Equitable decarbonization of heat supply in residential multi-apartment rental buildings: Optimal subsidy allocation between the property owner and tenants

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Abstract

The core objective of this work is to demonstrate equitable decarbonization of heat supply in residential multi-apartment rental buildings. A modeling framework is developed determining a socially balanced financial governance support strategy between the property owner and tenants to trigger a heating system change. The results of different decarbonization scenarios of a partly renovated old building switching from gas-fired heat supply to either the district heating network or being equipped with a heat pump system show that an equitable heating system change is possible, but with massive public subsidy payments. Particularly, the investment grant to the property owner and additional rent-related revenues due to building renovation are decisive for the profitability of the investment. Simultaneously, subsidy payments to the tenants are required at the beginning of the investment period to limit their energy and rent-related spendings. Results also show that the heat pump alternative is not competitive compared with district heating, even in case of extensive retrofitting of the building. Allocating the costs of inaction (opportunity costs associated with rising CO_2 prices) between the governance, property owner, and tenants turns out as an important lever, as required subsidy payments can be reduced significantly.

Keywords: Equitability, decarbonization, residential, heat supply, subsidy payments, heat system change, property owner, 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 property owner	EUR
$\Omega_{y,m}$	Subsidy payment to a tenant in y and m	EUR
$\lambda_{y,m}$	Rent-related revenues of the property owner in y and m	EUR
$q_{y,m}$	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, property owner, 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 with that in 1990 in the European 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 heating 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, and (iii) complex building ownership structures and the property owner/tenant nexus in rented apartments or dwellings.

In fact, buildings are responsible for 40 % of the EU energy consumption and 36 % of the greenhouse gas emissions in 2021. Moreover, the European Commission states that 75 % of the 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 the EU's buildings are older than 50 years. However, the current renovation rate of 1 %/year alone will not be sufficient for a deep decarbonization of the European building stock [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 of 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]).

In the last decades, federal financial incentives have already led to the massive market penetration of renewable energy technologies. For example, in recent years, solar photovoltaic (PV) has flooded the electricity markets driven by 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 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 is that the public monetary diffusion of renewable energy must be accompanied by measures ensuring demand-side 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. Second is that the support in energy transition must be socially balanced in a society with and without private ownership.

The scope of this paper aims at exploring how to deal with one of the "hot potatoes" on the road to a sustainable society: 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 property owner (building or at least apartment owner) and numerous tenants plays a key role in the analysis as this is a generally crucial relationship. Typically, a property owner is the investment decision-maker in terms of potential (active and passive) renovation measures but is not affected in its decision process by an increasing CO_2 price as the most significant parameter determining deep decarbonization. On the contrary, the tenants are at the mercy of the future CO_2 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 property owner and the tenants. Monetary support can be direct payments in the form of an investment grant for the property owner or a subsidy payment for the tenant. Besides, the property owner can also be indirectly financially supported by allowing a rent adjustment as the building is retrofitted. 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 (or apartment's owner) and the tenants.

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 monetary support over time. The property owner's and tenants' strategy to minimize 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 categorization (size and number of tenants, building efficiency, initial rent price, etc.). This can be helpful to analyze different building stocks.

The numerical example examined is an old multi-apartment building with a single property owner 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 the 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, input data, and scenarios. 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 increasing importance of justice in the energy system transition (see Section 2.2). The third dimension is dedicated to the trade-off analyses of investment decisions into renewable energy technologies including contracting business cases (see Section 2.3). The choice of these focal points is deliberately chosen in order to reflect the DNA of the analysis. We intentionally did not include in the literature review the already widely discussed topic of sharing renewable energy generation and related peer-to-peer innovations in the light of energy communities[1].

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

[1] 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 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 of Cabeza et al. [15] and Zhang et al. [16] collect a variety of contributions focusing on similar topics acknowledged above.

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 proposing changes on both the demand-side and supply-side. In addition to significant heat demand savings, the utilization of renewable heat sources into centralized heat (or district heating) networks and the electrification of heat supply (e.g., heat pump) are proposed. Seyboth et al. [18] focus on supportive energy policy recommendations to enhance the deployment of renewable energy heating and cooling technologies such as solar, geothermal, and biomass.

In general, the 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, but certain trends such as e.g., that renewable-fed district heating networks have significant potential to supply heat demand in urban areas (see also Popovski et al. [20] and Zwickl-Bernhard and Auer [21]). In this context, Lake et al. [22] 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. [23] study the optimal combination of heat pumps and solar thermal assisting district heating networks. Sopha et al. [24] focus on the potential of wood-pellet in Norway and conclude that a stable financial support (i.e., stable wood-pellet price) has the highest impact on the transition of wood-pellet. A follow-up of the discussion on financial incentives for renewable energy technologies in the heating sector is conducted in Section 2.3.

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 highly efficient way (e.g., [23] and [24]) or to compensate non-existing networks. Popovski et al. [20] identify the electrification of the heat supply using heat pumps with PVs as the most cost-competitive alternative from a socio-economic perspective. Leibowicz et al. [25] 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 overall building retrofitting. Particularly, Kamel et al. review solar systems and their integration with heat pumps [26].

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 between different types of retrofitting measures (e.g., purely passive, passive, and active) and refer in this context to the comprehensive literature review of Fina et al. in [5]. Ma et al. [27] provide an extensive literature and state-of-the-art analysis of retrofitting focusing on existing buildings. Vieites et al. [28] elaborate in this context European initiatives improving the energy efficiency in existing and old (historic) buildings. Matrucci et al. estimate the potential of energy savings for the residential building stock of an entire city [29]. Recently, Weinberger et al. [30] investigate the impact of retrofitting on district heating network design. Fina et al. [5] put their focus on the profitability of retrofitting multi-apartment buildings with special consideration of different heating systems. They thoroughly study the implementation of the combination of building-attached/integrated PVs supporting sustainable 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 CO_2 price and end-user investment grants for building renovation.

2.2. *Justice in energy systems: socially balanced sustainable energy transitions*

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 procedural[2]. Recently, they are comprehensively discussed and reviewed by Pellegrini et al. [32]. 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 [31].

Dealing with sustainable energy systems is a monumental task and seems to be very challenging to be generalized. However, studies focusing on certain local areas is 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 [33]. Besides that, Lacey-Barnacle et al. [34] elaborate on energy justice in developing countries. Coming back to this paper's content and spatial scope, Mundaca et al. [35] 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. [36] showing that energy justice and transition frameworks can be combined and achieved simultaneously. However, Hiteva and Soacool [37] 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 (monetary) incentives that foster sustainable energy transition.

Recently, Hanke et al. [38] 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

[2] In some works, restorative and cosmopolitan justice are also mentioned in this context; see exemplarily in [31].

low-income households. Exemplarily, Xu and Chen [39] 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. [40] point in the same direction and discuss the difficulties for households who lack the capital for sustainable energy investments and are predominantly tenants and not owners of their homes. Moreover, renters also often have higher residential heating energy consumption; an indicator for energy efficiency [41]. In this context, Greene [42] discusses 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 energy transition and energy justice. Sovacool et al. [3] show that unfolding the energy transition results in deeper injustices.

2.3. Financial policy instruments

In particular, the following section is about different financial instruments supporting the transition in 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. [43] provide a fundamental review paper investigating a wide range of policy options that can support the deployment of renewable heat technologies. Masini and Menichetti [44] 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 (public) financing investment incentives. Reuter et al. [45] compare different policy instruments (feed-in tariffs, investment subsidies, tax credits, portfolio requirements, and certificate systems) and conclude that feed-in tariffs are an effective means to promoting these investments[3]. Similar results can also be found in the study of Couture and Gagnon [47]. 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, 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 [48]. This distinction and targeted adjustment of public financial incentives is important since private investments are key drivers of the diffusion of renewable energy technologies [49]. Østergaard et al. [50] conclude that the investment costs of households to adapt existing buildings for highly efficient and sustainable heating systems is economical[4]. 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. [51] 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., property owners and tenants/renters). It is, therefore, obvious that Hecher et al. [52] focus in their work on the decision-making processes of the sustainable heating system investments of homeowners. The ownership structure is often neglected in the literature and insufficiently considered.

[3] Zhou et al. [46] provide a study in dealing with the effectiveness of public financial incentives. The authors define effectiveness/efficiency as the amount of intervention (taxes collected, subsidies paid, etc.) to achieve a policy goal in the electricity sector.

[4] In particular, Østergaard et al. [50] 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.

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 [53]. Kindström and Ottosson [54] as well as Fine et al. [55] conclude little optimistically that the contracting framework itself decreases the economic viability since the contractor business companies (third party) aim to gain profits. Suhonen and Okkonen [56] conduct an analysis of energy service companies in the residential heating sector and show a wide-ranging set of barriers resulting in non-profitability of contracting business models.

2.4. Progress beyond state-of-the-art

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

- An equitable and socially balanced change of a currently gas-based heating system toward a sustainable alternative in a rented multi-apartment old building is modeled considering the complex ownership structure and relations between the property owner and tenants to "take action".

- Since the governance's first and foremost aim is that the heat system exchange in the multi-apartment building takes place, it is shown how the governance incentivizes the sustainable investment through monetary and regulative support for both the property owner and tenants. While respecting the property owner's and tenants' individual financial interests, the governance's optimal financial support strategy puts particular emphasis on the highly efficient provision of the residential heat service needs, 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 property owner and the tenants, as well as the abovementioned financial support parity among both sides. Especially, the proposed optimization model allows detailed quantitative analyses of justice in low-carbon residential buildings and the heating sector with an eye on the complex ownership structure within buildings. Moreover, this work focuses on the economic trade-offs between different agents in the energy transition, particularly the government's role in triggering private investments and social balance with an eye on the costs of inaction (opportunity costs) and increasing carbon prices.

- Different sensitivity analyses play a key role in this paper, understanding that the impact of varying allocations of the costs of inaction among the governance, the property owner, 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 monetary payments is critically discussed. Insights in that respect can help build a more reliable understanding of a sustainable future urban society predominantely living in highly efficient rental apartments.

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, input data, and scenario description comprise Section 3.3, followed by the open-source programming environment in Section 3.4

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 decarbonize the residential heating sector. Therefore, the policy is to trigger a heating system change to a sustainable alternative on the multi-apartment building level through financial support for both property owner and tenants. The avowed aim is to find a cost-minimal and socially balanced solution. The financial support for the property owner can be realized either or both by an investment grant (paid directly from the governance) and 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.

Property owner. The property 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 is only realized in case of the economic viability of an investment. In this context, the property owner can achieve profitability of the alternative heating system by receiving an investment grant (to reduce the overnight investment costs) from the governance and a rent-charge-related revenue cash flow (from the tenants).

Tenant. The tenant rents a dwelling/unit within the multi-apartment building from the property owner and has rent-related and energy-related spendings. The tenant cannot change the heating system on its authority but depends on the property owner's willingness to invest into a sustainable alternative. In connection with the existing heating system, the tenant's costs are increasing in consideration of CO_2 emissions and associated CO_2 prices. 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 property owner, and the tenants. The governance can support the property owner financially by investment grants and by the permission of rent charge adjustments. At the same time, tenants are supported by a heating cost 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 property owner and the tenant.

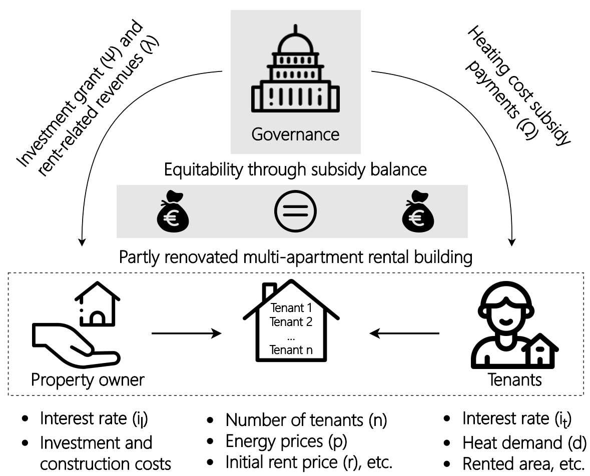

Figure 1: Sketch of the model illustrating the interrelations between the governance, property owner, and tenants. Financial support from the governance is socially balanced at the partly renovated multi-apartment rental building.

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[5]. Therefore, the objective function can be written as follows:

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

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

where Ψ is the investment grant paid to the property owner and $\Omega_{y,m}$ is the heating costs subsidy payment paid to a single tenant in year y and month m. In addition, n is the number of tenants[6] 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 defines the financial support parity between the property owner and all tenants at the multi-apartment building level from the governance's perspective

$$\underbrace{\Psi + n \cdot \sum_y \sum_m \frac{a \cdot r_{y,m}}{(1+i_g)^y}}_{\text{property owner financial support}} = \underbrace{n \cdot \sum_y \sum_m \frac{\Omega_{y,m}}{(1+i_g)^y}}_{\text{tenants financial support}} \tag{2}$$

where a is the area of a tenant's dwelling and $r_{y,m}$ is the rent charge adjustment associated with the heating system change in y and m. The equation operationalizes equitability as a subsidy balance. Moreover, social equity between the property owner and tenants consists in both bearing no economic burden of the energy transition (i.e., higher energy and/or CO_2 prices). These costs are born by the governance. Note that other definitions of and views on equitability in sustainable energy systems exist in literature[7]. Equation 3 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)

$$n \cdot d_{y,m} \leq q_{y,m} \quad : \forall y, m \tag{3}$$

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

[6] It is assumed that the multi-apartment building consists of n equal tenants/units.
[7] E.g., Green and Gambhir [57].

this, Equation 4 defines the minimum required newly installed capacity of the heating system alternative

$$\alpha_m \cdot q_{y,m} \leq \pi \quad : \forall y, m \tag{4}$$

where α_m is the load factor transforming the monthly amount of heat demand to the corresponding peak demand. Equation 5 defines the property owner's overnight investment costs (ζ)

$$\zeta = \pi \cdot c_{alt} + n \cdot c_{con} - \Psi \tag{5}$$

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 6 defines the upper bound for the investment grant

$$\Psi \leq \hat{d} \cdot c_{alt} + n \cdot c_{con} \tag{6}$$

where $\hat{d}$ is the peak value of the heat demand. Equation 7 defines the rent-related revenues of the property owner ($\lambda_{y,m}$)

$$\lambda_{y,m} = a \cdot n \cdot r_{y,m} \quad : \forall y, m \tag{7}$$

As defined here (and as used in Equation 8), this is the adjustment of the rent-related revenues (not the total rent-related revenues). The initial rent price does not enter this definition. Equation 8 sets the property owner's net present value of the alternative heating system investment equal to 0

$$-\zeta + \sum_y \sum_m \frac{1}{(1+i_l)^y} \cdot \lambda_{y,m} = 0 \tag{8}$$

where i_l is the property owner's interest rate. The equation ensures that the landlord does not gain profits through the subsidy payments from the governance (i.e., avoidance of a snowball effect for the governance). Equation 9 defines the initial annual spendings of all tenants (κ_y) using the existing heating system

$$\kappa_y = n \cdot (\bar{r} \cdot a + \sum_m q_{load,y,m} \cdot p_{init,y,m}) \quad : y = y_0 \tag{9}$$

where $\bar{r}$ is the initial rent price and $p_{init,y,m}$ the price of the conventional fuel initially supplying the heat demand in y and m. Building on this, Equation 10 sets the tenants' total spendings (K_{init})

$$K_{init} = -\sum_y \frac{1}{(1+i_t)^y} \cdot \kappa_{y_0} \tag{10}$$

where κ_{y_0} represents the initial tenants' spendings from Equation 9 above, and i_t the tenant's interest rate. Equation 11 defines the total spendings of all tenants (K_{alt}) in case of implementing the sustainable heating system alternative.

$$K_{alt} = -\sum_y \sum_m \frac{n}{(1+i_t)^y} \left(a \cdot (\bar{r} + r_{y,m}) + q_{y,m} \cdot p_{alt,y,m} - \Omega_{y,m}\right) \tag{11}$$

The middle term within the brackets on the right-hand side represents the fuel costs of the heat system alternative. Equation 12 defines constant remaining spendings (i.e., economic viability) for the tenants in case of a heating system change. The equation ensures that the tenant does not gain profits through the subsidy payments from the governance (i.e., avoidance of a snowball effect for the governance).

$$K_{alt} = K_{init} \tag{12}$$

Equation 13 defines constant heating costs subsidy payments and Equation 14 is the constant total rent price for a tenant in y.

$$\Omega_{y,m} = \Omega_{y,m-1} \quad : y \tag{13}$$

$$\bar{r} + r_{y,m} = \bar{r} + r_{y,m-1} \quad : y \tag{14}$$

Equation 15 allows rent charge adjustments by the property owner only every two years and Equations 16 and 17 set an upper bound to the rent charge adjustment

$$\bar{r} + r_{y,m} = \bar{r} + r_{y-1,m} \quad : \forall y \backslash \{y_0\}, m \text{ if } y \bmod 2 = 0 \tag{15}$$

$$\bar{r} + r_{y,m} \leq \rho \cdot \bar{r} \quad : y = y_0 \tag{16}$$

$$\bar{r} + r_{y,m} \leq \rho \cdot (\bar{r} + r_{y-1,m}) \quad : \forall y \backslash \{y_0\} \tag{17}$$

by introducing ρ as the rent charge adjustment upper bound. Table 1 summarizes the mathematical formulation and provides a qualitative overview of the model. Furthermore, Appendix A illustrates the model results for a small case example.

3.3. Definition of the case study, input data, and scenarios

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) [58]. 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[8].

It is assumed that the multi-apartment building (including all dwellings) are privately owned by the property owner. 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 an individual natural gas-based heating system. The decarbonization of the existing heating systems can be realized by two different

[8] For example, there are more than 600,000 natural gas-based systems covering residential heat demand in dwellings in Berlin, Germany, in 2020 [59].

Equation		Qualitative/high-level explanation of the mathematical formulation		
Number	Dimension	Agent/party	Keyword	Brief description
1	1	G	Obj. function	Minimize governance's total costs, including investment grants and subsidy payments
2	1	PO & T	Parity	Financial support parity between the property owner and all tenants at the multi-apartment building
3	$y \times m$	T	Load	Load satisfaction of the total heat demand within the multi-apartment building
4	$(y \times m)$	PO	Capacity	Minimum required newly installed capacity of the heating system alternative
5	1	PO	Investment	Property owner's overnight investment costs
6	1	PO	Upper-bound	Upper bound for the investment grant of the property owner
7	1	PO	Revenues	Rent-related revenues of the property owner
8	1	PO	NPV_{alt}	Property owner's net present value of the alternative heating system investment is 0
9	1	T	Costs*init*	Initial annual spendings of all tenants using the existing heating system
10	1	T	$\text{Total}_{\text{init}}$	Tenants' total spendings using the existing heating system
11	1	T	$\text{Total}_{\text{alt}}$	Tenants' total spendings using the alternative heating system
12	1	T	Equality	Constant remaining spendings for the tenants in case of a heating system change
14	1	T	Rent	Constant total rent price for a tenant per year

Table 1: Overview of the model's mathematical formulation. Abbreviations: Governance (G), Property owner (PO), and Tenants (T)

options, namely, a connection to the district heating network or the installation of an air-sourced heat pump[9]. It is assumed, that only one of the two technology alternatives is realized for all the dwellings.

3.3.2. Input data

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 property owner's interest rate i_l implicitly considers the natural change of tenants and the associated temporary empty dwelling state. We use a measured normalized heat demand profile of a multi-apartment building from [60] to convert the annual values to monthly. The heat demand includes space heating and hot water demands. The construction costs include the necessary construction measures within the building only.

Symbol	Variable	Unit	Value
n	Number of tenants	-	30
i_g	Governance's interest rate	%	3
i_l	Property owner's interest rate	%	10
i_t	Tenant's interest rate	%	5
q	Heat demand (per dwelling)	kWh	8620
$\hat{d}$	Peak heat demand (per dwelling)	kW	5
c_{alt}	Heat pump|Investment costs	EUR/kW	1000
c_{con}	Heat pump|Construction costs (per dwelling)	EUR	1000
c_{alt}	District heating|Investment costs	EUR/kW	320
c_{con}	District heating|Construction costs (per dwelling)	EUR	2000
$\bar{r}$	Initial rent price	EUR/m^2	10
ρ	Maximum rent charge adjustment (ρ)	%	10
a	Rented area (per dwelling)	m^2	60

Table 2: Data assumptions of the partly renovated multi-apartment rental building and the agents (property owner, tenants, and governance). Source: [60].

In addition, Table 3 shows specific emissions, energy prices, and further technical assumptions. The values correspond to the initial input parameters in

[9]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 work and is not further examined.

2025 in our analysis. Maintenance costs are considered implicitly as part of the fuel costs. 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 B.2 in Appendix B shows the CO_2 price development in the different scenarios.

Variable	Unit	Value	Ref.
Specific emissions|Electricity	$kgCO_2/kWh$	0.130	[61]
Specific emissions|District heating	$kgCO_2/kWh$	0.132	[62]
Specific emissions|Natural gas	$kgCO_2/kWh$	0.220	[61]
Price|District heating	EUR/kWh	0.047	[63]
Price|Natural gas	EUR/kWh	0.050	[64]
Price|Electricity	EUR/kWh	0.200	[65]
Coefficient of performance (average)	1	2.35	[66]

Table 3: Relevant economic parameters and further empirical settings for Austria in 2020

3.3.3. Scenarios

Four different quantitative scenarios are studied with the tailor-made model presented above. Input 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* (DT), *Societal Commitment* (SC), and *Gradual Development* (GD) scenario[10]. The first two scenarios consider the remaining CO_2 budget of the

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

1.5 °C climate target. Below, we briefly summarize the three openENTRANCE scenarios used in this work and refer to a detailed description to the studies in [67] and [68]. For the reader with a particular interest in the openENTRANCE scenarios, we refer to the work in [69] in which the underlying storylines outlining the narrative frames of the quantitative scenarios can be found. Note that the scenarios are used to set an empirical framework at the aggregate level for this work's analysis, which is carried out ultimately at the local level. Against this background, European decarbonization scenarios are projected to the building level, making them accessible in practical applications.

The 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 to reflect the strong policy driven character of implementing an alternative sustainable heating system. In the DT scenario, the CO2 price rising from 196 EUR/tCO_2 (in 2025) to 680 EUR/tCO_2 (in 2040) results in a deep decarbonization of the European electricity and the heating sector, which is achieved in 2040.

The 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 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 novel technologies. Therefore, the multi-apartment building implements an air-sourced heat pump as a sustainable heating system alternative. A CO2 price increase from 62 EUR/tCO_2 (in

2025) to 497 EUR/tCO_2 (in 2040) achieves deep decarbonization of the European electricity and heating sector in the SC scenario by 2040.

The GD scenario aims at limiting the global temperature increase of 2.0 °C. In general, this describes a more conservative expression of a 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/tCO_2 (in 2025) and 261 EUR/tCO_2 (in 2040). Deep decarbonization of the European electricity and heating sector is achieved in 2050.

In addition to the three openENTRANCE scenarios, the so-called "Low CO_2 price development" (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 changed with 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 for achieving deep decarbonization of the European electricity and heating sector is set.

3.4. 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 [70]. It is solved with the solver Gurobi version 9.0.3. We use for data analysis the common data format template developed by the Integrated Assessment Modeling Consortium using the open-source Python package pyam [71]. Note that all materials used in this study are disclosed as part of the publication at GitHub [11]. 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 a lower heat demand only (compared with 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 CO_2 pricing cost allocation between the property owner and the tenants.

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 2 shows the net present value of cash flows in general, and revenues in particular, of the property owner and a single tenant within the time horizon of 2025-2040. Figure 2 (top left) presents the different items of the property owner consisting of the overnight investment costs, investment grant, and rent-related revenues. Note that the latter represent the additional rent-related revenues due to the newly installed sustainable heating system. Figure 2 (bottom left) shows the development of the property owner's net present value of their cashflow over time. Thereby, it is shown that the investment pays off for the property owner by zero in 2040. The two Figures 2 (top right, bottom right) illustrate the corresponding tenant's cash flow items (top) and total net present value (bottom) until 2040.

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

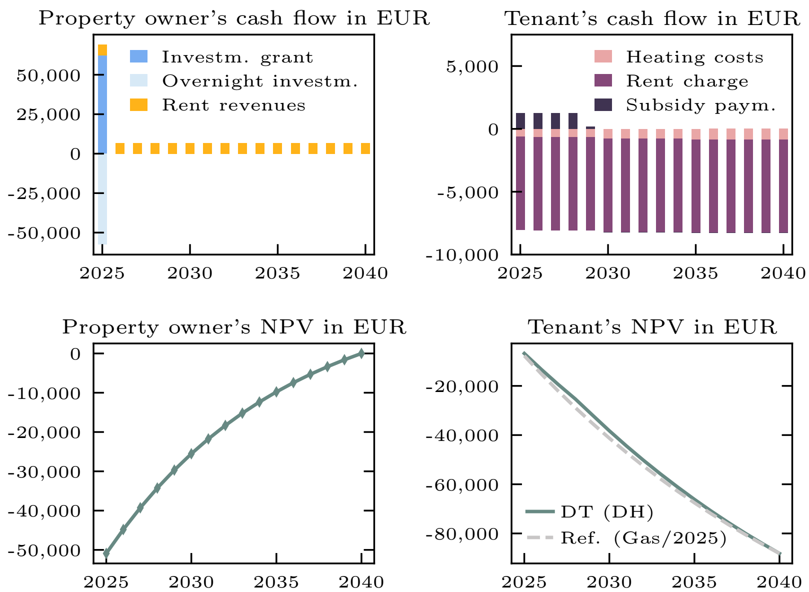

Figure 2: Development of the property owner's and tenant's economic viability of the district heating option in the *Directed Transition* scenario. Top left: property owner's cash flows, bottom left: property owner's net present value, top right: tenant's cash flows, bottom right: tenant's net present value

The tenant receives subsidy payments from the governance between 2025 and 2030. Thus, the tenant's net present value in 2040 matches with the 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-based heat system parameters, and CO_2 prices as of 2025. In the years 2025-2029, the subsidy payments exceed the heating costs of the tenant. Note that the tenant already pays a higher rent charge to the property owner within the same period (see the yellow bars in Figure 2 top left). Most importantly, the tenant's reference net present value ("Ref. (Gas/2025)"; gray dashed line in the Figure 2 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 CO_2 price). Note that the openENTRANCE decarbonization scenarios used in this work do consider both a significant increase of the CO_2 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 subsidies. However, a detailed discussion of the allocation of CO_2 price-related opportunity costs is 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[12]. 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 3 shows the results of the heat pump implementation in the *Societal Commitment* scenario for four different building qualities (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 demands. In Figure 3 (top left), the corresponding settings of the specific heat load (describing building quality) are indicated. In case of a 10 % reduction of the heat demand, the property owner receives a significant investment grant equivalent to 29 % of the property owner's total overnight investment costs of the building retrofitting measures (Fig. 3 top right). The associated tenant's subsidy payment takes place between 2025 and 2030 with a maximum of 2040 EUR/year (Fig. 3 bottom left). The rent charge

[12]The high electricity demand resulting from the low COP and related increasing electricity costs need high subsidy payments for the tenants in this case. Against the background of comparable low investment costs of the property owner, Equation 2 cannot be satisfied.

adjustment and related revenues remain almost constant during the period (Fig. 3 bottom right). In case of a 20 % reduction of the heat demand, the property owner 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/year. The property owner's rent-related revenues increase until 2031 and then remain constant. In case of a 30 % reduction of the heat demand, the property owner receives as before a small investment grant (3 %). Instead, the property owner 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 CO_2 price and the specific CO_2 emissions of the fueling energy mix). The maximum is 2796 EUR/year 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 property owner 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 4 and Figure 4 present the result of this comparison.

Governance's total financial support	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	2.8	-			82.6
CO_2 tax revenues in thous. EUR	66.6	38.9	25.7			10.3
Public financial deficit in thous. EUR	144.8	156.6	164.4			341.2

Table 4: Comparison of governance's total financial support for the different heating system alternatives and scenarios (incl. CO_2 tax revenues and public financial deficit)

In summary, the following interesting observations are made:

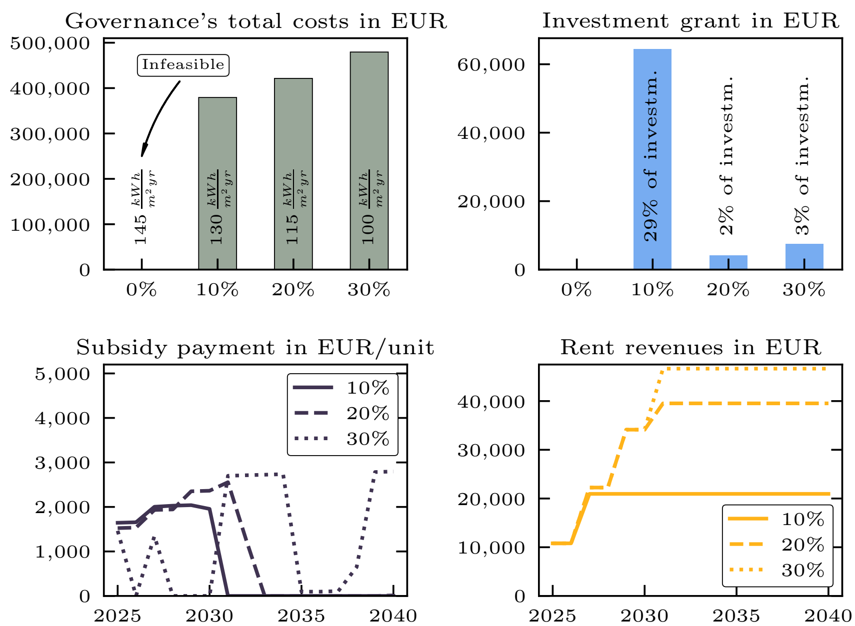

Figure 3: Comparison of the heat pump option in the *Societal Commitment* (SC) scenario for different renovation levels. Top left: governance's objective value, top right: property owner's investment grant, bottom left: tenant's subsidy payment per unit, bottom right: property owner's rent-related revenues in total

- 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 CO_2 price development scenario provides a solution for the heat pump but with a significantly higher subsidy +82.6 % compared with the lowest subsidy scenario.
- The public financial deficit (governance's total financial support minus CO_2 tax revenues) is the lowest (144.8 thous. EUR) in the *Directed Transition* scenario.

When comparing Table 4 and Figure 4, it is important to note that the property

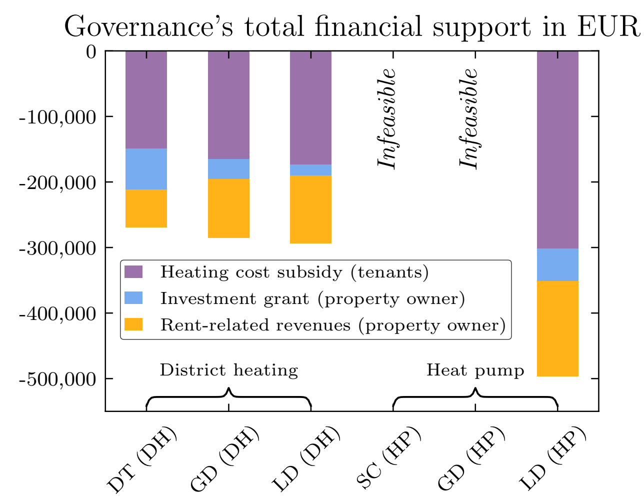

Figure 4: Comparison of governance's total financial support for the property owner and the tenants for the district heating (DH) and heat pump (HP) implementations in the different scenarios

owner's rent-related revenues (orange bar) are an "implicit" subsidy. Hence, the governance's total financial support is equal to the sum of the tenants' heating costs subsidy (purple bar) and the property owner's investment grant (blue bar).

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

This section examines the impact of the costs of inaction (i.e., sticking to the initial gas-based heating system) on the governance's total financial support. In detail, this means that the CO_2 costs (i.e., opportunity costs) to be expected due to increasing CO_2 prices have to be allocated to the different parties/agents (or a single one): governance, property owner, and tenant. Table 5 shows the objective value (absolute value and relative change in % from GD (DH)) for different allocations of opportunity costs. Exemplarily, "Equally" (first row in Table 5) takes into account that the CO_2 costs are shared equally among the governance, property owner, and tenants. Each of them bear one third of the costs. Note that the scenario setups from Section 3.3.3 (i.e., GD (DH)) considered so far that the total costs of inaction are covered by the governance (see

Equations 10 and 12). The mathematical formulation of the modifications here in this section can be found in Appendix D. Most importantly, the highest total subsidy reduction is obtained when the property owner has to cover the costs of inaction (-49 % compared with the reference value). The second highest reduction is achieved when the opportunity costs are shared equally within the building among the property owner and tenants (-34 %). Equally allocated opportunity costs reduce the total subsidy by 25 %. It is evident that an even allocation between the governance and the tenants (fourth row in Table 5) hardly leads to a reduction of the objective value. The main reason for this is the financial support of the property owner, which is necessary to create an investment incentive, and the fact that the financial support between the property owner and tenants necessarily has the same net present value.

Building upon, Figure 5 shows the objective value for the varying property owner's interest rates. The varying property owner's interest rates have two important impacts. First, a decreasing interest rate reduces the objective value as revenues are discounted less (see Fig. 5 for a fixed property owner'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 property owner's share in costs of inaction depends on the property owner's interest rate i_l (e.g., 100 % for $i_l = 10\,\%$, 70 % for $i_l = 5\,\%$ and 60 % for $i_l = 3\,\%$). Two interesting energy policy implications can be derived from the results here:

- In case the property owner is very much profit-oriented (e.g., interest rate of 10 %) and the governance's total subsidy payments are to be kept as low as possible, complete allocation of the CO_2-related opportunity costs to the property owner results in a cost-optimal strategy.
- In contrast, in case the property owner rather serves a public-benefit purpose (e.g., interest rate of 3 %), the CO_2-related opportunity costs allocation among governance, property owner, and tenants is an adequate strategy.

	Rel. allocation of opportunity costs			Objective value	
Brief summary	Governance	Property owner	Tenant	Absolute in EUR	Rel. change in % from GD (DH)
Equally	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	146.6	-25%
Property owner & tenant	0	$\frac{1}{2}$	$\frac{1}{2}$	129.0	-34%
Property owner	0	1	0	99.7	-49%
Governance & tenant	$\frac{1}{2}$	0	$\frac{1}{2}$	183.8	-6%
GD (DH) from Sec. 3.3.3 (Governance)	1	0	0	195.5	-

Table 5: Comparison of objective value (absolute and in %) for varying allocations of CO_2-related opportunity costs. As reference serves the *Gradual Development* scenario with district heating (GD (DH)) from Section 3.3.3 where the total opportunity costs are allocated to the governance.

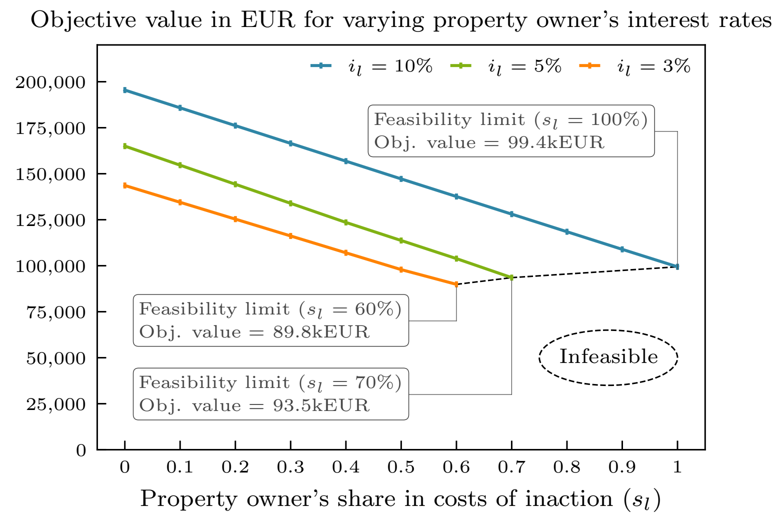

Figure 5: Comparison of the objective value for varying property owner's interest rates and share in costs of inaction

5. Conclusions and outlook

Rapid and equitable decarbonization of the heat sector in buildings is an indispensable cornerstone in a sustainable society. Special attention is needed for the rented residential buildings sector since an investment decision in sustainable technologies is in the property owner's hands. Simultaneously, an expected increase in the CO_2 price primarily impacts the tenant's energy costs. This work studies cost-optimal subsidy payment strategies incentivizing sustainable heat system implementation 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. Thus, the heating system change is implemented against the background of decarbonization of the feeding energy mix for both technology alternatives.

We find that a fair and equitable switch to a sustainable heat system is possible but with massive public subsidy payments. In particular, the property's owner investment grant and additional rent-related revenues derived from the building renovation measures are crucial to trigger the profitability of the investment. At 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 needs in partly renovated old buildings. Either the subsidy payments are significantly higher than in the district heating case, or the equitability constraints of the model cannot be satisfied. Deep building renovation and associated reduction of heat demand enable feasible solutions but with high total costs. In this case, passive retrofitting measures need to be incentivized, too.

Furthermore, the results demonstrate that allocating the costs of inaction between the governance, the property owner, 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 property owner. Also, a decrease in the property owner's interest rate reduces the total costs but limits the maximum share of the costs of inaction allocated to the property owner and implies a lower bound of the cost-minimized solution.

Future work may investigate a stronger coupling of active and passive building renovation measures as a necessary precondition for subsidy payments. This could bring further insights to decarbonization and public financial 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). In this context, further in-depth analyses regarding the public financial deficit (i.e., the interaction between governance's subsidy payments and CO_2 tax revenues) should be conducted for different sustainable technology alternatives and retrofitting levels. Besides, the tenant's diversification within the building could be improved (e.g., different willingness to pay to contribute to CO_2 mitigation).

More generally, this study could be extended by introducing further technology options, such as solar PV 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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References

[1] European Commission, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions 'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality, retrieved on 04.09.2021, `https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021DC0550` (2021).

[2] P. Korkmaz, F. Gardumi, G. Avgerinopoulos, M. Blesl, U. Fahl, A comparison of three transformation pathways towards a sustainable european society-an integrated analysis from an energy system perspective, Energy Strategy Reviews 28 (2020) 100461. `doi:https://doi.org/10.1016/j.esr.2020.100461`.

[3] B. K. Sovacool, M. Martiskainen, A. Hook, L. Baker, Decarbonization and its discontents: a critical energy justice perspective on four low-carbon transitions, Climatic Change 155 (4) (2019) 581–619. doi:https://doi.org/10.1007/s10584-019-02521-7.

[4] European Comission, Energy performance of buildings directive, online available under: http://eur-lex.europa.eu/legal-content/EN/ALL/;ELX_SESSIONID=FZMjThLLzfxmmMCQGp2Y1s2d3TjwtD8QS3pqdkhXZbwqGwlgY9KN!2064651424?uri=CELEX:32010L0031 (2021).

[5] B. Fina, H. Auer, W. Friedl, Profitability of active retrofitting of multi-apartment buildings: Building-attached/integrated photovoltaics with special consideration of different heating systems, Energy and Buildings 190 (2019) 86–102. doi:https://doi.org/10.1016/j.enbuild.2019.02.034.

[6] I. Weber, A. Wolff, Energy efficiency retrofits in the residential sector–analysing tenants' cost burden in a german field study, Energy Policy 122 (2018) 680–688. doi:https://doi.org/10.1016/j.enpol.2018.08.007.

[7] G. Kumbaroğlu, R. Madlener, Evaluation of economically optimal retrofit investment options for energy savings in buildings, Energy and Buildings 49 (2012) 327–334. doi:https://doi.org/10.1016/j.enbuild.2012.02.022.

[8] J. Hoppmann, J. Huenteler, B. Girod, Compulsive policy-making—The evolution of the German feed-in tariff system for solar photovoltaic power, Research Policy 43 (8) (2014) 1422–1441. doi:https://doi.org/10.1016/j.respol.2014.01.014.

[9] R. Haas, C. Panzer, G. Resch, M. Ragwitz, G. Reece, A. Held, A historical review of promotion strategies for electricity from renewable energy sources in eu countries, Renewable and sustainable energy reviews 15 (2) (2011) 1003–1034. doi:https://doi.org/10.1016/j.rser.2010.11.015.

[10] D. Poponi, R. Basosi, L. Kurdgelashvili, Subsidisation cost analysis of renewable energy deployment: A case study on the italian feed-in tariff programme for photovoltaics, Energy Policy 154 (2021) 112297. doi:https://doi.org/10.1016/j.enpol.2021.112297.

[11] C. Codagnone, B. Martens, Scoping the sharing economy: Origins, definitions, impact and regulatory issues, Cristiano Codagnone and Bertin Martens (2016). Scoping the Sharing Economy: Origins, Definitions, Impact and Regulatory Issues. Institute for Prospective Technological Studies Digital Economy Working Paper 1 (2016). doi:https://dx.doi.org/10.2139/ssrn.2783662.

[12] T. Sousa, T. Soares, P. Pinson, F. Moret, T. Baroche, E. Sorin, Peer-to-peer and community-based markets: A comprehensive review, Renewable and Sustainable Energy Reviews 104 (2019) 367–378. doi:https://doi.org/10.1016/j.rser.2019.01.036.

[13] B. P. Koirala, E. Koliou, J. Friege, R. A. Hakvoort, P. M. Herder, Energetic communities for community energy: A review of key issues and trends shaping integrated community energy systems, Renewable and Sustainable Energy Reviews 56 (2016) 722–744. doi:https://doi.org/10.1016/j.rser.2015.11.080.

[14] S. Zwickl-Bernhard, H. Auer, Open-source modeling of a low-carbon urban neighborhood with high shares of local renewable generation, Applied Energy 282 (2021) 116166. doi:https://doi.org/10.1016/j.apenergy.2020.116166.

[15] L. F. Cabeza, A. de Gracia, A. L. Pisello, Integration of renewable technologies in historical and heritage buildings: A review, Energy and Buildings 177 (2018) 96–111. doi:https://doi.org/10.1016/j.enbuild.2018.07.058.

[16] C. Zhang, C. Cui, Y. Zhang, J. Yuan, Y. Luo, W. Gang, A review of

renewable energy assessment methods in green building and green neighborhood rating systems, Energy and Buildings 195 (2019) 68–81. doi:https://doi.org/10.1016/j.enbuild.2019.04.040.

[17] D. Connolly, H. Lund, B. V. Mathiesen, S. Werner, B. Möller, U. Persson, T. Boermans, D. Trier, P. A. Østergaard, S. Nielsen, Heat roadmap Europe: Combining district heating with heat savings to decarbonise the eu energy system, Energy Policy 65 (2014) 475–489. doi:https://doi.org/10.1016/j.enpol.2013.10.035.

[18] K. Seyboth, L. Beurskens, O. Langniss, R. E. Sims, Recognising the potential for renewable energy heating and cooling, Energy Policy 36 (7) (2008) 2460–2463. doi:https://doi.org/10.1016/j.enpol.2008.02.046.

[19] C. Su, H. Madani, B. Palm, Heating solutions for residential buildings in china: Current status and future outlook, Energy Conversion and Management 177 (2018) 493–510. doi:https://doi.org/10.1016/j.enconman.2018.10.005.

[20] E. Popovski, T. Fleiter, H. Santos, V. Leal, E. O. Fernandes, Technical and economic feasibility of sustainable heating and cooling supply options in southern european municipalities-a case study for matosinhos, portugal, Energy 153 (2018) 311–323. doi:https://doi.org/10.1016/j.energy.2018.04.036.

[21] S. Zwickl-Bernhard, H. Auer, Demystifying natural gas distribution grid decommissioning: An open-source approach to local deep decarbonization of urban neighborhoods, Energy 238 (2022) 121805. doi:https://doi.org/10.1016/j.energy.2021.121805.

[22] A. Lake, B. Rezaie, S. Beyerlein, Review of district heating and cooling systems for a sustainable future, Renewable and Sustainable Energy Reviews 67 (2017) 417–425. doi:https://doi.org/10.1016/j.rser.2016.09.061.

[23] M. Rämä, M. Wahlroos, Introduction of new decentralised renewable heat supply in an existing district heating system, Energy 154 (2018) 68–79. doi:https://doi.org/10.1016/j.energy.2018.03.105.

[24] B. M. Sopha, C. A. Klöckner, E. G. Hertwich, Exploring policy options for a transition to sustainable heating system diffusion using an agent-based simulation, Energy Policy 39 (5) (2011) 2722–2729. doi:https://doi.org/10.1016/j.enpol.2011.02.041.

[25] B. D. Leibowicz, C. M. Lanham, M. T. Brozynski, J. R. Vázquez-Canteli, N. C. Castejón, Z. Nagy, Optimal decarbonization pathways for urban residential building energy services, Applied Energy 230 (2018) 1311–1325. doi:https://doi.org/10.1016/j.apenergy.2018.09.046.

[26] R. S. Kamel, A. S. Fung, P. R. Dash, Solar systems and their integration with heat pumps: A review, Energy and Buildings 87 (2015) 395–412. doi:https://doi.org/10.1016/j.enbuild.2014.11.030.

[27] Z. Ma, P. Cooper, D. Daly, L. Ledo, Existing building retrofits: Methodology and state-of-the-art, Energy and Buildings 55 (2012) 889–902. doi:https://doi.org/10.1016/j.enbuild.2012.08.018.

[28] E. Vieites, I. Vassileva, J. E. Arias, European initiatives towards improving the energy efficiency in existing and historic buildings, Energy Procedia 75 (2015) 1679–1685. doi:https://doi.org/10.1016/j.egypro.2015.07.418.

[29] A. Mastrucci, O. Baume, F. Stazi, U. Leopold, Estimating energy savings for the residential building stock of an entire city: A gis-based statistical downscaling approach applied to rotterdam, Energy and Buildings 75 (2014) 358–367. doi:https://doi.org/10.1016/j.enbuild.2014.02.032.

[30] G. Weinberger, S. Amiri, B. Moshfegh, Investigating techno-economic effects and environmental impacts of energy renovation of residential build-

ing clusters on a district heating system, Energy and Buildings 251 (2021) 111327. doi:https://doi.org/10.1016/j.enbuild.2021.111327.

[31] Oxford Institute for Energy Studies, Examining the balance between ambitious pledges and realistic expectations – Issue 129, online available under: https://www.oxfordenergy.org/wpcms/wp-content/uploads/2021/09/OEF-129.pdf, Oxford Energy Forum – COP 26 (2021).

[32] G. Pellegrini-Masini, A. Pirni, S. Maran, Energy justice revisited: A critical review on the philosophical and political origins of equality, Energy Research & Social Science 59 (2020) 101310. doi:https://doi.org/10.1016/j.erss.2019.101310.

[33] N. van Bommel, J. I. Höffken, Energy justice within, between and beyond european community energy initiatives: A review, Energy Research & Social Science 79 (2021) 102157. doi:https://doi.org/10.1016/j.erss.2021.102157.

[34] M. Lacey-Barnacle, R. Robison, C. Foulds, Energy justice in the developing world: A review of theoretical frameworks, key research themes and policy implications, Energy for Sustainable Development 55 (2020) 122–138. doi:https://doi.org/10.1016/j.esd.2020.01.010.

[35] L. Mundaca, H. Busch, S. Schwer, 'successful'low-carbon energy transitions at the community level? an energy justice perspective, Applied Energy 218 (2018) 292–303. doi:https://doi.org/10.1016/j.apenergy.2018.02.146.

[36] K. Jenkins, B. K. Sovacool, D. McCauley, Humanizing sociotechnical transitions through energy justice: An ethical framework for global transformative change, Energy Policy 117 (2018) 66–74. doi:https://doi.org/10.1016/j.enpol.2018.02.036.

[37] R. Hiteva, B. Sovacool, Harnessing social innovation for energy justice: A

business model perspective, Energy Policy 107 (2017) 631–639. doi:https://doi.org/10.1016/j.enpol.2017.03.056.

[38] F. Hanke, R. Guyet, M. Feenstra, Do renewable energy communities deliver energy justice? exploring insights from 71 european cases, Energy Research & Social Science 80 (2021) 102244. doi:https://doi.org/10.1016/j.erss.2021.102244.

[39] X. Xu, C.-f. Chen, Energy efficiency and energy justice for us low-income households: An analysis of multifaceted challenges and potential, Energy Policy 128 (2019) 763–774. doi:https://doi.org/10.1016/j.enpol.2019.01.020.

[40] B. K. Sovacool, M. M. Lipson, R. Chard, Temporality, vulnerability, and energy justice in household low carbon innovations, Energy Policy 128 (2019) 495–504. doi:https://doi.org/10.1016/j.enpol.2019.01.010.

[41] T. G. Reames, Targeting energy justice: Exploring spatial, racial/ethnic and socioeconomic disparities in urban residential heating energy efficiency, Energy Policy 97 (2016) 549–558. doi:https://doi.org/10.1016/j.enpol.2016.07.048.

[42] D. L. Greene, Uncertainty, loss aversion, and markets for energy efficiency, Energy Economics 33 (4) (2011) 608–616. doi:https://doi.org/10.1016/j.eneco.2010.08.009.

[43] P. Connor, V. Bürger, L. Beurskens, K. Ericsson, C. Egger, Devising renewable heat policy: Overview of support options, Energy Policy 59 (2013) 3–16. doi:https://doi.org/10.1016/j.enpol.2012.09.052.

[44] A. Masini, E. Menichetti, The impact of behavioural factors in the renewable energy investment decision making process: Conceptual framework and empirical findings, Energy Policy 40 (2012) 28–38. doi:https://doi.org/10.1016/j.enpol.2010.06.062.

[45] W. H. Reuter, J. Szolgayová, S. Fuss, M. Obersteiner, Renewable energy investment: Policy and market impacts, Applied Energy 97 (2012) 249–254. doi:https://doi.org/10.1016/j.apenergy.2012.01.021.

[46] Y. Zhou, L. Wang, J. D. McCalley, Designing effective and efficient incentive policies for renewable energy in generation expansion planning, Applied Energy 88 (6) (2011) 2201–2209. doi:https://doi.org/10.1016/j.apenergy.2010.12.022.

[47] T. Couture, Y. Gagnon, An analysis of feed-in tariff remuneration models: Implications for renewable energy investment, Energy policy 38 (2) (2010) 955–965. doi:https://doi.org/10.1016/j.enpol.2009.10.047.

[48] A. Roth, M. Boix, V. Gerbaud, L. Montastruc, P. Etur, Impact of taxes and investment incentive on the development of renewable energy self-consumption: French households' case study, Journal of Cleaner Production 265 (2020) 121791. doi:https://doi.org/10.1016/j.jclepro.2020.121791.

[49] R. Wüstenhagen, E. Menichetti, Strategic choices for renewable energy investment: Conceptual framework and opportunities for further research, Energy Policy 40 (2012) 1–10. doi:https://doi.org/10.1016/j.enpol.2011.06.050.

[50] D. S. Østergaard, S. Svendsen, Costs and benefits of preparing existing danish buildings for low-temperature district heating, Energy 176 (2019) 718–727. doi:https://doi.org/10.1016/j.energy.2019.03.186.

[51] C. Nägeli, M. Jakob, G. Catenazzi, Y. Ostermeyer, Policies to decarbonize the swiss residential building stock: An agent-based building stock modeling assessment, Energy Policy 146 (2020) 111814. doi:https://doi.org/10.1016/j.enpol.2020.111814.

[52] M. Hecher, S. Hatzl, C. Knoeri, A. Posch, The trigger matters: The decision-making process for heating systems in the residential building sec-

tor, Energy Policy 102 (2017) 288–306. doi:https://doi.org/10.1016/j.enpol.2016.12.004.

[53] L. Brinker, A. J. Satchwell, A comparative review of municipal energy business models in germany, california, and great britain: Institutional context and forms of energy decentralization, Renewable and Sustainable Energy Reviews 119 (2020) 109521. doi:https://doi.org/10.1016/j.rser.2019.109521.

[54] D. Kindström, M. Ottosson, Local and regional energy companies offering energy services: Key activities and implications for the business model, Applied Energy 171 (2016) 491–500. doi:https://doi.org/10.1016/j.apenergy.2016.03.092.

[55] B. Fina, H. Auer, W. Friedl, Profitability of contracting business cases for shared photovoltaic generation and renovation measures in a residential multi-apartment building, Journal of Cleaner Production 265 (2020) 121549. doi:https://doi.org/10.1016/j.jclepro.2020.121549.

[56] N. Suhonen, L. Okkonen, The energy services company (esco) as business model for heat entrepreneurship-a case study of north karelia, finland, Energy Policy 61 (2013) 783–787. doi:https://doi.org/10.1016/j.enpol.2013.06.047.

[57] F. Green, A. Gambhir, Transitional assistance policies for just, equitable and smooth low-carbon transitions: who, what and how?, Climate Policy 20 (8) (2020) 902–921. doi:https://doi.org/10.1080/14693062.2019.1657379.

[58] Statistik Austria, Heizungen 2003 bis 2020 nach Bundesländern, verwendetem Energieträger und Art der Heizung, retrieved on 18.10.2021, https://www.statistik.at/web_de/statistiken/energie_umwelt_innovation_mobilitaet/energie_und_umwelt/energie/energieeinsatz_der_haushalte/index.html (2020).

[59] BDEW Bundesverband der Energie- und Wasserwirtschaft e.V., Wie heizt Deutschland 2019, retrieved on 18.10.2021, https://www.bdew.de/energie/studie-wie-heizt-deutschland/ (2019).

[60] EEG-EC, Energy Community Technology Database. Internal Database at Energy Economics Group (EEG) at Vienna University of Technology (2022).

[61] Umweltbundesamt, Berechnung von Treibhausgas (THG)-Emissionen verschiedener Energieträger, online available under: https://secure.umweltbundesamt.at/co2mon/co2mon.html (2019).

[62] Werner Pölz (Umweltbundesamt), Emissionen der Fernwärme Wien 2005: Ökobilanz der Treibhausgas- und Luftschadstoffemissionen aus dem Anlagenpark der Fernwärme Wien GmbH, online available under: https://www.umweltbundesamt.at/fileadmin/site/publikationen/rep0076.pdf (2007).

[63] Arbeiterkammer Wien, Klima- und Energiefonds, Nah- und Fernwärme - Preisanalyse: Analyse des Angebots aus Konsumentenperspektive in Wien, Niederösterreich und der Steiermark, online available under: https://www.arbeiterkammer.at/infopool/akportal/Nah-und_Ferrnwaerme_Preisanalyse_Kreutzer.pdf (2020).

[64] Eurostat, Natural gas price statistics: Development of gas prices for house- hold consumers, EU-28 and EA, 2008-2018, online available under: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Development_of_electricity_prices_for_household_consumers,_EU-28_and_EA,_2008-2018_(EUR_per_kWh).png (2019).

[65] Eurostat, Development of electricity prices for household consumers, EU-28 and EA, 2008-2018, online available under: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Development_of_electricity_prices_for_household_consumers,_EU-28_and_EA,_2008-2018_(EUR_per_kWh).png (2019).

[66] Fraunhofer ISE, Wärmepumpen in Bestandsgebäuden (Abschlussbericht "WPsmart im Bestand"), online available under: https://www.ise.fraunhofer.de/content/dam/ise/de/downloads/pdf/Forschungsprojekte/BMWi-03ET1272A-WPsmart_im_Bestand-Schlussbericht.pdf (2020).

[67] H. Auer, P. C. del Granado, P.-Y. Oei, K. Hainsch, K. Löffler, T. Burandt, D. Huppmann, I. Grabaak, Development and modelling of different decarbonization scenarios of the European energy system until 2050 as a contribution to achieving the ambitious 1.5°C climate target–establishment of open source/data modelling in the European H2020 project openENTRANCE, e & i Elektrotechnik und Informationstechnik (2020) 1–13. doi:https://doi.org/10.1007/s00502-020-00832-7.

[68] H. Auer, P. C. del Granado, D. Huppmann, P.-Y. Oei, K. Hainsch, K. Löffler, T. Burandt, Quantitative Scenarios for Low Carbon Futures of the Pan-European Energy System, Deliverable D3.1, openENTRANCE, https://openentrance.eu/ (2020).

[69] H. Auer, P. C. del Granado, S. Backe, P. Pisciella, K. Hainsch, Storylines for low-carbon futures of the European energy system, Deliverable D7.1, openENTRANCE, https://openentrance.eu/ (2019).

[70] W. Hart, C. Laird, J. Watson, D. Woodruff, G. Hackebeil, B. Nicholson, J. Siirola, Optimization Modeling in Python—Springer Optimization and Its Applications (2017).

[71] D. Huppmann, M. Gidden, Z. Nicholls, J. Hörsch, R. Lamboll, P. Kishimoto, T. Burandt, O. Fricko, E. Byers, J. Kikstra, et al., pyam: Analysis and visualisation of integrated assessment and macro-energy scenarios, Open Research Europe 1 (74) (2021) 74. doi:https://doi.org/10.12688/openreseurope.13633.2.

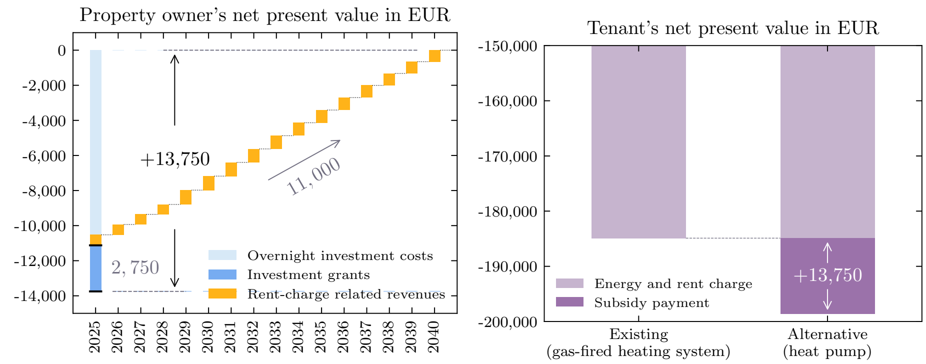
Appendix A. Illustration of the model

This section aims to test and illustrate the presented model and its functionalities. However, a model validation using existing empirical data cannot 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 property owner and a tenant in a representative single-family house switching to a heat pump. In this simple verification example, it is assumed that the property owner's and tenant's interest rate is equal (3 %). A detailed description of the empirical settings can be found in A.1. Figure A.1 shows the net present value of the financial support for both property owner (a) and tenant (b).

Variable	Unit	Value
Investment cost (heat pump)	EUR/kW	1000
Construction cost	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 A.1: Case example's parameters and assumptions

Until 2040, both agents receive equal financial support with a total of 13,750 EUR. One-fifth of the property owner's support is paid as an investment grant directly and four-fifths as rent-charge related revenues from the tenants. 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 property owner's net present value of cash flows equal to zero within the time horizon of 15 years (see Figure A.1a) and (ii) a constant remaining net present value of the tenant's energy and rent charges compared with the



(a) Development of property owner's net present value

(b) Comparison of tenant's net present value

Figure A.1: Property owner's and tenant's net present value and equal financial support. The property owner 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.

existing (e.g., gas-fired) heating system (see Figure A.1b).

Appendix B. CO_2 prices between 2020 and 2040

Scenario (EUR/tCO_2)	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 B.2: CO_2 price development

Appendix C. 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 [55]. Accordingly, we assume passive retrofitting investment costs of 1.75 EUR/kWh. Besides, the following relationships between the specific heat demand and the heat pump's (average) coefficient of performance (COP) are assumed: 130 kWh/m^2 (COP= 2.5), 115 kWh/m^2 (3.0), 100 kWh/m^2 (3.5).

Appendix D. 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.2 shows the property owner's net present value in total when a part of the total OC is allocated to the property owner'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 property owner. Consequently, Equation 8 is modified as follows by considering the property owner'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. The tenant's share of the costs of inaction (OC_t) are considered in Equation 12. 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).

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