Justice in decarbonizing heating systems consistent with the Paris Climate Agreement: subsidy balance between landlords and tenants at the multi-apartment building level

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Abstract

Keywords:

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Nomenclature

Type	Description	Unit
Set and index		
$y \in \mathcal{Y} = \{1, \ldots, Y\}$	Years, index by y	
$m \in \mathcal{M} = \{1, \ldots, M\}$	Months, index by m	
Decision variables		
inv_{grant}	Landlord's investment grants	EUR
$sub_{heat,y,m}$	Tenant's heating costs subsidy in y and m	EUR
$q_{init,y,m}$	Heat demand supplied by the initial heating system	kWh
$q_{alt,y,m}$	Heat demand supplied by the heating system alternative	kWh
Π_{alt}	Newly installed heating system alternative capacity	kW
$r_{y,m}$	Rent charge adjustment in y and m	EUR/m^2
Parameters		
n_{ten}	Number of tenants	1
i	Interest rate	%
$q_{load,y,m}$	Total heat demand in y and m	kWh
α_m	Ratio between total heat demand and peak load in m	1
$c_{alt,hs}$	Specific heating system alternative investment costs	EUR/kW
$c_{alt,con}$	Heating system alternative construction costs	EUR
$\bar{r}$	Initial rent price	EUR/m^2
a	Rented area per tenant	m^2
$p_{init,y}$	Energy price fueling the initial heating system	EUR/kWh
$p_{alt,y,m}$	Energy price fueling the heating system alternative	EUR/kWh

1. Introduction

Friday 29.10.2021

- Green Deal und Fit for 55 Package
- Leaving no one left behind
- Wärmesektor, Emissionen, Ineffiziente Energiedienstleistungsbereitstellung
- Besondere Bedinungen: (i) high shares of fossil fuels, and (ii) ownership structure buildings
- Building renovation (active+passive): federal financial incentives - Bernadette paper
- Wie konkret?

Against this background $\cdots$

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

This section aims to provide an overview of relevant scientific contributions with respect to this paper's scope. Explicitly not part of the literature review is the already widely discussed topic of sharing renewable energy generation and related peer-to-peer innovations in the light of energy communities. A general study comprehensively dealing with the sharing economy is provided by Codagnone and Martens [1]. The reviews from Sousa et al. [2] and Koirala et al. [3] go into even more depth and with resepect to peer-to-peer energy sharing and energy communities. Against this background, the focus here lies on three different aspects without claiming to be absolutely complete in each case. The first aspect is the decarbonization of heating and cooling systems from a system analysis perspective and is described in Section 2.1. The second aspect deals with the increasingly importance of justice in the energy system transition and is presented in Section 2.2. The third aspect is dedicated to the trade-offs analysis of investment decisions into renewable energy technologies including realted contracting business cases and is discussed in Section 2.3. The choice of these focal points, as well as the explicit exclusion of the mentioned topics, are deliberately chosen in order to reflect the DNA of the analysis.

2.1. Decarbonizing the provision of heating service needs

The insights obtained from various scientific studies allow us to see the big picture of a decarbonized heating and cooling sector. A fundamental change of the energy carrier mix, alongside a significant efficiency increase, is necessary for a sustainable heating and cooling service need supply. For example, Connolly et al. [4] provide in their study such a strategy and present a decarbonization roadmap for the European heating sector. They propose a new sustainable heat strategy that is based on changes on the demand-side and supply-side. In addition to significant heat savings, integrating sustainable heat sources into centralized heat networks (or district heating networks) and electrifying heat supply (e.g., heat pump) are suggested to achieve a low-carbon heating sector.

Seyboth et al. [5] focus in their study on supportive energy policy recommendations to enhance the deployment of renewable energy heating and cooling technologies. In particular, this means the integration of renewable sources such as solar, geothermal, and biomass into heating and cooling systems.

In general, the sustainable heat source or heat generation technology that is ultimately implemented/used at the end-user levels depends on a number of factors. Among these, geographical and spatial characteristics, in particular, play a crucial role. Su et al. [6] deal in their study with optimal sustainable heating system alternatives with a special focus on local geographical features of the application site. Their results show that there might not be a one-fits-all solution if decarbonizing local heating systems. However, certain trends are very much emerging in their findings, which can also be confirmed by further case studies. Renewable-fed district heating networks have significant potential to supply heat demand in urban areas. This is exemplarily also shown by the results of Popovski et al. [7]. They state that from a socio-economic perspective, district heating networks with excess heat are the most favorable supply option in densely populated areas. Lake et al. [8] present a comprehensive review of district heating and cooling systems. They analyze among others the economic feasibility and system identification based on primary energy sources of centralized heating and cooling networks. Rama et al. [9] study the optimal combination of different sustainable heating alternatives.In particular, they show how heat pumps and solarthermal can assist district heating networks. There exist also other alternatives. Sopha et al. [10] focus in their study on the potential of wood-pellet in Norway, a country with high shares of district heating-based heat supply. They use an agent-based model to identify energy policy options supporting the uptake of such sustainable heating systems. The authors conclude that a stable financial support (i.e., stable wood-pellet price) has the highest impact on the transition of wood-pellet. We refer to Section 2.3 in this context for a detailed discussion of financial incentives for renewable energy technologies in the heating sector.

In any case, there is a need for sustainable alternatives to district heating. Either to complement existing district heating networks in a high-efficient way (e.g., [9] and [10]) and/or because to compensate non-existing networks in the future. Popovski et al. [7] identify the electrification of the heat supply using heat pumps with photovoltaics as the most cost-competitive alternative from a socio-economic perspective. Leibowicz et al. [11] also show end-use electrification as an optimal strategy for the decarbonization of the heating sector. However, the authors state that the electrification using heat pumps for example only makes sense in combination with building thermal efficiency improvements.

In order to emphasize the importance of building renovation measures, we dedicate this concluding paragraph the corresponding literature. In particular, we select papers focusing on the impact of different retorfitting measures on sustainable heating system alternatives. However, we do not differentiate here in detail between different types of retrofitting measures (e.g., purely passive, passive, active, etc.) and refer in this context to the comprehensive literature review of Fina et al. in [12]. Ma et al. [13] provide an extensive literature and state-of-the-art analysis of retrofitting focusing on existing buildings. Vieites et al. [14] elaborate in this context of European initiatives improving the energy efficiency in existing and old (historic) buildings. Recently, Weinberger et al. [15] investigate the impact of retrofitting on district heating networks. Fina et al. [12] put their focus on the profitability of retrofitting of multi-apartment buildings with special consideration of different heating systems. They thoroughly study the implementation of the combination of building-attached/integrated photovoltaics supporting sustainable heating systems. Their results show how (passive) retrofitting measures result in a reduction of the required installed heating system capacity. However, the energy cost reduction achieved from higher building standards are not able to compensate the initial passive renovation investment costs. They conclude that latter significantly depend on the development of the CO_2 price and the assumptions of end-user investment grants as well as subsidies. We again take up these findings associated with financial support in Section 2.3

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

Tuesday - 26.10.2021

- Erklärung, was ist energy justice überhaupt + Review paper
- Allgemein sehr schwer, weil geographische Charakteristic berücksichtigt werden muss, western welt nicht auf die gesamte im allgemeinen
- Sieht man davon ab und beschränkt sich auf westliche welt, unterschiedliche besitzverhältnisse bezüglich Wärmesektor ...nur kurzer satz, nicht zu weit aufmachen, fokussieren auf Europa/Österreich
- Erste Versuche, das auf lokaler Ebene anzugehen
- Beispiele von Studies anführen und Study ob Energy Communities justice sind - social welfare Theresia's paper
- Und frage stellen, ist es gerecht wenn nichts passiert oder transition scheitert ...weglassen? denke eher schon wichtig, also nichts tun ist auch ungerecht. untermauern, dass was getan werden muss.
- müssen speziell auf low-income households schauen und haben oft höhere residential heating energy use intensity im zusammenhang mit efficiency improvements /energy demand reduction wichtig

the three energy justice tenets (distributive, recognitional and procedural)
A review Energy justice - equality [16] Sehr schwer aber zu generalisieren weil geopgraphische und lokale Apsekte berücksichtigt werden sollten Energy justice in the transition to low carbon energy systems: Exploring key themes in interdisciplinary research: non-western Westliche Welt nicht auf die ganze Welt schließen (inklusive nicht entwickelte Länder) [17] case study von Mozambik
Harnessing social innovation for energy justice: A business model perspective: Energy justice may be operationalised through market principles but not through the market alone [18]

We examine two local energy transitions from an energy justice perspective [19] show that energy justice and transitions frameworks can be combined [20] Recently 2021, do renewable energy communities deliver energy justice? Exploring insights from 71 European cases [21]

- "We aim to show how when low-carbon transitions unfold, deeper injustices related to equity, distribution, and fairness invariably arise" [22]
- energy justice in household low carbon innovations; low carbon heating; collection of opportunities but also threats; who wins and who loses; difficulties to people without the capital, or who do not own their own home. ([23])

Wir müssen speziell auf low-income households und renters schauen: Energy efficiency and energy justice for U.S. low-income households: An analysis of multifaceted challenges and potential: Low-income households and renters have fewer energy efficiency appliances; need tailored assistance [24]
low-income haben auch höheren residential heating energy use intensity, an energy efficiency proxy [25]
"They are grinding us into the ground" – The lived experience of (in)energy justice amongst low-income older households: Energy justice was experienced on four separately distinguishable levels of social relationships: intra-households, household-energy retailer relations, immediate social networks and wider social relations. simple retrofits improved householder heating capabilities [26]

2.3. Trade-offs between overnight investments and net present value decisions

Wednesday - 27.10.2021

- Review paper welche Kriterien/Aspekte beeinflussen Investition in erneuerbare Energien
- Finanzielle Unsicherheit der Hauptgrund warum nicht stärker investiert wird
- neben investoren private investitionen sehr wichtig, damit gemeint auf lokaler ebene small-scale

- Problem zum Beispiel Fernwärmeausbau in Gebiet profitabel für Unternehmen, aber nicht für Endkunden beispielsweise.
- die meisten Arbeiten sprechen davon, dass öffentliche Anreize notwendig sind.
- Effizienz wird so bestimmt, dass möglichst wenig eingegriffen werden soll
- Einspeisetarif aber das bei Wärmesektor schwer
- Studien Wärmesektor homeowners' decision-making processes, 1-Familien und 2-Familien homeowners' decision-making processes aber nicht Besitzverhältnisse auf Mehrparteienhäuser
- Ozorhon et al. (2018) [27] Literaturübersicht welche Kriterien Investitionsentscheidung in erneuerbare Energien Technologien am stärksten beeinflussen. Allerdings wird allgemein von Investoren gesprochen und nicht explizit auf den privaten Sektor bzw. Staat fokussiert.
- Masini et al. (2012) [28] finanzielle Anreize sind der Hauptgrund warum erneuerbare Energien nicht stärker umgesetzt werden.
- Reuter et al. (2012) [29] allgemeinen überblick welche öffentlichen Anreize für Investitionen in erneuerbare Energie
- Zhou et al. (2011) [30] effizienz einer Maßnahme nach dem notwendigen Maß an Eingriff
- Couture et al. (2010) [31]: bestätigt, dass feed-in tariffs are the most effective policy to encourage the rapid and sustained deployment of renewable energy. Stromsektor aber nicht Wärmesektor/Gebäudesektor
- Hecher et al. (2017) [32] fokussiert auf homeowners' decision-making processes, single and double-family houses. subsidies for heating system tabinvestments and infrastructural adjustments reveal to be most effective for homeowners in problem situations to foster alternative heating systems.

- Wustenhagen et al. (2012) [33] Wir brauchen private Investitionen in erneuerbare Energien
- Eitan et al. (2019) [34] Review, Beschreibt das so-called "phenomenon" of community and private sector renewable energy partnerships
- Aslani et al. (2012) [35] Stellt auf Basis einer umfassenden Literaturübersicht fest, dass private Sektor und dessen Investitionen sehr wichtig sind, fokussiert dabei sehr stark auf Stromsektor und kommt zu dem Schluss, dass der Staat als stärkster Treiber gesehen werden kann.
- Rodriguez et al. (2015) [36] Effekte des Staates auf private Investitionen in erneuerbare Energien. Wieder Strom
- Schmidt et al. (2013) [37] Selbst wenn der Wärmesektor untersucht wird, geht es oftmals um elektrifizierung
- Williams et al. (2015) [38] Barrieren für Teilnahme des privaten Sektors an dezentraler Elektrifizierungsprojekten
- Ostergaard et al. [39] Investments in heating systems are attractive from an energy system perspective, Customer investments in heating systems should be motivated economically.
- Nageli et al. (2020) [40] increase in the CO2 tax as well as subsidies are effective in speeding up the transition in the beginning, aber eben auch hier nicht die unterschiedlichen Besitzverhältnisse

2.4. Progress beyond state-of-the-art

Thursday - 28.10.2021

- heating system change and sustainable heat supply takes place justice in the heating sector
- analytical and modeling framework; justice; qualitative analysis
- Trade-off analysis between governance, landlords, and tenants ⟶ required incentives

- Sensitivity analysis helps us to bettter understand the different ownership structure and its influence on the sustainable energy transition

3. Materials and methods

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

3.1. Introduction and model overview

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

Governance. The governance's main objective is to decarbonizing the residential heating sector. Therefore, the intention is to trigger a heating system change to a sustainable alternative on the multi-apartment building level by financial support for both landlord and tenants. The avowed aim is to find a cost-minimal and socially balanced solution. The financial support can be realized by an investment grant (paid directly from the governance) or rent-charge-related revenues (from the tenants and refunded by the governance) for the landlord and heating costs subsidy payments for the tenants.

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

Tenant. rents a dwelling within the multi-apartment building from the landlord and has rent-related and energy-related spendings. He cannot change the heating system on his authority but depends on the landlord's willingness to realize a low-emission sustainable alternative. Especially in the case of the existing heating system, its costs are directly subject to a higher pricing of CO_2 emissions. Nevertheless, the tenant aims to limit total costs in case of a heating system change at the level of the initial condition.

Figure 1 shows a sketch illustrating the interrelations between the governance, the landlord, and the tenants. The governance can support the landlord financially by investment grants and by the allowance of rent charge adjustments. At the same time, tenants are supported by a heating costs subsidy payment. The gray bar in the middle indicates that these financial benefits need to be socially balanced and overcome the differences in ownership within the multi-apartment building. The rent or rent charge adjustment is the direct financial exchange between the landlord and the tenant.

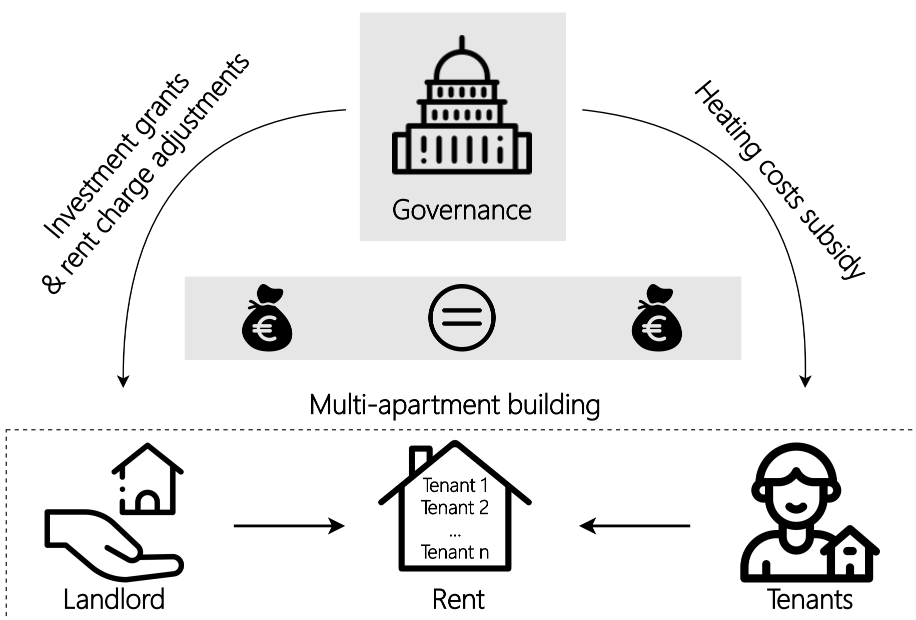


Figure 1: Sketch of the model illustrating the iterrelations between the governance, landlord, and tenants. Financial support from the governance is socially balanced at the multi-apartment building.

3.2. Mathematical formulation of the model

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

3.2.1. Model's objective function

The objective function of the model is to minimize governance's total costs, including investment grants and subsidy payments[1]. Therefore, the objective function can be written as follows:

$$\min_{x} \Psi + \sum_{y} \sum_{m} \frac{n}{(1+i_g)^y} \cdot \Omega_{y,m} \tag{1}$$

where Ψ is the investment grant paid tothe landlord and $\Omega_{y,m}$ the heating costs subsidy payment paid to a single tenant in year y and month m. In addition, n is the number of tenants[2] and i_g the governance's interest rate. The model's decision variables are included in the decision variable vector x. We refer to the nomenclature at the beginning of the paper containing a list of all decision variables.

3.2.2. Model's constraints

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

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

where $d_{y,m}$ is the total heat demand of a tenant's dwelling and $q_{y,m}$ the heat demand covered by the alternative heating system in y and m. Building on this, Equation 3 defines the minimum required newly installed capacity of the

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

heating system alternative

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

where α_m is the load factor transforming the monthly amount of heat demand to the corresponding peak demand. Equation 4 defines the landlord's overnight investment costs (ζ)

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

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

$$\Psi \leq \hat{d} + n \cdot c_{con} \tag{5}$$

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

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

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

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

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

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

where $p_{init,y,m}$ is the price of the conventional fuel initially supplying the heat demand in y and m. Building on this, Equation 9 sets the tenants' total spendings (K_{init})

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

where σ_{y_0} represents the initial tenants' spendings from Equation 8 above and i_t the tenant's interest rate. Equation 10 defines the total spendings of all tenants (K_{alt}) realizing the sustainable heating system alternative

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

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

$$K_{alt} = K_{init} \tag{11}$$

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

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

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

Equation 14 allows rent charge adjustment by the landlord only every two years and Equation 15 and 16 set a upper bound to the rent charge adjustment

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

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

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

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

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

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

3.3.1. Multi-apartment building

The model proposed in this paper is applied to a typical multi-apartment building in an urban area. In particular, a partially renovated and natural gas-based heated old building in Vienna, Austria is investigated. In 2020, there were over 440 000 natural gas-based heated dwellings in Vienna, Austria (48.5 % of the total building stock) [41]. Nevertheless, this case study is representative for the European building stock in densely populated areas, as similar proportions of natural gas heating systems exist in the heating sector there as well[3].

It is assumed that the multi-apartment building (incl. all dwellings) are privately owned by the landlord. The number of dwellings is 30, whereby the area and rent price for each is equal. Each dwelling is rented by a tenant and heated by a individual natural gas-based heating system. The decarbonization of the heating systems can be realized by two different options, namely, a connection

[3]For example, there are more than 600 000 natural gas-based heat dwellings in Berlin, Germany in 2020 [42].

to the district heating network and a installation of a air-sourced heat pump[4]. It is assumed, that only of the two options is realized for all the dwellings. We refer to the empirical scaling and data in Section 3.3.3 for a detailed quantitative description of the multi-apartment building.

3.3.2. Scenarios

Four different quantitative scenarios are studied in this work. Three of them are developed in the Horizon 2020 research project openENTRANCE (`https://openentrance.eu/`) and describe a future European energy system development under achieving the 1.5 °C or 2.0 °C climate target. These scenarios are called *Directed Transition*, *Societal Commitment*, and *Gradual Development* scenario[5]. The first two scenarios consider the remaining CO_2 budget of the 1.5 °C climate target. Below, we qualitatively describe the three openENTRANCE scenarios used in this work and refer for further information to the studies in [43] and [44]. For the reader with a particular interest in the openENTRANCE scenarios, we refer to the work in [45], in which the underlying storylines outlining the narrative frames of the quantitative scenarios can be found.

The *Directed Transition* (DT) scenarios leads to limiting the global temperature increase well below 1.5 °C. This is achieved by a breakthrough of new sustainable technologies triggered through strong policy incentives. The markets themselves do not push this development and only deliver insufficient financial impulse for the clean energy transition. Besides, society is also too passive in supporting the penetration of renewable energy sources. Thus, it is assumed that multi-apartment building is connected to the district heating network. The CO2 price is between 196 EUR/tCO_2 (in 2025) and 680 EUR/tCO_2 (in 2040). Deep decarbonization of the European electricity and heating sector is achieved in 2040.

[4]In general, it is assumed that the heat pump can be installed in the basement of the building. Nevertheless, the installation on the rooftop may also be considered. However, this explicit distinction is out of the scope of this paper and is not further examined.
[5]The openENTRANCE scenario *Techno-Friendly* is not part of this work.

The *Societal Commitment* (SC) scenario also leads to limiting the global temperature increase well below 1.5 °C. In contrast to the previous scenario, decentralization of the energy system and participatory as well as societal acceptance of energy transition pushes the sustainable development. In addition, currently existing technologies significantly driven by policy incentives contribute to a decarbonized energy system since no fundamental breakthroughs of new clean technologies are in sight. Therefore, the multi-apartment building implements an air-source heat pump as sustainable heating system alternative. The CO2 price in this scenario is between 62 EUR/tCO_2 (in 2025) and 497 EUR/tCO_2 (in 2040). Deep decarbonization of the European electricity and heating sector is achieved in 2040.

The *Gradual Development* (GD) scenario reaches a global temperature increase of 2.0 °C and the corresponding climate target. In general, it is a very conservative expression of an European energy system future. This scenario includes a little of each sustainable development consisting of limited policy incentives, social acceptance, and technological advances. Both heating system alternatives (district heating connection and air-sourced heat pump installation) are examined. The CO2 price in this scenario is between 83 EUR/tCO_2 (in 2025) and 261 EUR/tCO_2 (in 2040). Deep decarbonization of the European electricity and heating sector is achieved in 2050.

In addition to the three openENTRANCE scenarios, the so-called "Low CO_2 price development" (LP) scenario is examined. This scenario neglects any remaining European CO_2 budget and misses both the 1.5 °C and 2.0 °C climate target. Thus, decarbonizing the electricity and heating sector develops only sluggishly. Therefore, neither the CO_2 price nor the specific emissions of electricity and district heating significantly significantly changed compared to today's values. Again, both heating system alternatives are studied. The CO2 price in this scenario is between 60 EUR/tCO_2 (in 2025) and 90 EUR/tCO_2 (in 2040). No target year achieving deep decarbonization of the European electricity and heating sector is set.

Scenario	Climat target	Heat pump (HP)	District heating (DH)
Directed Transition (DT)	1.5 C	-	✓
Societal Commitment (SC)	1.5 C	✓	-
Gradual Development (GD)	2.0 C	✓	✓
Low CO_2 price (LP)	none	✓	✓

Table 1: Four different scenarios are studied, including three ambitious deep decarbonization scenarios, developed in the Horizon 2020 project openENTRANCE and a low CO_2 price development scenario. The scenario specific heating system alternative is marked by the check.

Table 1 summarizes the scenarios and the corresponding heating system alternative implemented.

3.3.3. Empircial settings

Table 2 contains the empirical settings of the multi-apartment building including the agent's specific interest rates and further economic parameters.

Variable	Unit	Value
Number of tenants	-	30
Governance's interest rate	%	3
Landlord's interest rate	%	10
Tenant's interest rate	%	5
Heat demand (per dwelling)	kWh	8620
Peak heat demand (per dwelling)	kW	5
Heat pump|Investment costs	EUR/kW	1000
Heat pump|Construction costs (per dwelling)	EUR	1000
District heating|Investment costs	EUR/kW	320
District heating|Construction costs (per dwelling)	EUR	2000
Initial rent price	EUR/m^2	10
Maximum rent charge adjustment (ρ)	%	10
Rented area (per dwelling)	m^2	60

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

Table 3 contains the data with a temporal development (e.g., CO_2 price, specific emissions of the district heating supply, etc.).

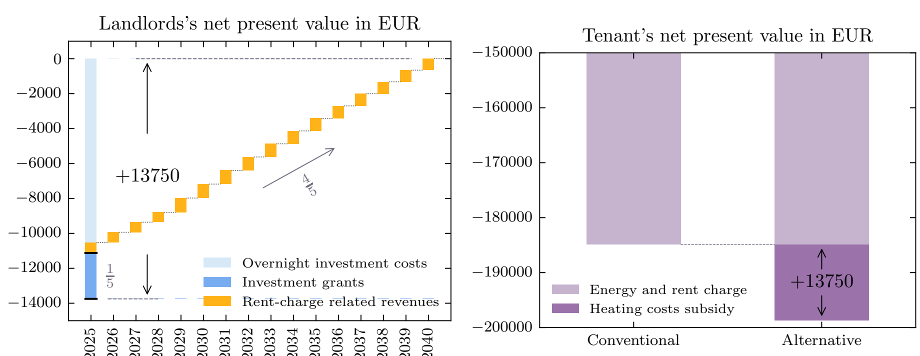
Scenario	Variable	Unit	2020	2025 − 30	2030 − 35	2035 − 40
DT	CO_2 price	EUR/tCO_2	30	196	357	510
SC	CO_2 price	EUR/tCO_2	30	62	137	273
GD	CO_2 price	EUR/tCO_2	30	83	128	183
LP	CO_2 price	EUR/tCO_2	30	60	70	80

Table 3: Empirical settings of the data with a temporal development between 2020 and 2040

Further empirical settings can be found in Appendix A.

3.4. Validation of the model

This section aims to test the presented model and its functionalities. However, a model validation using existing empirical data can not be applied in this case. There is simply a lack of comparable data from real cases. Therefore, a small illustrative case study is chosen to demonstrate the main functionalities and to verify the model. We assume a single landlord and tenant in a representative single-family household implementing a heat pump. It is assumed that the landlord's and tenant's interest rate is equal (3 %). A detailed description of the empirical settings can be found in Appendix B. Figure 2 shows the landlord's (a) and tenant's (b) net present value.



(a) Development of landlord's net present value

(b) Comparison of tenant's net present value

Figure 2: Landlord's and tenant's net present value and equal financial support. The landlord reaches a net present value equal to zero in 2040 resulting from an investment grant and rent-charge related revenues. The tenant's net present value remains constant compared to the conventional heating system resulting from heating costs subsidy payments.

Both agents receive equal financial support with a total of 13 750 EUR. One finfth of the landlord's support is paid as an investment grant and four-fifths as rent-charge related revenues. The tenant receives a heating costs subsidy. The level of financial support results exactly in (i) a landlord's net present value equal to zero within the time horizon of 15 years (see Figure 2a) and (ii) a constant remaining net present value of tenant compared to the conventional (existing) heating system (including the initial rent charge) (see Figure 2b).

3.5. Open-source programming environment and data format

The developed optimization model is implemented in Python using the modeling framework Pyomo [46]. 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 (IAMC) using the open-source Python package pyam [47]. Note that all materials used in this study are disclosed as part of the publication at GitHub [6]. We refer to the repository for the codebase, data collection, and further information.

4. Results and discussion

5. Sensitivity analysis

6. Conclusions and recommendations

sozial ausgewogenen bedeutet hier, dass kosten für den mieter dürfen nicht stark ansteigen investitionsförderung und dem mieter erlauben höhere mieten zu verlangen aufgrund von renewable enery systems
viel mehr muss der staat hier geld in die hand nehmen um profitability sicherzustellen
Socially-balanced heating system transition in urban areas (landlords and tenants) hilft uns CO2 nicht als Trigger anders als in übrigen analysen

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

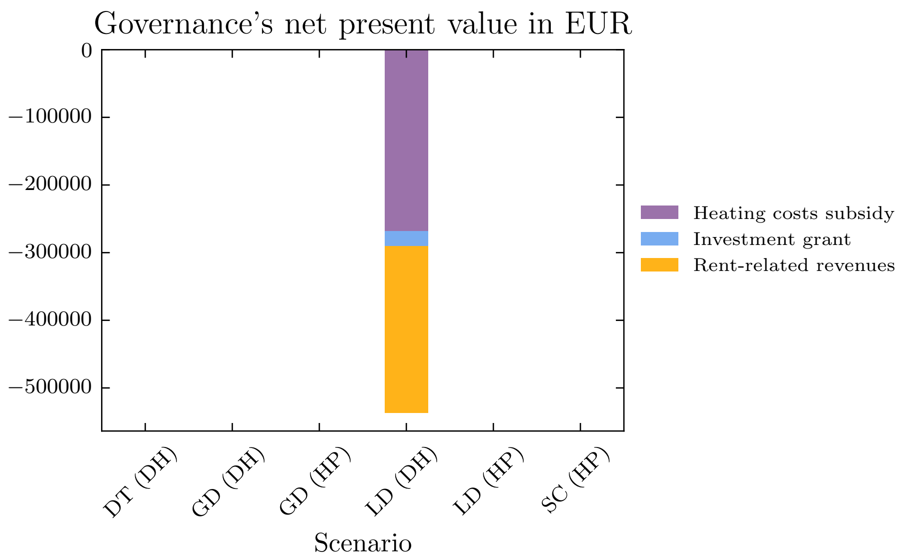


Figure 3

co2 nur als trigger wenn man die kosten auf des co2 preises auf beide akteure aufteilt und nicht nur auf den mieter packt, dann kann co2 preis trigger sein, dass hat die sensitivität analyse gezeigt
zeigt, dass wir uns nicht nur alleine auf den co2 verlassen dürfen, im wärmesektor muss geld in die hand genommen werden.
Future work: investment grants depend on buidling renovation

Declaration of interests

None.

Declaration of Competing Interest

The authors report no declarations of interest.

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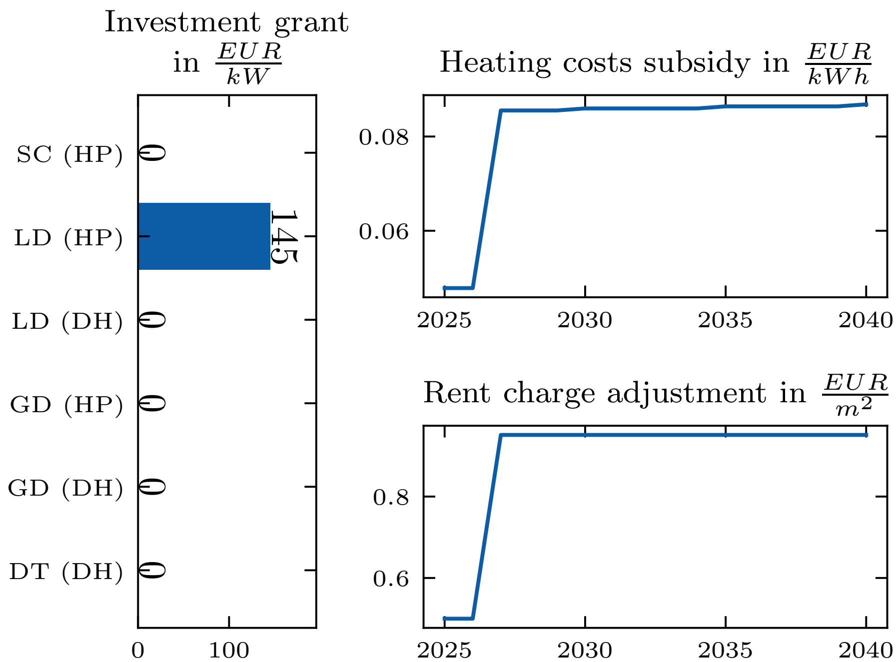

Figure 4

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Appendix A. Data

Variable	Unit	Value
Specific emissions|Electricity	$kgCO_2/kWh$	0.130
Specific emissions|District heating	$kgCO_2/kWh$	0.130
Specific emissions|Natural gas	$kgCO_2/kWh$	0.220
Price|District heating	EUR/kWh	0.047
Price|Natural gas	EUR/kWh	0.05
Price|Electricity	EUR/kWh	0.2
Coefficient of performance (heat pump)	1	3

Table A.1: 2020's economic parameters and empirical settings

Appendix B. Empirical settings of the small case example

Variable	Unit	Value
Heat pump investment costs	EUR/kW	1000
Construction costs	EUR	1000
Initial rent price	EUR/m^2	10
Rented area	m^2	100
Total heat demand	kWh	22 000
Peak heat demand	kW	13
CO_2 price (2025-2034)	EUR/tCO_2	50
CO_2 price (2035-2040)	EUR/tCO_2	100
Natural gas price	EUR/kWh	0.05
Electricty price	EUR/kWh	0.2
Specific emissions|Electricity	kgCO_2/kWh	0.130

Table B.2: Small case example's parameters