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

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Abstract:	<p>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 CO₂ prices) between the governance, property owner, and tenants turns out as an important lever, as required subsidy payments can be reduced significantly.</p>
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Dear Reviewers, dear Associate Editors,

Please find attached our manuscript "*Equitable decarbonization of heat supply in residential multi-apartment rental buildings: Optimal subsidy allocation between the property owner and tenants*" which we would like to submit for publication in your journal *Energy and Buildings*.

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. Allocating the costs of inaction (opportunity costs associated with rising CO₂ prices) between the governance, property owner, and tenants turns out as an important lever as required subsidy payments can be reduced significantly.

We believe that with this work, we can contribute to your journal's agenda as our focus lies on the energy use in multi-apartment rental buildings and the equitable decarbonization of the residential heat supply.

We would like to propose the following researchers as reviewers:

Alessio Mastrucci (mastrucc@iiasa.ac.at) from the International Institute of Applied Systems Analysis (IIASA);
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This manuscript is original; no part of this work has been published before nor is it under consideration for publication in another journal. The authors declare that there are no conflicts of interest regarding the publication of this paper. The paper has been professionally proofread.

The corresponding author is Sebastian Zwickl-Bernhard. The contact details can be found above.

I am looking forward to your reply and thank you in advance for your consideration.

Yours sincerely,



Sebastian Zwickl-Bernhard

- Equitable decarbonization of heat supply in residential rental buildings
- Fair financial governance support strategy between property owner and tenants
- Equitable switch is possible but with massive public subsidy payments
- Heat pump alternative is not competitive compared with district heating
- Allocating the costs of inaction between governance, property owner, and tenants

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

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7 **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 CO₂ prices) between the governance, property owner, and tenants turns out as an important lever, as required subsidy payments can be reduced significantly.

8 *Keywords:* Equitability, decarbonization, residential, heat supply, subsidy
9 payments, heat system change, property owner, tenants

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10 **Nomenclature**

11

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
$d_{y,m}$	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, 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

12

13 1. Introduction

14 The recently published "Fit for 55" package [1] by the European Commission
15 outlines the pathway until 2030 to reduce greenhouse gas emissions by 55 %
16 compared with that in 1990 in the European Union (EU). With an eye on
17 the therein described energy policy recommendations, undisputedly, massive
18 efforts across sectors are necessary to enable a sustainable transformation of
19 the energy system (see also [2]). At the same time, there is a need for energy
20 justice complying with the manner of "no one left behind" [3]. Against this
21 background, the residential building sector calls for particular attention. There
22 are at least three reasons for this: (i) high shares of fossil fuels in the provision
23 of heating service needs (and increasingly cold services as well), (ii) inefficient
24 ways of delivering the heat demand caused by low standards of both building
25 stock and heating devices, and (iii) complex building ownership structures and
26 the property owner/tenant nexus in rented apartments or dwellings.

27 In fact, buildings are responsible for 40 % of the EU energy consumption and
28 36 % of the greenhouse gas emissions in 2021. Moreover, the European Commis-
29 sion states that 75 % of the EU's buildings are energy inefficient. The essential
30 factor to improve these indicators is building retrofitting. Passive renovation
31 measures can already make a significant contribution, as 35 % of the EU's build-
32 ings are older than 50 years. However, the current renovation rate of 1 %/year
33 alone will not be sufficient for a deep decarbonization of the European building
34 stock [4]. Thus, the share of passive (e.g., building insulation) alongside active
35 renovation (e.g., heating system change) measures needs to be increased rapidly
36 to be compliant with European climate plans such as the abovementioned Fit
37 for 55 package. Indeed, European decarbonization scenarios assume a much
38 higher renovation rate of up to 3 % per year in order to achieve climate neutral-
39 ity [2]. To increase this rate, most scientific literature findings suggest federal
40 financial incentives since renovation measures do not achieve economic viability
41 under current market environments in the EU (see, e.g., Fina et al. [5], Weber

42 and Wolff [6], and Kumbaroğlu and Madlener [7]).

43 In the last decades, federal financial incentives have already led to the massive
44 market penetration of renewable energy technologies. For example, in recent
45 years, solar photovoltaic (PV) has flooded the electricity markets driven by feed-
46 in tariff programs [8]. In addition, significant cost reductions were achieved due
47 to efficiency improvements and economies of scale [9]. In principle, there are
48 good reasons to learn from the diffusion pathway of solar PV and related expe-
49 riences. Nevertheless, two aspects are crucial in this context that have received
50 too little attention in the past. First is that the public monetary diffusion of
51 renewable energy must be accompanied by measures ensuring demand-side en-
52 ergy efficiency and thus energy savings. Recently, Poponi et al. [10] conducted a
53 subsidization cost analysis of solar PV in Italy where they concluded that public
54 monetary support strategies are cost-ineffective policy instruments if energy ef-
55 ficiency investments are ignored. Second is that the support in energy transition
56 must be socially balanced in a society with and without private ownership.

57 The scope of this paper aims at exploring how to deal with one of the "hot
58 potatoes" on the road to a sustainable society: to trigger investments for deep
59 decarbonization of the rented residential building sector in terms of heating
60 system change and passive retrofitting. The focus is put on multi-apartment
61 buildings in urban areas that are often heated by natural gas-based heating
62 systems. Moreover, the frequently occurring ownership structure within the
63 building with a single property owner (building or at least apartment owner)
64 and numerous tenants plays a key role in the analysis as this is a generally
65 crucial relationship. Typically, a property owner is the investment decision-
66 maker in terms of potential (active and passive) renovation measures but is not
67 affected in its decision process by an increasing CO₂ price as the most significant
68 parameter determining deep decarbonization. On the contrary, the tenants are
69 at the mercy of the future CO₂ development and have no decision-making power
70 to counteract it, e.g., by changing the heating system.

71 Against this background, the core objective of this work is to set up a cost-
72 optimal and socially balanced subsidization strategy for a multi-apartment build-
73 ing to trigger investments in a sustainable heat supply. A public authority (gov-
74 ernance) incentivizes the replacement of the initial natural gas-based heating
75 system toward a sustainable alternative along with building renovation measures
76 (accompanied by reduced heat demand) by monetary support to the property
77 owner and the tenants. Monetary support can be direct payments in the form of
78 an investment grant for the property owner or a subsidy payment for the tenant.
79 Besides, the property owner can also be indirectly financially supported by al-
80 lowing a rent adjustment as the building is retrofitted. Social balance is defined
81 at the building level from a monetary perspective using the net present value of
82 the governance’s total payments for the building’s owner (or apartment’s owner)
83 and the tenants.

84 The method applied is the development of a linear optimization model. Thereby,
85 the objective function is to minimize the governance’s net present value of mone-
86 tary support over time. The property owner’s and tenants’ strategy to minimize
87 individual total costs is considered by tailor-made constraints in the modeling
88 framework. The generalized formulation of the model allows to investigate dif-
89 ferent building types and categorization (size and number of tenants, building
90 efficiency, initial rent price, etc.). This can be helpful to analyze different build-
91 ing stocks.

92 The numerical example examined is an old multi-apartment building with a
93 single property owner and 30 units (tenants). The partially renovated building
94 is located in an urban area (Vienna, Austria) and initially heated by individual
95 gas heating systems at the unit’s level. The decarbonization of the heat supply
96 can be achieved by two different investment options, namely, a connection to
97 the district heating network or an implementation of an air-sourced heat pump
98 system on the building level.

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

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

107 This section aims to provide an overview of relevant scientific contributions with
 108 respect to this paper’s scope. The focus here lies on three different dimensions.
 109 The first dimension covers the decarbonization of heating and cooling systems
 110 from a system analysis perspective (see Section 2.1). The second dimension
 111 deals with the increasing importance of justice in the energy system transition
 112 (see Section 2.2). The third dimension is dedicated to the trade-off analyses of
 113 investment decisions into renewable energy technologies including contracting
 114 business cases (see Section 2.3). The choice of these focal points is deliberately
 115 chosen in order to reflect the DNA of the analysis. We intentionally did not
 116 include in the literature review the already widely discussed topic of sharing
 117 renewable energy generation and related peer-to-peer innovations in the light of
 118 energy communities¹.

119 *2.1. Decarbonizing heating and cooling service needs*

120 The insights obtained from various scientific studies discloses the big picture of
 121 a decarbonized heating and cooling sector, which requires a fundamental change

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

122 of the energy carrier mix alongside a significant energy efficiency increase. For
123 example, Connolly et al. [17] present a corresponding decarbonization roadmap
124 for the European heating sector proposing changes on both the demand-side
125 and supply-side. In addition to significant heat demand savings, the utilization
126 of renewable heat sources into centralized heat (or district heating) networks
127 and the electrification of heat supply (e.g., heat pump) are proposed. Seyboth
128 et al. [18] focus on supportive energy policy recommendations to enhance the
129 deployment of renewable energy heating and cooling technologies such as solar,
130 geothermal, and biomass.

131 In general, the heat source or heat technology that is ultimately used at the
132 end-user levels depends on a number of factors. Among these, geographical and
133 spatial characteristics (e.g., availability of heat network infrastructure, building
134 construction features, outdoor temperature, etc.) play a crucial role. In this
135 context, Su et al. [19] focus on local geographical features of the application site.
136 They conclude that there might not be a one-fits-all solution when decarbonizing
137 local heating systems, but certain trends such as e.g., that renewable-fed district
138 heating networks have significant potential to supply heat demand in urban
139 areas (see also Popovski et al. [20]). In this context, Lake et al. [21] present
140 a comprehensive review of district heating and cooling systems with special
141 consideration of the economic feasibility based on primary energy sources. Rama
142 et al. [22] study the optimal combination of heat pumps and solar thermal
143 assisting district heating networks. Sopha et al. [23] focus on the potential
144 of wood-pellet in Norway and conclude that a stable financial support (i.e.,
145 stable wood-pellet price) has the highest impact on the transition of wood-
146 pellet. A follow-up of the discussion on financial incentives for renewable energy
147 technologies in the heating sector is conducted in Section 2.3.

148 In any case, there are local circumstances where district heating does not fit.
149 Sustainable alternatives must be sought, either to complement existing district
150 heating networks in a highly efficient way (e.g., [22] and [23]) or to compensate

151 non-existing networks. Popovski et al. [20] identify the electrification of the heat
 152 supply using heat pumps with PVs as the most cost-competitive alternative
 153 from a socio-economic perspective. Leibowicz et al. [24] also show end-use
 154 electrification as an optimal strategy for the decarbonization of the heating
 155 sector. However, the authors state that the electrification of the heat sector is
 156 only meaningful in combination with overall building retrofitting. Particularly,
 157 Kamel et al. review solar systems and their integration with heat pumps [25].

158 In order to emphasize the importance of building renovation in combination
 159 with heating system exchange, this paragraph is dedicated to the correspond-
 160 ing literature. In general, we do not differentiate between different types of
 161 retrofitting measures (e.g., purely passive, passive, and active) and refer in this
 162 context to the comprehensive literature review of Fina et al. in [5]. Ma et al.
 163 [26] provide an extensive literature and state-of-the-art analysis of retrofitting
 164 focusing on existing buildings. Vieites et al. [27] elaborate in this context Eu-
 165 ropean initiatives improving the energy efficiency in existing and old (historic)
 166 buildings. Matrucci et al. estimate the potential of energy savings for the res-
 167 idential building stock of an entire city [28]. Recently, Weinberger et al. [29]
 168 investigate the impact of retrofitting on district heating network design. Fina et
 169 al. [5] put their focus on the profitability of retrofitting multi-apartment build-
 170 ings with special consideration of different heating systems. They thoroughly
 171 study the implementation of the combination of building-attached/integrated
 172 PVs supporting sustainable heating systems. Their results show how (passive)
 173 retrofitting measures result in a reduction of both optimal installed heating sys-
 174 tem and solar PV capacity. However, the energy cost reduction achieved from
 175 higher building standards are not sufficient to compensate the initial passive ren-
 176 ovation investment costs. They conclude that economic viability significantly
 177 depends on the development of the CO₂ price and end-user investment grants
 178 for building renovation.

179 *2.2. Justice in energy systems: socially balanced sustainable energy transitions*

180 The aspect of justice in energy systems is addressed in various studies. Accord-
181 ing to them, a key part of achieving climate targets is to ensure that no one is
182 left behind in the climate action. More generally, the three energy justice tenets
183 are distributional, recognition, and procedural². Recently, they are comprehen-
184 sively discussed and reviewed by Pellegrini et al. [31]. Considering this work’s
185 scope, we put our focus on procedural justice, as it represents measures that
186 reduce potential barriers to new clean energy investments [30].

187 Dealing with sustainable energy systems is a monumental task and seems to be
188 very challenging to be generalized. However, studies focusing on certain local
189 areas is likely to be the most promising approach. Recently, van Bommel and
190 Höffken conducted a review study focusing on energy justice at the European
191 community level [32]. Besides that, Lacey-Barnacle et al. [33] elaborate on
192 energy justice in developing countries. Coming back to this paper’s content and
193 spatial scope, Mundaca et al. [34] present two local European case studies in
194 Germany and Denmark assessing local energy transition from an energy justice
195 perspective. Their findings are in line with those from Jenkins et al. [35]
196 showing that energy justice and transition frameworks can be combined and
197 achieved simultaneously. However, Hiteva and Soacool [36] conclude from a
198 business model perspective that energy justice may be realized through market
199 principles but not through the market alone. We continue discussing this point
200 in Section 2.3 when dealing with necessary (monetary) incentives that foster
201 sustainable energy transition.

202 Recently, Hanke et al. [37] have investigated renewable energy communities
203 and their capability to deliver energy justice. They explore insights from 71
204 European cases and highlight the necessity of distributing affordable energy to
205 vulnerable households. Furthermore, it is necessary to focus in this regard on

²In some works, restorative and cosmopolitan justice are also mentioned in this context; see exemplarily in [30].

low-income households. Exemplarily, Xu and Chen [38] 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. [39] 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 [40]. In this context, Greene [41] 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. [42] provide a fundamental review paper investigating a wide range of policy options that can support the deployment of renewable heat technologies. Masini and Menichetti [43] 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. [44] compare different policy instruments (feed-in tariffs, investment subsidies, tax credits, portfolio requirements, and certificate systems) and conclude that

234 feed-in tariffs are an effective means to promoting these investments³. Similar
235 results can also be found in the study of Couture and Gagnon [46]. Neverthe-
236 less, the two latter studies only investigate the deployment of renewable energy
237 technologies in the electricity sector and not in the heating sector.

238 Building on these literature findings, it is of particular importance to differenti-
239 ate between renewable energy technology investments from companies and pri-
240 vate households. In contrast to companies, private households are incentivized
241 more effectively by investment grants to invest in renewable energy technologies
242 [47]. This distinction and targeted adjustment of public financial incentives is
243 important since private investments are key drivers of the diffusion of renewable
244 energy technologies [48]. Østergaard et al. [49] conclude that the investment
245 costs of households to adopt existing buildings for highly efficient and sustain-
246 able heating systems is economical⁴. In this context, the role of an increasing
247 CO₂ price should also be interpreted with particular circumspection. Although,
248 in general, the literature sees carbon pricing as the most important measure
249 speeding up the sustainable energy system transition (see, for example, Nägeli
250 et al. [50] focusing on the impact of carbon pricing on the residential building
251 sector). However, this does not solve the inherent problem of differential own-
252 ership in the residential sector (i.e., property owners and tenants/renters). It
253 is, therefore, obvious that Hecher et al. [51] focus in their work on the decision-
254 making processes of the sustainable heating system investments of homeowners.
255 The ownership structure is often neglected in the literature and insufficiently
256 considered.

³Zhou et al. [45] 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.

⁴In particular, Østergaard et al. [49] 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.

257 Eventually, energy and heat contracting business models tangent this work's
 258 scope. However, we explicitly aim to give only a small overview, as contracting
 259 business models themselves do not constitute the core of the analysis in this
 260 paper. A comparative review of municipal energy business models in different
 261 countries is given by Brinker and Satchwell [52]. Kindström and Ottosson [53]
 262 as well as Fine et al. [54] conclude little optimistically that the contracting
 263 framework itself decreases the economic viability since the contractor business
 264 companies (third party) aim to gain profits. Suhonen and Okkonen [55] conduct
 265 an analysis of energy service companies in the residential heating sector and
 266 show a wide-ranging set of barriers resulting in non-profitability of contracting
 267 business models.

268 *2.4. Progress beyond state-of-the-art*

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

- 271 • An equitable and socially balanced change of a currently gas-based heat-
 272 ing system toward a sustainable alternative in a rented multi-apartment
 273 old building is modeled considering the complex ownership structure and
 274 relations between the property owner and tenants to "take action".
- 275 • Since the governance's first and foremost aim is for the heat system ex-
 276 change in the multi-apartment building takes place, it is shown in how
 277 the governance incentivizes the sustainable investment through monetary
 278 and regulative support for both the property owner and tenants. While
 279 respecting the property owner's and tenants' individual financial inter-
 280 ests, the governance's optimal financial support strategy puts particular
 281 emphasis on the highly efficient provision of the residential heat service
 282 needs, heat demand reduction, and building efficiency improvements.
- 283 • The developed analytical framework determines a cost-optimal and so-
 284 cially balanced governance's subsidization strategy for the decarbonization
 285 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 predominantly 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 and scenario description comprise 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:

313 *Governance.* The governance's main objective is to decarbonize the residential
314 heating sector. Therefore, the policy is to trigger a heating system change to a
315 sustainable alternative on the multi-apartment building level through financial
316 support for both property owner and tenants. The avowed aim is to find a cost-
317 minimal and socially balanced solution. The financial support for the property
318 owner can be realized either or both by an investment grant (paid directly
319 from the governance) and adjusted rent-charge-related revenues (paid from the
320 tenants). The tenants, for their part, can be financially supported directly by
321 the governance through heating costs subsidy payments.

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

329 *Tenant.* The tenant rents a dwelling/unit within the multi-apartment building
330 from the property owner and has rent-related and energy-related spendings.
331 The tenant cannot change the heating system on its authority but depends on
332 the property owner's willingness to invest into a sustainable alternative. In
333 connection with the existing heating system, the tenant's costs are increasing
334 in consideration of CO₂ emissions and associated CO₂ prices. Nevertheless, the
335 tenant aims to limit total costs in case of a heating system change at the level
336 of the initial condition.

337 Figure 1 shows a sketch illustrating the interrelations between the governance,
338 the property owner, and the tenants. The governance can support the property
339 owner financially by investment grants and by the permission of rent charge
340 adjustments. At the same time, tenants are supported by a heating cost subsidy
341 payment. The gray bar in the middle indicates that these financial benefits need

342 to be socially balanced and overcome the differences in ownership within the
 343 multi-apartment building. The rent or rent charge adjustment is the direct
 344 financial exchange between the property owner and the tenant.

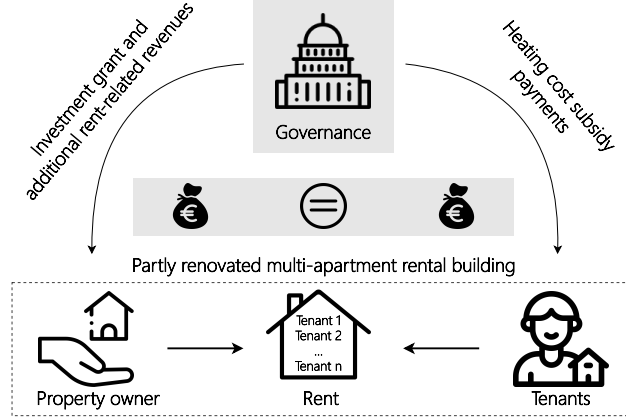


Figure 1: Sketch of the model illustrating the interrelations between the governance, property owner, and tenants. Financial support from the governance is socially balanced at the partly renovated multi-apartment rental building.

345 3.2. Mathematical formulation of the model

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

349 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:

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

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

350 where Ψ is the investment grant paid to the property owner and $\Omega_{y,m}$ is the
 351 heating costs subsidy payment paid to a single tenant in year y and month m .
 352 In addition, n is the number of tenants⁶ and i_g the governance's interest rate.
 353 The model's decision variables are included in the decision variable vector x .
 354 We refer to the nomenclature at the beginning of the paper containing a list of
 355 all decision variables.

356 3.2.2. Model's constraints

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

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

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 heating system alternative

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

where α_m is the load factor transforming the monthly amount of heat demand to the corresponding peak demand. Equation 4 defines the property owner'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

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

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 property owner ($\lambda_{y,m}$)

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

where \bar{r} is the initial rent price, $r_{y,m}$ is the rent charge adjustment associated with the heating system change in y and m and a are the areas of a tenant's dwelling. Equation 7 sets the property owner's net present value of the alternative heating system investment equal to 0

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

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

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

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 a heating system change.

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

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

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

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

Equation 14 allows rent charge adjustments by the property owner only every two years and Equations 15 and 16 set an upper bound to the rent charge adjustment

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

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

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

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

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

357 3.3. Definition of the case study, scenarios, and empirical settings

358 3.3.1. Multi-apartment building

359 The model proposed in this work is applied to a typical multi-apartment build-
360 ing in an urban area. In particular, a partially renovated and natural gas-fired
361 heating system in an old building in Vienna, Austria, is investigated. In 2020,
362 more than 440,000 natural gas-based heated dwellings existed in Vienna, Aus-
363 tria (48.5 % of the total building stock) [56]. Nevertheless, this case study is
364 representative for the European multi-apartment building stock in densely pop-
365 ulated areas, as similar proportions of natural gas-fired heating systems exist in
366 the residential heating sector there as well⁷.

367 It is assumed that the multi-apartment building (including all dwellings) are
368 privately owned by the property owner. The number of dwellings is 30, whereby
369 the area and rent price for each unit is equal. Each dwelling is rented by a
370 tenant and heated by an individual natural gas-based heating system. The
371 decarbonization of the existing heating systems can be realized by two different
372 options, namely, a connection to the district heating network or the installation
373 of an air-sourced heat pump⁸. It is assumed, that only one of the two technology
374 alternatives is realized for all the dwellings. We refer to the empirical scaling
375 and data in Section 3.3.3 for a detailed quantitative description of the multi-
376 apartment building.

377 3.3.2. Scenarios

378 Four different quantitative scenarios are studied with the tailor-made model
379 presented above. Input settings of three of them have been developed in the
380 Horizon 2020 research project openENTRANCE (<https://openentrance.eu/>)
381 and describe a future European energy system development assuming to achieve

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

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.

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) 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 to 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 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/tCO₂ (in 2025) to 680 EUR/tCO₂ (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 rollout. 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 sustain-

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

able 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 GD scenario aims at achieving a 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/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 changed with 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.

3.3.3. Empirical 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 property owner's interest rate i_l implicitly considers the natural change of tenants and the associated temporary empty dwelling state. Further empirical

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 scenarios studied in this work and the corresponding scenario specific heating system alternative (marked by the check)

437 settings can be found in Appendix A.

Variable	Unit	Value
Number of tenants	-	30
Governance’s interest rate	%	3
Property owner’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 partly renovated multi-apartment rental building and the agents (property owner, tenants, and governance)

438 3.4. Validation of the model

439 This section aims to test the presented model and its functionalities. However,
440 a model validation using existing empirical data cannot be applied in this case.
441 There is simply a lack of comparable data from real world examples. There-
442 fore, an illustrative case study is chosen to demonstrate the main functionalities
443 and to verify the model. We assume a single property owner and a tenant in
444 a representative single-family house switching to a heat pump. In this simple
445 verification example, it is assumed that the property owner’s and tenant’s in-
446 terest 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 property owner (a) and tenant (b).

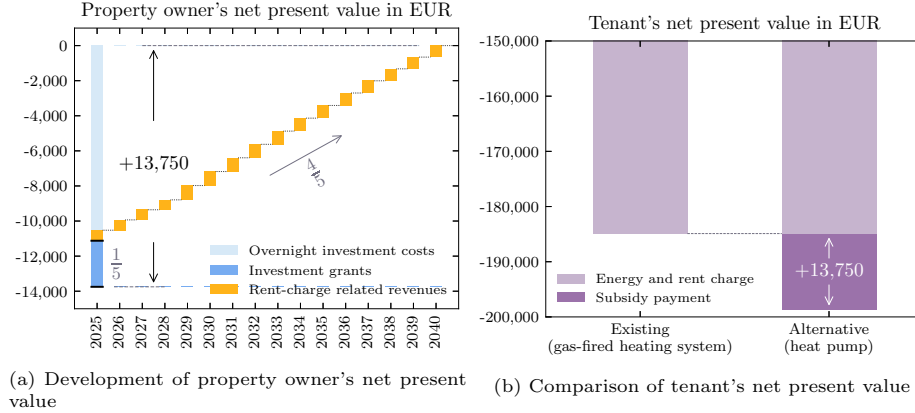


Figure 2: Property owner's and tenant's net present value and equal financial support. The property owner reaches a net present value equal to zero in 2040 resulting from an investment grant and adjusted rent-charge related revenues. The tenant's net present value remains constant compared to the existing (e.g., gas-fired) heating system due to heating costs subsidy payments.

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 2a) and (ii) a constant remaining net present value of the tenant's energy and rent charges compared with 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 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

463 Python package pyam [62]. Note that all materials used in this study are dis-
464 closed as part of the publication at GitHub ¹⁰. We refer to the repository for
465 the codebase, data collection, and further information.

466 4. Results and sensitivity analysis

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

477 4.1. District heating in the *Directed Transition* scenario

478 Following up Table 2 in Section 3.3.3, this section presents the results of the
479 district heating implementation in the *Directed Transition* scenario in detail.
480 Figure 3 shows the net present value of cash flows in general, and revenues in
481 particular, of the property owner and a single tenant within the time horizon
482 of 2025-2040. Figure 3 (top left) presents the different items of the property
483 owner consisting of the overnight investment costs (light blue), investment grant
484 (blue), and rent-related revenues (yellow). Note that the latter represent the
485 additional rent-related revenues due to the newly installed sustainable heating
486 system. Figure 3 (bottom left) shows the development of the property owner's
487 net present value of their cashflow over time. Thereby, it is shown that the
488 investment pays off for the property owner by zero in 2040. The two Figures 3

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

489 (top right, bottom right) illustrate the corresponding tenant's cash flow items
 490 (top) and total net present value (bottom) until 2040.

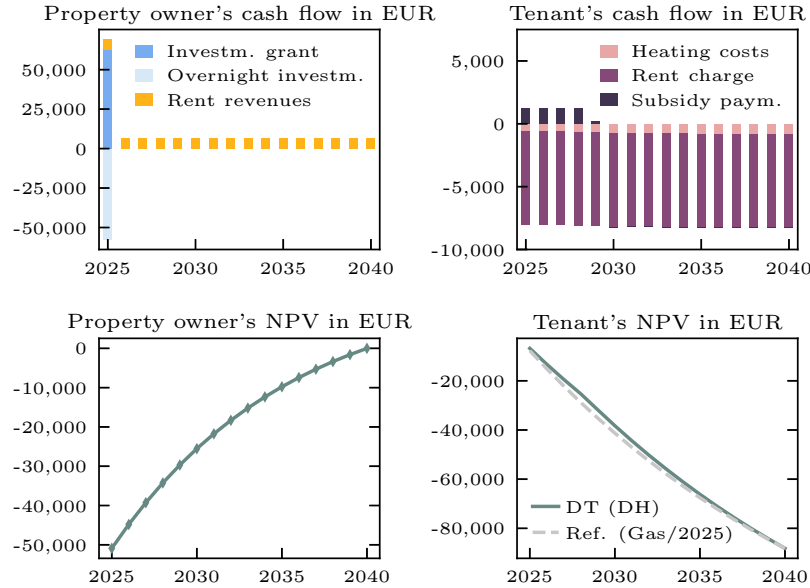


Figure 3: Development of the property owner's and tenant's economic viability of the district heating option in the *Directed Transition* scenario. Top left: property owner's cash flows, bottom left: property owner's net present value, top right: tenant's cash flows, bottom right: tenant's net present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

491 The tenant receives subsidy payments from the governance between 2025 and
 492 2030. Thus, the tenant's net present value in 2040 matches with the value as
 493 in the reference case. The reference case considers constant remaining rent and
 494 heat-related costs for the tenant based on the initial rent, gas-based heat system
 495 parameters, and CO₂ prices as of 2025. In the years 2025-2029, the subsidy
 496 payments exceed the heating costs of the tenant. Note that the tenant already
 497 pays a higher rent charge to the property owner within the same period (see
 498 the yellow bars in Figure 3 top left). Most importantly, the tenant's reference
 499 net present value ("Ref. (Gas/2025)"; gray dashed line in the Figure 3 bottom
 500 right) shows a crucial aspect of the results and assumptions of the analysis
 501 which requires an explanation. Since "Ref. (Gas/2025)" is used as the initial
 502 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 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 subsidies. However, a detailed discussion of the allocation of CO₂ 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. 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 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 4 (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. 4 top right). The associated tenant’s subsidy payment takes place between 2025 and 2030 with a maximum of 2040 EUR/year (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 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 CO₂ price and the specific CO₂ 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.

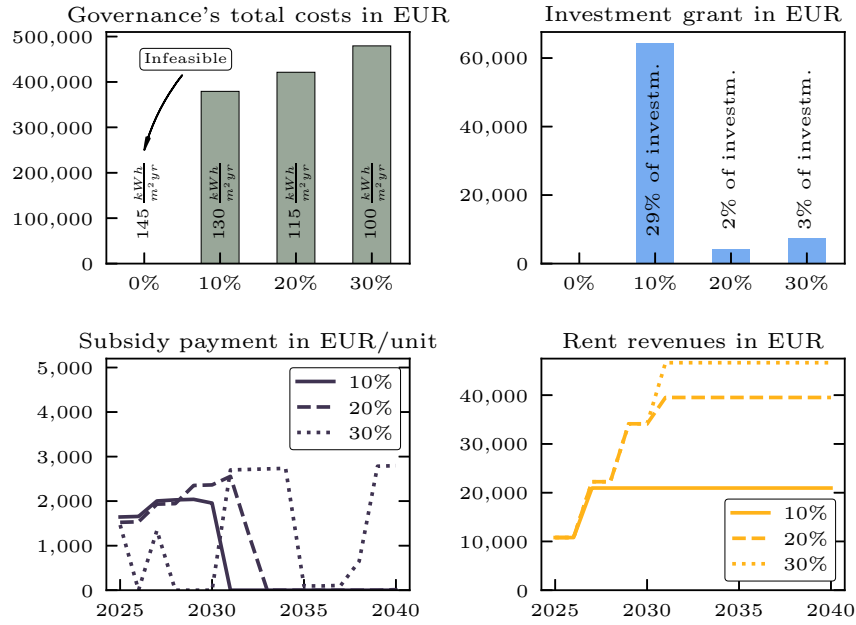


Figure 4: Comparison of the heat pump option in the *Societal Commitment* (SC) scenario for different renovation levels. Top left: governance's objective value, top right: property owner's investment grant, bottom left: tenant's subsidy payment per unit, bottom right: property owner's rent-related revenues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

546 *4.3. Governance’s total subsidies in the different scenarios*

547 In this section, a comparison of the governance’s total subsidies for district
 548 heating (DH) or heat pump (HP) implementation in the different scenarios is
 549 conducted. Table 3 and Figure 5 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	<i>infeasible</i>	<i>infeasible</i>	351.5
Rel. change in % of LD (DH)	11.2	2.6	-			82.6

Table 3: Comparison of governance’s total financial support for the different heating system alternatives and scenarios (explanations of shortcuts in Table 1)

550 In summary, the following interesting observations are made:

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

559 When comparing Table 3 and Figure 5, it is important to note that the property
 560 owner’s rent-related revenues (orange bar) are an ”implicit” subsidy. Hence, the
 561 governance’s total financial support is equal to the sum of the tenants’ heating
 562 costs subsidy (purple bar) and the property owner’s investment grant (blue bar).

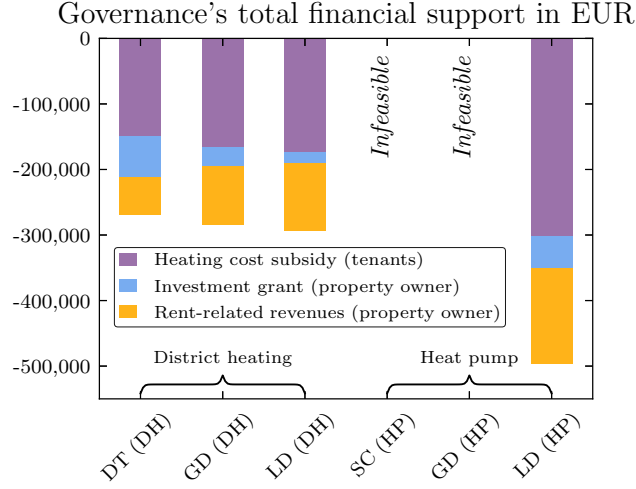


Figure 5: Comparison of governance's total financial support for the property owner and the tenants for the district heating (DH) and heat pump (HP) implementations in the different scenarios

4.4. Allocation of CO₂ 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 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, property owner, 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 with the alternative on district heating implementation in the *Gradual Development* scenario.

Rel. allocation of opportunity costs	Governance	Property owner	Tenants
Case A (equally)	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$
Case B (property owner & tenant)	0	$\frac{1}{2}$	$\frac{1}{2}$
Case C (property owner)	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 property owner, and tenants

573 Exemplarily, "Case A (equally)" takes into account that the CO₂ costs are
 574 shared equally among the governance, property owner, and tenants. Each of
 575 them bear one third of the costs. Note that the scenario setups from Section
 576 3.3.2 considered so far that the total costs of inaction are covered by the gov-
 577 ernance (see Equations 9 and 11). The mathematical formulation of the mod-
 578 ifications here in this section can be found in Appendix D. Figure 6 presents
 579 the results of the varying allocation of the opportunity costs. The metric used
 580 is the relative change of the objective value (i.e., governance's total subsidies).
 581 The objective value of the district heating option in the *Gradual Development*
 582 scenario (GD (DH)) is used as the reference value and marked by the black
 583 point in the upper left corner in Figure 6. The negative signs indicate that the
 584 consideration of the costs associated with the withdrawal of the problem (i.e.,
 585 CO₂ price related opportunity costs) results in a reduction of the necessary
 586 governance total subsidies.

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

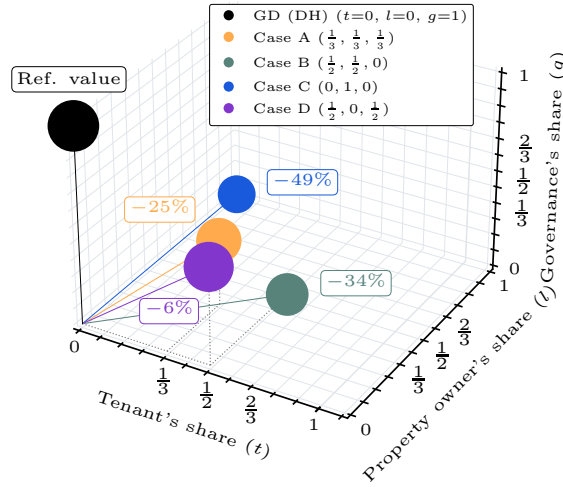


Figure 6: Comparison of the objective value for varying allocations of opportunity cost among the tenants (x-axis), property owner (y-axis), and governance (z-axis) switching to district heating. The size of the points corresponds to the objective function value in proportion to the *Gradual Development*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

Most importantly, the highest total subsidy reduction is obtained in "Case C" where the property owner has to cover the costs of inaction (-49 % compared with 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 property owner 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 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.

Figure 7 shows the objective value for the varying property owner's interest rates. Note that these results are located in the YZ-plane spanned by the property owner'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 $i_l = 10\%$.

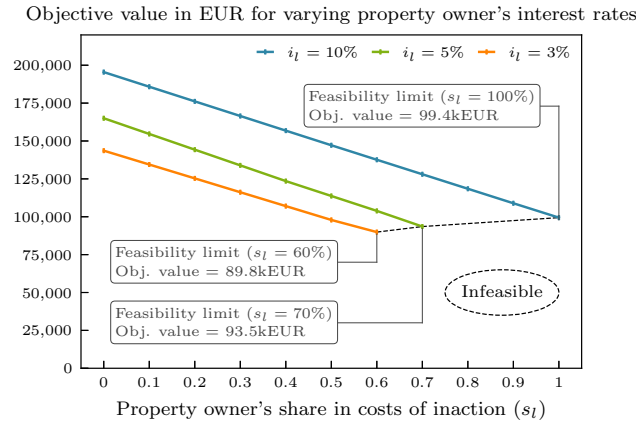


Figure 7: Comparison of the objective value for varying property owner's interest rates and share in costs of inaction

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. 7 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 CO₂-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 CO₂-related opportunity costs allocation among governance, property owner, and tenants is an adequate strategy.

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 CO₂ 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.

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 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 PV and heat and electricity storage systems.

660 **Declaration of interests**

661 None.

662 **Declaration of Competing Interest**

663 The authors report no declarations of interest.

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951 Appendix A. Data

952 Table A.1 shows specific emissions, energy prices, and further technical assump-
 953 tions. The values correspond to the initial input parameters in 2025 in our
 954 analysis. Furthermore, it is assumed that the specific emissions of electricity
 955 and district heating decrease linearly between 2025 and the corresponding de-
 956 carbonization target year of the scenario (2040 in the *Directed Transition* and
 957 *Societal Commitment* scenario as well as 2050 in the *Gradual Development sce-*
 958 *nario*). The energy price development of electricity, natural gas, and district
 959 heating is in line with the assumptions in [5]. According to this, the (retail)
 960 electricity price increases by 2.37% and the district heating price by 5% per
 961 year. Additionally, the CO₂ price increases the energy price according to the
 962 specific emissions per year. Table A.2 shows the CO₂ price development in the
 963 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

964 **Appendix B. Passive building retrofitting measures**

965 We consider passive retrofitting measures in this study in a very simplified way
 966 and focus here on the insulation of the building skin and the wall to neighboring
 967 buildings only. The economic and technical assumptions are oriented to the
 968 study from Fina et al. in [54]. The following relationships between the specific
 969 heat demand and the heat pump’s (average) coefficient of performance (COP)
 970 are assumed: 130 kWh/m² (COP= 2.5), 115 kWh/m² (3.0), 100 kWh/m² (3.5).

971 **Appendix C. Empirical settings of the case example**

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 C.3: Case example’s parameters and assumptions

972 **Appendix D. Varying allocation of the costs of inaction**

973 This work considers the CO₂ price-related costs as the costs of inaction and
 974 opportunity costs (OC) respectively. Hence, Equation D.1 describes the costs
 975 of inaction per year y and month m

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

976 where γ_{init} is the specific emissions of the initial heating system (i.e., natural
 977 gas) and $p_y^{CO_2}$ the CO₂ price in year y and month m . Exemplarily, Equation
 978 D.2 shows the property owner's net present value in total when a part of the
 979 total OC is allocated to the property owner's net present value

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

980 where s_l is the share in the costs of inaction borne by the property owner.
 981 Consequently, Equation 7 is modified as follows by considering the property
 982 owner's costs of inaction.

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

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

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

987

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: