and 60 % for $i_l = 3\%$). At least two interesting energy policy implications can be derived from the results here. In case the landlord is very much profit oriented (e.g., interest rate of 10 %) and governance's total subsidy payments are to be kept as low as possible, complete allocation of the CO₂-related opportunity costs to the landlord results in a cost-optimal strategy. In contrast, in case the landlord serves rather a public-benefit purpose (e.g., interest rate of 3 %),

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the CO₂-related opportunity costs allocation among governance, landlord, and tenants is an adequate strategy.

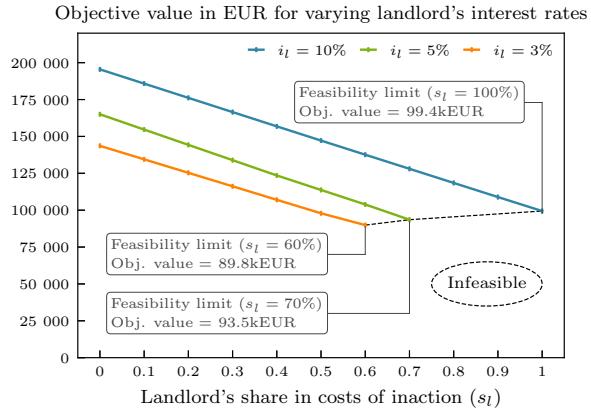


Figure 7: Comparison of the objective value for varying landlord's interest rates and share in costs of inaction

5. Conclusions and outlook

Rapid and equitable decarbonization of the ~~heat~~ 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 CO₂ price primarily impacts the tenant's energy costs. This work studies cost-optimal subsidy payment strategies incentivizing sustainable heat system ~~change~~ and retrofitting measures at the multi-apartment building level. We analyze the results of the application of the developed modeling framework to a partly renovated old building switching either to the district heating network or implementing an air-sourced heat pump system under several decarbonization storylines.

We find that a fair and equitable switch to a sustainable heat system is possible but with massive public subsidy payments. In particular, the building's owner (landlord) investment grant and additional rent-related revenues ~~from~~ in the building renovation are crucial to trigger the profitability of the investment. At

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the same time, subsidy payments to the tenants are required at the beginning of the investment period to limit the energy and rent-related spendings. Furthermore, the results impressively show that the heat pump alternative is not competitive in supplying heat service need 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. Deep building renovation and associated reduction of heat demand enable feasible solutions but with high total costs. ~~Willingness~~ passive retrofitting measures need to be incentivized, too.

Furthermore, the results demonstrate that allocating the costs of inaction (~~sticking to the existing gas-based heating system and paying the increasing CO₂ costs~~) between the governance, the building owner (landlord), and the tenants is an important lever and can reduce the required subsidy payments. First and foremost, the biggest drop of the total subsidies (to nearly half) takes place when the costs of inaction are completely borne by the building owner (landlord). 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 subsidy payments. This could bring further insights to decarbonization strategies with an eye on the heat demand and sustainable heat source alternatives in the multi-apartment residential building sector (i.e., climate neutrality in 2050). Besides, the tenant's diversification within the building could be improved (e.g., different willingness to pay to contribute to CO₂ mitigation). More generally, this study could be extended by introducing further technology options, such as solar photovoltaic, solar thermal, and heat and electricity storage systems.

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Declaration of interests

None.

Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgments

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 835896. The authors acknowledge TU Wien Bibliothek for financial support through its Open Access Funding Programme.

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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 de-carbonization 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 CO₂ price increases the energy price according to the specific emissions per year. Table A.2 shows the CO₂ price development in the different scenarios.

Variable	Unit	Value	Ref.
Specific emissions Electricity	kgCO ₂ /kWh	0.130	[63]
Specific emissions District heating	kgCO ₂ /kWh	0.132	[64]
Specific emissions Natural gas	kgCO ₂ /kWh	0.220	[63]
Price District heating	EUR/kWh	0.047	[65]
Price Natural gas	EUR/kWh	0.050	[66]
Price Electricity	EUR/kWh	0.200	[67]
Coefficient of performance (average)	1	2.35	[68]

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

Scenario (EUR/tCO ₂)	2020	2025 – 30	2030 – 35	2035 – 40
<i>Directed Transition</i>	30	196	357	510
<i>Societal Commitment</i>	30	62	137	273
<i>Gradual Development</i>	30	83	128	183
<i>Low Development</i>	30	60	70	80

Table A.2: CO₂ price development

Appendix B. Passive building retrofitting measures

We consider passive retrofitting measures in this study in a very simplified way and focus here on the insulation of the building skin and the wall to neighboring buildings only. The economic and technical assumptions are oriented to the study from Fina et al. in [53]. Moreover, we assume the following relationships between the specific heat demand and the heat pump's (average) coefficient of performance (COP): 130 kWh/m² (COP= 2.5), 115 kWh/m² (3.0), 100 kWh/m² (3.5).

Appendix C. Empirical settings of the 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
Electricity price	EUR/kWh	0.2
Specific emissions Electricity	kgCO ₂ /kWh	0.130

Table C.3: Case example's parameters and assumptions

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

This work considers the CO₂ 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

$$OC_{y,m} = \gamma_{init} \cdot p_y^{CO_2} \cdot d_{y,m} \quad (\text{D.1})$$

where γ_{init} is the specific emissions of the initial heating system (i.e., natural gas) and $p_y^{CO_2}$ the CO₂ price in year y and month m . Exemplarily, Equation D.2 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

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

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.

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

A similar logic is developed in the modification of the tenant's net present value. Therefore, 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).

$$K_{alt} = K_{init} - OC_t \quad (\text{D.4})$$