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

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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

- Green deal: climate neutrality in Europe until 2050
- Fit for 55: measures until 2030 ensuring a CO_2 reduction of at least 55 %
- Fair and sustainable future for all citizens (leaving no one left behind)
- Special initial conditions in the heating sector: (i) high shares of fossil fuels, and (ii) ownership structure in urban areas
- Natural gas face out

- Renewable energy: historical development of PV systems: investment grants and feed-in tariffs

Against this background $\cdots$

How much subsidy should solar energy receive? [1]

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

- Wir fokussieren in unserer Literaturübersicht auf drei wesentliche Aspekte ohne dabei Anspruch auf Vollständigkeit zu erheben. Focus here on renewable technologies in the heating sector
- (1) Wie kann aus Sicht einer Systemanalyse die Dekarbonisierung des Wärmesektors umgesetzt werden. Welche erneuerbaren Energie spielen dabei eine wesentliche Rolle
- (2) Wie kann socially-balance erreicht werden im Zusammenhang mit der Penetration von erneuerbaren Energien
- (3) Wie kann die Investition wirtschaftlich attratktiv gestaltet werden, Instrumente und welche Barrieren: Trade-offs between overnight investments and net present value decisions
- (4) explizit nicht Teil der Literaturübersicht ist: energy communities, sharing renewable energy generation, electricity battery storage, willingness to pay, etc. nur kurz bei justice chapter

Fehlt noch etwas explizit zu erwähnen, was nicht behandelt wird?

2.1. Decarbonizing the provision of heating service needs

- Large-scale decarbonization roadmap of the heating sector - "Was ist das große ganze"
- Renewable energy heating and cooling - "Welche Quellen haben wir grundsätzlich"
- Geograpical characteristics - "Nicht jede Lösung ist überall optimal"
- Case study analyses: Fernwärme in urban areas aber wenn nicht vorhanden dann Wärmepumpen
- Fernwärme review paper
- Bei Fernwärme und insbesondere Wärmepumpen müssen wir über Effizienz reden - "Gebäudestandards"

- "Retroffitting absatz in Bezug auf Heizsystem"
- "Muss gemacht werden aber oft nicht wirtschaftlich ohne finanziellen Anreize (verweis auf nächstes und übernächstes Kapitel)"

Ist hier ein roter Faden erkennbar?

Connolly et al. (2014) [2] A new heat strategy based on district heating and individual heat pumps is designed for the EU27.
Seyboth et al. (2008) [3] analyse current policies and experiences and makes recommendations to support enhanced market deployment of REHC technologies to provide greater energy supply security and climate change mitigation.solar, geothermal and biomass resources.
Su et al. (2018) [4] geographische Eigenschaften sehr wichtig, beim der Wahl der optimale Lösung für das Heizsystem, district heating für urban areas. Deswegen gibt es eine vielzahl von lokalen Studien, die für einen bestimmten Ort/Charakteristic die optimale Lösung bestimmt.
Popovski et al. (2018) [5] From a socio-economic perspective, DHC with excess heat is the most feasible solution Heat pumps with photovoltaics are cost-competitive from a socio-economic perspective. Policies are required to support RES from a private-economic perspective.
Lake et al. (2017) [6] Review of district heating and cooling systems for a sustainable future, economic feasibility, system identification based on primary energy sources, including the deployment of more and more renewable energy streams. Leibowicz et al. [7]: Consider scenarios including carbon policy and building thermal efficiency improvement. Optimal strategy features end-use electrification and power sector decarbonization. Building thermal efficiency improvements lower the cost of reducing carbon emissions.

- Ma et al. (2012) [8] retrofitting of existing buildings
- Vieites et al. (2015) [9] European Initiatives Towards Improving the Energy Efficiency in Existing and old (historic) Buildings
- Weinberger et al. (2021) [10] Welche Auswirkungen hat es auf das Heizsystem - hier speziell auf District heating

- Fina et al. (2019) [11] Profitability of active retrofitting of multi-apartment buildings: Building-attached/integrated photovoltaics with special consideration of different heating systems, energy cost reductions achieved by better building quality cannot compensate for the initial renovation costs (passive retrofitting). hängt sehr stark von dem CO2 Preis ab und welche Investitionsförderung angenommen ist, subsidies sind nicht angenommen hier.

Rama et al. (2018) [12] combination of different sustainable heating alternatives. In particular, wie Wärmepumpen und Solarthermie Fernwärme assistieren können und hier speziell wenn Gas in die Fernwärme einspeist.
Exploring policy options for a transition to sustainable heating system diffusion using an agent-based simulation The present paper aims to identify potential interventions for the uptake of wood-pellet heating in Norway using an agent-based model (ABM). stable financial support, i.e., a stable wood-pellet price [13]

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

- 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
- 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

- 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 [14] 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) [15] 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 [16]
We examine two local energy transitions from an energy justice perspective [17] show that energy justice and transitions frameworks can be combined [18]
Recently 2021, do renewable energy communities deliver energy justice? Exploring insights from 71 European cases [19]

- "We aim to show how when low-carbon transitions unfold, deeper injustices related to equity, distribution, and fairness invariably arise" [20]

- 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. ([21])

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 [22]
low-income haben auch höheren residential heating energy use intensity, an energy efficiency proxy [23]

"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 [24]

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

- 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) [25] 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) [26] finanzielle Anreize sind der Hauptgrund warum erneuerbare Energien nicht stärker umgesetzt werden.
- Reuter et al. (2012) [27] allgemeinen überblick welche öffentlichen Anreize für Investitionen in erneuerbare Energie
- Zhou et al. (2011) [28] effizienz einer Maßnahme nach dem notwendigen Maß an Eingriff
- Couture et al. (2010) [29]: 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) [30] 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) [31] Wir brauchen private Investitionen in erneuerbare Energien
- Eitan et al. (2019) [32] Review, Beschreibt das so-called "phenomenon" of community and private sector renewable energy partnerships
- Aslani et al. (2012) [33] 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) [34] Effekte des Staates auf private Investitionen in erneuerbare Energien. Wieder Strom
- Schmidt et al. (2013) [35] Selbst wenn der Wärmesektor untersucht wird, geht es oftmals um elektrifizierung
- Williams et al. (2015) [36] Barrieren für Teilnahme des privaten Sektors an dezentraler Elektrifizierungsprojekten

- Ostergaard et al. [37] Investments in heating systems are attractive from an energy system perspective, Customer investments in heating systems should be motivated economically.
- Nageli et al. (2020) [38] 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

- heating system change and sustainable heat supply takes place
- analytical and modeling framework; justice; qualitative analysis
- Trade-off analysis between governance, landlords, and tenants $\longrightarrow$ 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.

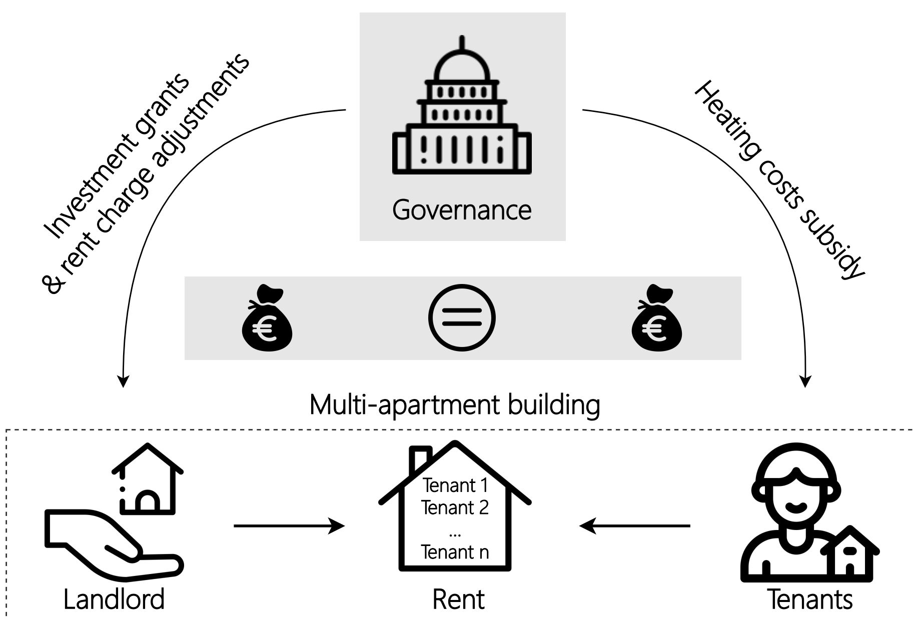


Figure 1: Sketch of the model illustrating the iterrelations between the governance, landlord, and tenants. Financial support from the governance is socially balanced at the multi-apartment building.

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) [39]. 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 [40].

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 [41] and [42]. For the reader with a particular interest in the openENTRANCE scenarios, we refer to the work in [43], 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.).

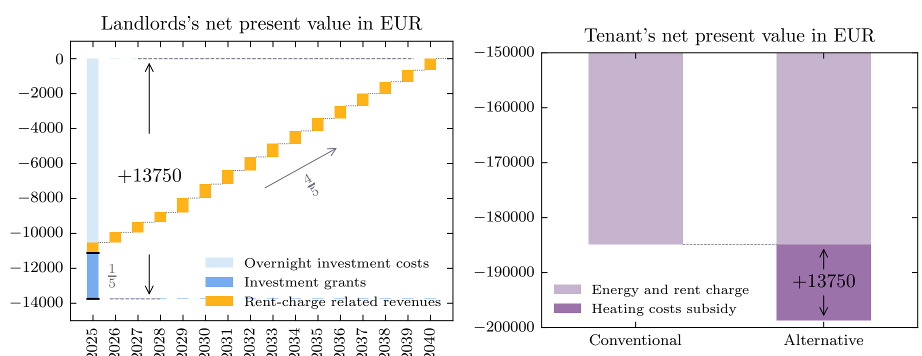
Scenario	Variable	Unit	2020	2025 − 30	2030 − 35	2035 − 40
DT	CO_2 price	EUR/tCO_2	30	196	357	510
SC	CO_2 price	EUR/tCO_2	30	62	137	273
GD	CO_2 price	EUR/tCO_2	30	83	128	183
LP	CO_2 price	EUR/tCO_2	30	60	70	80

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 [44]. 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 [45]. 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

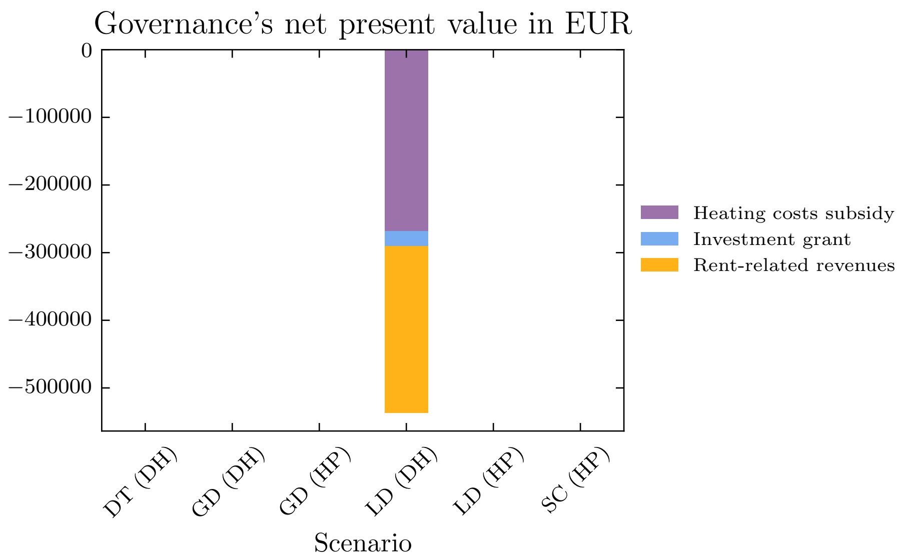


Figure 3

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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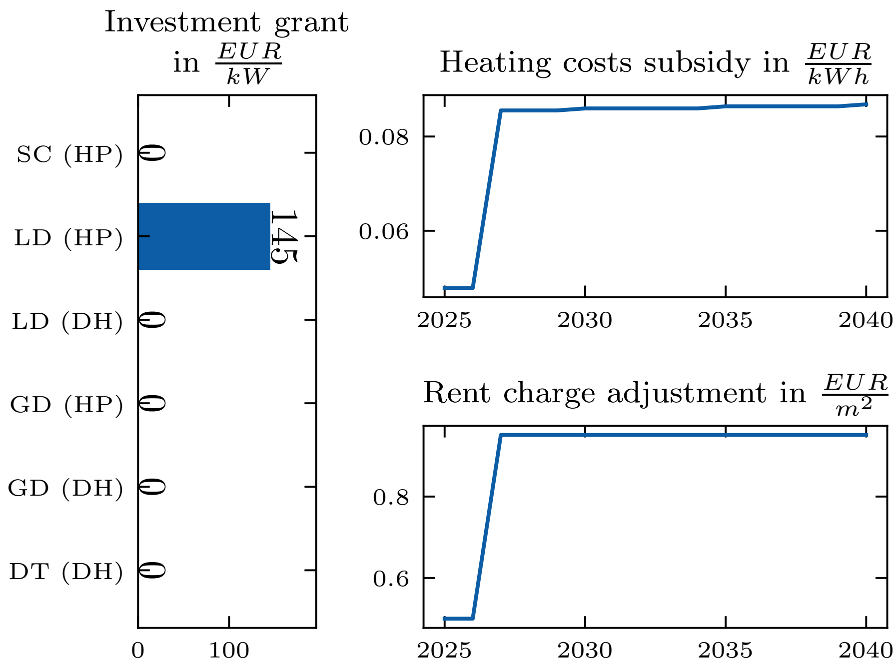

Figure 4

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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