

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
$\lambda_{y,m}$	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

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, [input data, and](#) scenarios.
103 Section 4 presents the results of this work, including sensitivity analyses of key
104 determining parameters. Section 5 discusses the results, concludes the work,
105 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] and Zwickl-Bernhard and Auer [21]). In
140 this context, Lake et al. [22] present a comprehensive review of district heating
141 and cooling systems with special consideration of the economic feasibility based
142 on primary energy sources. Rama et al. [23] study the optimal combination of
143 heat pumps and solar thermal assisting district heating networks. Sopha et al.
144 [24] focus on the potential of wood-pellet in Norway and conclude that a stable
145 financial support (i.e., stable wood-pellet price) has the highest impact on the
146 transition of wood-pellet. A follow-up of the discussion on financial incentives
147 for renewable energy technologies in the heating sector is conducted in Section
148 2.3.

149 In any case, there are local circumstances where district heating does not fit.
150 Sustainable alternatives must be sought, either to complement existing district

151 heating networks in a highly efficient way (e.g., [23] and [24]) or to compensate
 152 non-existing networks. Popovski et al. [20] identify the electrification of the heat
 153 supply using heat pumps with PVs as the most cost-competitive alternative
 154 from a socio-economic perspective. Leibowicz et al. [25] also show end-use
 155 electrification as an optimal strategy for the decarbonization of the heating
 156 sector. However, the authors state that the electrification of the heat sector is
 157 only meaningful in combination with overall building retrofitting. Particularly,
 158 Kamel et al. review solar systems and their integration with heat pumps [26].

159 In order to emphasize the importance of building renovation in combination
 160 with heating system exchange, this paragraph is dedicated to the correspond-
 161 ing literature. In general, we do not differentiate between different types of
 162 retrofitting measures (e.g., purely passive, passive, and active) and refer in this
 163 context to the comprehensive literature review of Fina et al. in [5]. Ma et al.
 164 [27] provide an extensive literature and state-of-the-art analysis of retrofitting
 165 focusing on existing buildings. Vieites et al. [28] elaborate in this context Eu-
 166 ropean initiatives improving the energy efficiency in existing and old (historic)
 167 buildings. Matrucci et al. estimate the potential of energy savings for the res-
 168 idential building stock of an entire city [29]. Recently, Weinberger et al. [30]
 169 investigate the impact of retrofitting on district heating network design. Fina et
 170 al. [5] put their focus on the profitability of retrofitting multi-apartment build-
 171 ings with special consideration of different heating systems. They thoroughly
 172 study the implementation of the combination of building-attached/integrated
 173 PVs supporting sustainable heating systems. Their results show how (passive)
 174 retrofitting measures result in a reduction of both optimal installed heating sys-
 175 tem and solar PV capacity. However, the energy cost reduction achieved from
 176 higher building standards are not sufficient to compensate the initial passive ren-
 177 ovation investment costs. They conclude that economic viability significantly
 178 depends on the development of the CO₂ price and end-user investment grants
 179 for building renovation.

180 *2.2. Justice in energy systems: socially balanced sustainable energy transitions*

181 The aspect of justice in energy systems is addressed in various studies. Accord-
182 ing to them, a key part of achieving climate targets is to ensure that no one is
183 left behind in the climate action. More generally, the three energy justice tenets
184 are distributional, recognition, and procedural². Recently, they are comprehen-
185 sively discussed and reviewed by Pellegrini et al. [32]. Considering this work’s
186 scope, we put our focus on procedural justice, as it represents measures that
187 reduce potential barriers to new clean energy investments [31].

188 Dealing with sustainable energy systems is a monumental task and seems to be
189 very challenging to be generalized. However, studies focusing on certain local
190 areas is likely to be the most promising approach. Recently, van Bommel and
191 Höffken conducted a review study focusing on energy justice at the European
192 community level [33]. Besides that, Lacey-Barnacle et al. [34] elaborate on
193 energy justice in developing countries. Coming back to this paper’s content and
194 spatial scope, Mundaca et al. [35] present two local European case studies in
195 Germany and Denmark assessing local energy transition from an energy justice
196 perspective. Their findings are in line with those from Jenkins et al. [36]
197 showing that energy justice and transition frameworks can be combined and
198 achieved simultaneously. However, Hiteva and Soacool [37] conclude from a
199 business model perspective that energy justice may be realized through market
200 principles but not through the market alone. We continue discussing this point
201 in Section 2.3 when dealing with necessary (monetary) incentives that foster
202 sustainable energy transition.

203 Recently, Hanke et al. [38] have investigated renewable energy communities
204 and their capability to deliver energy justice. They explore insights from 71
205 European cases and highlight the necessity of distributing affordable energy to
206 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 [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

235 feed-in tariffs are an effective means to promoting these investments³. Similar
 236 results can also be found in the study of Couture and Gagnon [47]. Neverthe-
 237 less, the two latter studies only investigate the deployment of renewable energy
 238 technologies in the electricity sector and not in the heating sector.

239 Building on these literature findings, it is of particular importance to differenti-
 240 ate between renewable energy technology investments from companies and pri-
 241 vate households. In contrast to companies, private households are incentivized
 242 more effectively by investment grants to invest in renewable energy technologies
 243 [48]. This distinction and targeted adjustment of public financial incentives is
 244 important since private investments are key drivers of the diffusion of renewable
 245 energy technologies [49]. Østergaard et al. [50] conclude that the investment
 246 costs of households to adapt existing buildings for highly efficient and sustain-
 247 able heating systems is economical⁴. In this context, the role of an increasing
 248 CO₂ price should also be interpreted with particular circumspection. Although,
 249 in general, the literature sees carbon pricing as the most important measure
 250 speeding up the sustainable energy system transition (see, for example, Nägeli
 251 et al. [51] focusing on the impact of carbon pricing on the residential building
 252 sector). However, this does not solve the inherent problem of differential own-
 253 ership in the residential sector (i.e., property owners and tenants/renters). It
 254 is, therefore, obvious that Hecher et al. [52] focus in their work on the decision-
 255 making processes of the sustainable heating system investments of homeowners.
 256 The ownership structure is often neglected in the literature and insufficiently
 257 considered.

³Zhou 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.

⁴In 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.

258 Eventually, energy and heat contracting business models tangent this work's
 259 scope. However, we explicitly aim to give only a small overview, as contracting
 260 business models themselves do not constitute the core of the analysis in this
 261 paper. A comparative review of municipal energy business models in different
 262 countries is given by Brinker and Satchwell [53]. Kindström and Ottosson [54]
 263 as well as Fine et al. [55] conclude little optimistically that the contracting
 264 framework itself decreases the economic viability since the contractor business
 265 companies (third party) aim to gain profits. Suhonen and Okkonen [56] conduct
 266 an analysis of energy service companies in the residential heating sector and
 267 show a wide-ranging set of barriers resulting in non-profitability of contracting
 268 business models.

269 *2.4. Progress beyond state-of-the-art*

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

- 272 • An equitable and socially balanced change of a currently gas-based heat-
 273 ing system toward a sustainable alternative in a rented multi-apartment
 274 old building is modeled considering the complex ownership structure and
 275 relations between the property owner and tenants to "take action".
- 276 • Since the governance's first and foremost aim is ~~that~~^{for} the heat system
 277 exchange in the multi-apartment building takes place, it is shown ~~in~~^{how}
 278 the governance incentivizes the sustainable investment through monetary
 279 and regulative support for both the property owner and tenants. While
 280 respecting the property owner's and tenants' individual financial inter-
 281 ests, the governance's optimal financial support strategy puts particular
 282 emphasis on the highly efficient provision of the residential heat service
 283 needs, heat demand reduction, and building efficiency improvements.
- 284 • The developed analytical framework determines a cost-optimal and so-
 285 cially balanced governance's subsidization strategy for the decarbonization
 286 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, [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:

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.

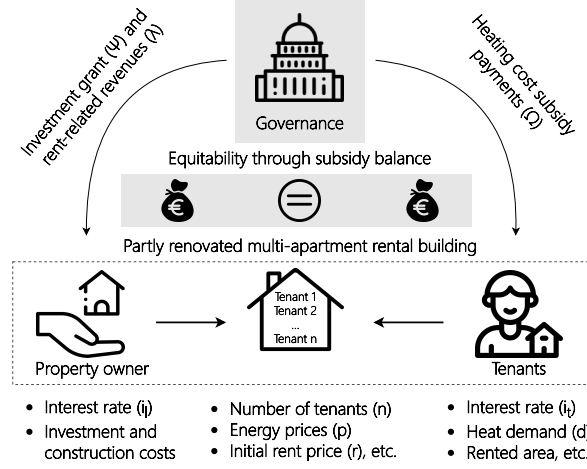


Figure 1: Sketch of the model illustrating the interrelations between the governance, property owner, and tenants. Financial support from the governance is socially balanced at the partly renovated multi-apartment rental building.

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.

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 tenants⁶ and i_g the governance's interest rate. The model's decision variables are included in the decision variable vector x . We refer to the nomenclature at the beginning of the paper containing a list of all decision variables.

3.2.2. Model's constraints

Equation 2 defines the financial support parity between the property owner and all tenants at the multi-apartment building level from the governance's perspective

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

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 CO₂ prices). These costs are born by the governance. Note that other definitions of and views on equitability in sustainable energy systems exist in literature⁷. 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)

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

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

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

⁷E.g., Green and Gambhir [57].

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

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

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)

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

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

$$\Psi \leq \hat{d} \cdot c_{alt} + n \cdot c_{con} \quad (6)$$

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

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

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

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

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

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

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})

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

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.

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

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).

$$K_{alt} = K_{init} \quad (12)$$

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

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

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

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

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

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

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

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 well⁸.

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 options, namely, a connection to the district heating network or the installation

⁸For 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	Total _{init}	Tenants' total spendings using the existing heating system
11	1	T	Total _{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 \(T\)](#)

of an air-sourced heat pump⁹. It is assumed, that only one of the two technology alternatives is realized for all the dwellings. ~~We refer to the input data in Section 3.3.2 for a detailed quantitative description of the multi-apartment building.~~

3.3.2. ~~Input data~~*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. 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.

<u>Symbol</u>	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

⁹In 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 CO₂ price increases the energy price according to the specific emissions per year. Table B.2 in Appendix B shows the CO₂ 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) scenario¹⁰. The first two scenarios consider the remaining CO₂ budget of the

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

409 1.5°C climate target. Below, we briefly summarize the three openENTRANCE
410 scenarios used in this work and refer to a detailed description to the studies in
411 [67] and [68]. For the reader with a particular interest in the openENTRANCE
412 scenarios, we refer to the work in [69] in which the underlying storylines outlining
413 the narrative frames of the quantitative scenarios can be found. [Note that the](#)
414 [scenarios are used to set an empirical framework at the aggregate level for this](#)
415 [work’s analysis, which is carried out ultimately at the local level. Against this](#)
416 [background, European decarbonization scenarios are projected to the building](#)
417 [level, making them accessible in practical applications.](#)

418 The DT scenario leads to limiting the global temperature increase to 1.5°C.
419 This is achieved by a breakthrough of new sustainable technologies triggered
420 through strong policy incentives. The markets themselves do not push this de-
421 velopment sufficiently and deliver weak financial impulses for the clean energy
422 transition only. Besides, society is also too passive in supporting to achieve
423 the ambitious 1.5°C target. Thus, in this work, it is assumed that the multi-
424 apartment building is connected to the district heating network to reflect the
425 strong policy driven character of implementing an alternative sustainable heat-
426 ing system. In the DT scenario, the CO₂ price rising from 196 EUR/tCO₂
427 (in 2025) to 680 EUR/tCO₂ (in 2040) results in a deep decarbonization of the
428 European electricity and the heating sector, which is achieved in 2040.

429 The SC scenario also leads to limiting the global temperature increase to 1.5°C.
430 In contrast to the previous scenario, decentralization of the energy system and
431 active participation as well as societal acceptance of energy transition pushes
432 sustainable development. In addition, currently existing clean technologies
433 are significantly supported by policy incentives to foster its accelerated roll-
434 out. Thus, the SC scenario assumes deep decarbonization of the energy sys-
435 tem without fundamental breakthroughs of novel technologies. Therefore, the
436 multi-apartment building implements an air-sourced heat pump as a sustain-
437 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 ~~limiting the~~[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.

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 dis-

465 closed as part of the publication at GitHub ¹¹. We refer to the repository for
466 the codebase, data collection, and further information.

467 4. Results and sensitivity analysis

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

478 4.1. District heating in the Directed Transition scenario

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

¹¹<https://github.com/sebastianzwickl>

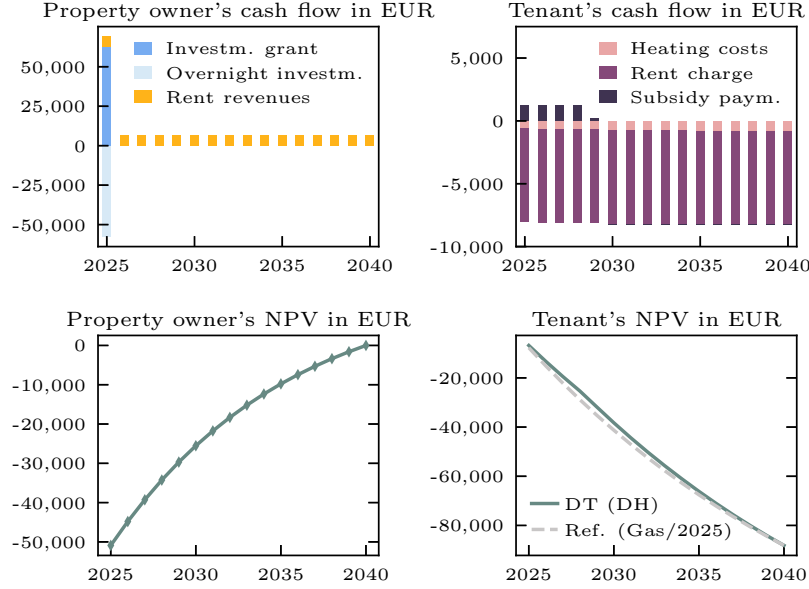


Figure 2: Development of the property owner's and tenant's economic viability of the district heating option in the *Directed Transition* scenario. Top left: property owner's cash flows, bottom left: property owner's net present value, top right: tenant's cash flows, bottom right: tenant's net present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

492 The tenant receives subsidy payments from the governance between 2025 and
 493 2030. Thus, the tenant's net present value in 2040 matches with the value as
 494 in the reference case. The reference case considers constant remaining rent and
 495 heat-related costs for the tenant based on the initial rent, gas-based heat system
 496 parameters, and CO₂ prices as of 2025. In the years 2025-2029, the subsidy
 497 payments exceed the heating costs of the tenant. Note that the tenant already
 498 pays a higher rent charge to the property owner within the same period (see
 499 the yellow bars in Figure 2 top left). Most importantly, the tenant's reference
 500 net present value ("Ref. (Gas/2025)"; gray dashed line in the Figure 2 bottom
 501 right) shows a crucial aspect of the results and assumptions of the analysis
 502 which requires an explanation. Since "Ref. (Gas/2025)" is used as the initial
 503 tenant's spendings, the results also take into account the total opportunity
 504 costs (i.e., those costs that would be incurred by sticking to the initial gas-
 505 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 settings¹². 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 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.

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	<i>infeasible</i>	<i>infeasible</i>	351.5
Rel. change in % of LD (DH)	11.2	2.8	-			82.6
<u>CO₂ tax revenues in thous. EUR</u>	<u>66.6</u>	<u>38.9</u>	<u>25.7</u>			<u>10.3</u>
<u>Public financial deficit in thous. EUR</u>	<u>144.8</u>	<u>156.6</u>	<u>164.4</u>			<u>341.2</u>

Table 4: Comparison of governance's total financial support for the different heating system alternatives and scenarios [\(incl. CO₂ tax revenues and public financial deficit\)](#)

In summary, the following interesting observations are made:

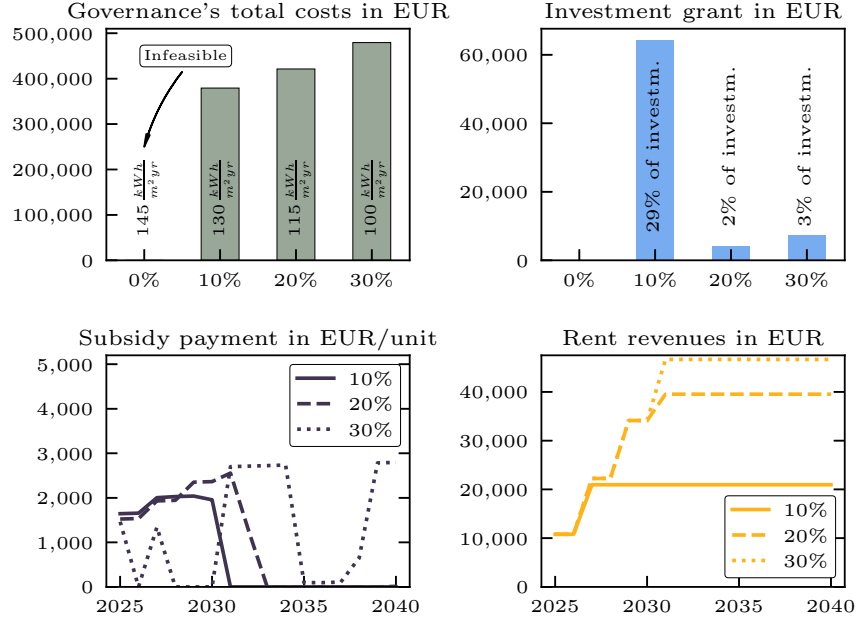


Figure 3: Comparison of the heat pump option in the *Societal Commitment* (SC) scenario for different renovation levels. Top left: governance's objective value, top right: property owner's investment grant, bottom left: tenant's subsidy payment per unit, bottom right: property owner's rent-related revenues 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 CO₂ 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 CO₂ 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

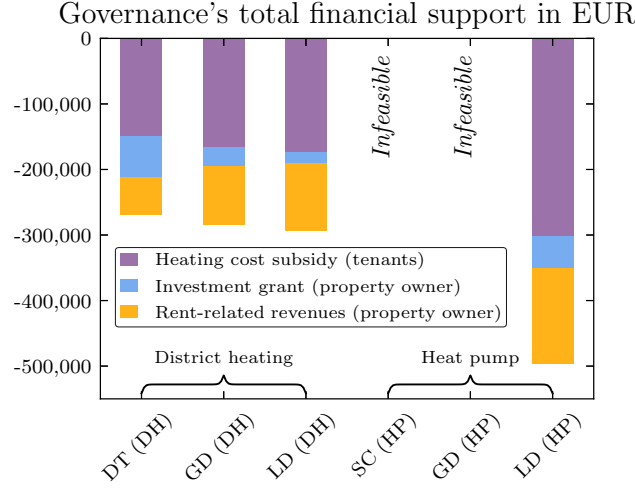


Figure 4: Comparison of governance's total financial support for the property owner and the tenants for the district heating (DH) and heat pump (HP) implementations in the different scenarios

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 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 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 CO₂ 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 ~~whenin "Case C" where~~ the property owner has to cover the costs of inaction (-49% compared with the reference value). The second highest reduction is ~~achieved whenin "Case B". In this case,~~ the opportunity costs are shared equally within the building among the property owner and tenants (-34%). ~~Equally allocated opportunity costs"Case A"~~ reduce the total subsidy by 25%. It is evident that an even allocation between the governance and the tenants (~~fourth row in Table 5"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.

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 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.

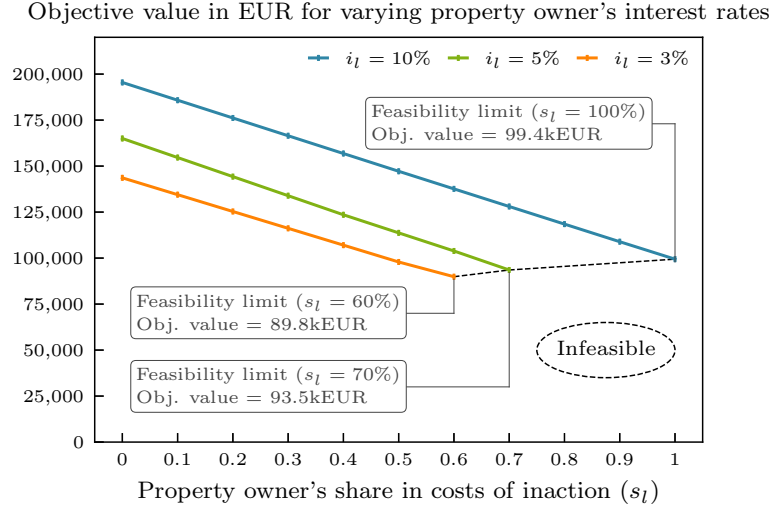


Figure 5: Comparison of the objective value for varying property owner's interest rates and share in costs of inaction

610 5. Conclusions and outlook

611 Rapid and equitable decarbonization of the heat sector in buildings is an indis-
 612 pensable cornerstone in a sustainable society. Special attention is needed for the
 613 rented residential buildings sector since an investment decision in sustainable
 614 technologies is in the property owner's hands. Simultaneously, an expected in-
 615 crease in the CO₂ price primarily impacts the tenant's energy costs. This work
 616 studies cost-optimal subsidy payment strategies incentivizing sustainable heat
 617 system implementation and retrofitting measures at the multi-apartment build-
 618 ing level. We analyze the results of the application of the developed modeling
 619 framework to a partly renovated old building switching either to the district
 620 heating network or implementing an air-sourced heat pump system under sev-
 621 eral decarbonization storylines. Thus, the heating system change is implemented
 622 against the background of decarbonization of the feeding energy mix for both
 623 technology alternatives.

Brief summary	Rel. allocation of opportunity costs			Objective value	
	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 CO₂-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.

624 We find that a fair and equitable switch to a sustainable heat system is possible
625 but with massive public subsidy payments. In particular, the property’s owner
626 investment grant and additional rent-related revenues derived from the building
627 renovation measures are crucial to trigger the profitability of the investment. At
628 the same time, subsidy payments to the tenants are required at the beginning
629 of the investment period to limit the energy- and rent-related spendings. Fur-
630 thermore, the results impressively show that the heat pump alternative is not
631 competitive in supplying heat service needs in partly renovated old buildings.
632 Either the subsidy payments are significantly higher than in the district heat-
633 ing case, or the equitability constraints of the model cannot be satisfied. Deep
634 building renovation and associated reduction of heat demand enable feasible
635 solutions but with high total costs. In this case, passive retrofitting measures
636 need to be incentivized, too.

637 Furthermore, the results demonstrate that allocating the costs of inaction be-
638 tween the governance, the property owner, and the tenants is an important lever
639 and can reduce the required subsidy payments. First and foremost, the biggest
640 drop of the total subsidies (to nearly half) takes place when the costs of inaction
641 are completely borne by the property owner. Also, a decrease in the property
642 owner’s interest rate reduces the total costs but limits the maximum share of
643 the costs of inaction allocated to the property owner and implies a lower bound
644 of the cost-minimized solution.

645 Future work may investigate a stronger coupling of active and passive build-
646 ing renovation measures as a necessary precondition for subsidy payments.
647 This could bring further insights to decarbonization [and public financial](#) strate-
648 gies with an eye on the heat demand and sustainable heat source alternatives
649 in the multi-apartment residential building sector (i.e., climate neutrality in
650 2050). [In this context, further in-depth analyses regarding the public financial](#)
651 [deficit \(i.e., the interaction between governance’s subsidy payments and CO₂ tax](#)

652 [revenues](#)) should be conducted for different sustainable technology alternatives
653 [and retrofitting levels](#). Besides, the tenant's diversification within the building
654 could be improved (e.g., different willingness to pay to contribute to CO₂ mit-
655 igation). More generally, this study could be extended by introducing further
656 technology options, such as solar PV and heat and electricity storage systems.

657 **Declaration of interests**

658 None.

659 **Declaration of Competing Interest**

660 The authors report no declarations of interest.

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959 **Appendix A. [Illustration of the model](#)**

960 This section aims to test [and illustrate](#) the presented model and its function-
961 alities. However, a model validation using existing empirical data cannot be
962 applied in this case. There is simply a lack of comparable data from real world
963 examples. Therefore, an illustrative case study is chosen to demonstrate the
964 main functionalities and to verify the model. We assume a single property
965 owner and a tenant in a representative single-family house switching to a heat
966 pump. In this simple verification example, it is assumed that the property
967 owner’s and tenant’s interest rate is equal (3 %). A detailed description of the
968 empirical settings can be found in A.1. Figure A.1 shows the net present value
969 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

970 Until 2040, both agents receive equal financial support with a total of 13,750 EUR.
971 One-fifth of the property owner’s support is paid as an investment grant directly
972 and four-fifths as rent-charge related revenues from the tenants. The tenant re-
973 ceives a heating costs subsidy. In sum, the governance pays 16,500 EUR. Thus,
974 the total level of financial support for exchanging the heating system results
975 exactly in (i) a property owner’s net present value of cash flows equal to zero
976 within the time horizon of 15 years (see Figure A.1a) and (ii) a constant remain-
977 ing net present value of the tenant’s energy and rent charges compared with the

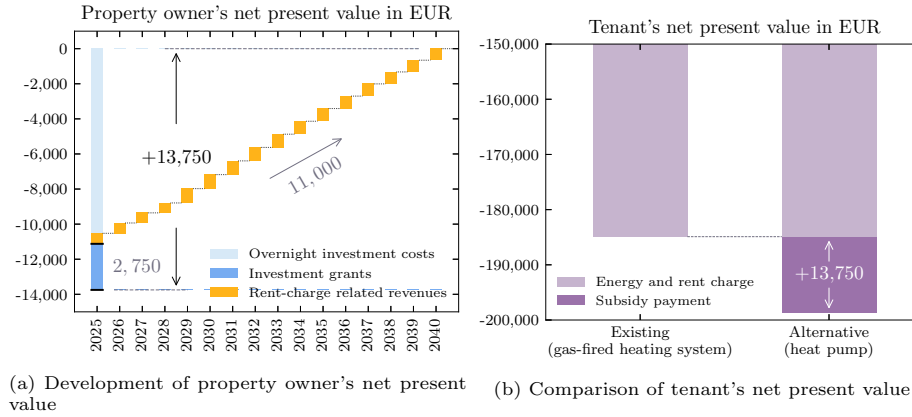


Figure A.1: Property owner's and tenant's net present value and equal financial support. The property owner reaches a net present value equal to zero in 2040 resulting from an investment grant and adjusted rent-charge related revenues. The tenant's net present value remains constant compared to the existing (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. CO₂ prices between 2020 and 2040

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 B.2: CO₂ 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/m² (COP= 2.5), 115 kWh/m² (3.0),
100 kWh/m² (3.5).

Appendix D. Varying allocation of the costs of inaction

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

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

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

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

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.

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

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).

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