Cost-optimal and socially balanced subsidization strategy incentivizing a just heating system decarbonization at the building level

Sebastian Zwickl-Bernhard[a,*], Hans Auer[a], Antonia Golab[a]

[a] *Energy Economics Group (EEG), Technische Universität Wien, Gusshausstrasse 25-29/E370-3, 1040 Wien, Austria*

Abstract

Keywords:

[*] Corresponding author
Email address: zwickl@eeg.tuwien.ac.at (Sebastian Zwickl-Bernhard)

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		
Ψ	Investment grant paid to the landlord	EUR
$\Omega_{y,m}$	Heating costs subsidy payment for a single tenant in y and m	EUR
$d_{y,m}$	Total heat demand per dwelling	kWh
$q_{y,m}$	Heat demand supplied by the heating system alternative	kWh
π	Newly installed heating system alternative capacity	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	%
$q_{load,y,m}$	Total heat demand in y and m	kWh
α_m	Monthly load factor (ratio between total and peak heat demand) in m	1
c_{alt}	Specific heating system alternative investment costs	EUR/kW
c_{con}	Heating system alternative construction costs	EUR
$\bar{r}$	Initial rent price	EUR/m^2
ρ	Upper bound of the biannual rent charge adjustment	%
a	Rented area per tenant/dwelling	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. Also the authors' literature review of this paper in [4] provides a comprehensive review of energy sharing on the local level.

Against this background, the focus here lies on three different dimensions without claiming to be absolutely complete in each case. The first dimension is the decarbonization of heating and cooling systems from a system analysis perspective and is described in Section 2.1. The second dimension deals with the increasingly importance of justice in the energy system transition and is presented in Section 2.2. The third dimension 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. [5] 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. [6] 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 (e.g., availability of heat network infrastructure, building construction features, outdoor temperature, etc.), in particular, play a crucial role. Su et al. [7] 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. [8]. 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. [9] 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. [10] 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. [11] 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., [10] and [11]) and/or because to compensate non-existing networks in the future. Popovski et al. [8] 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. [12] 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 [13]. Ma et al. [14] provide an extensive literature and state-of-the-art analysis of retrofitting focusing on existing buildings. Vieites et al. [15] elaborate in this context of European initiatives improving the energy efficiency in existing and old (historic) buildings. Recently, Weinberger et al. [16] investigate the impact of retrofitting on district heating networks. Fina et al. [13] 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

The issue of justice in energy systems is addressed in various studies. According to them, a key part of achieving climate targets is to ensure that no one is left behind in the climate action. More generally, the three energy justice tenets are distributive, recognition, and procedural[1]. Recently, these are comprehensively discussed and reviewed by Pellegrini et al. [18]. Considering this work's scope, we put our focus on procedural justice, as it represents measures that reduce potential barriers to new clean energy investments [17].

Generally speaking, dealing with just sustainable energy systems is a monumental task and seems to be very challenging to be generalized. However, studies focusing on certain local regions are likely to be the most promising approach. Recently, van Bommel and Höffken conducted a review study focusing on energy justice at the European community level [19]. Besides that, Lacey-Barnacle et al. [20] focus in their study on energy justice in developing countries. Coming back to this paper's content and spatial scope, Mundaca et al. [21] propose two local European case studies in Germany and Denmark investigating local energy transition from an energy justice perspective. Their findings are in line with those from Jenkins et al. [22] showing that energy justice and transitions framework can be combined and achieved simultaneously. However, Hiteva and Soacool [23] conclude from a business model perspective that energy justice

[1] In some works, restorative and cosmopolitan justice are also mentioned in this context. See, exemplarily in [17].

may be realized through market principles but not through the market alone. We continue discussing this point in Section 2.3 when dealing with necessary (financial) incentives that foster the sustainable energy transition.

Recently, Hanke et al. [24] investigate renewable energy communities and their capability to deliver energy justice. They explore insights from 71 European cases and highlight the necessity of distributing affordable energy to vulnerable households. Furthermore, it is necessary to focus in this regard on low-income households. Exemplarily, Xu and Chen [25] propose on the basis of their generated 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 fewer energy efficiency appliances. Sovacool et al. [26] heat in the same direction and discuss the special difficulties for households without the capital for sustainable energy investments and for those that do not own their own home such as renters. Moreover, renters also often have higher residential heating energy use intensity, an energy efficiency proxy [27]. In this context, Greene [28] discussed the so-called "efficiency gap" or "energy paradox". He showed that consumers have a bias leading 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 the energy transition and energy justice. Sovacool et al. [29] show that unfolding the energy transition result in deeper injustices investigating four different low-carbon transitions.

2.3. Overnight investments versus net present value

In particular, this concluding section is about looking at different renewable energy promotion instruments focusing on 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 parallels and differences between the two sectors through comparison. Connor et al. [30] provide a fundamental review paper investigating a wide range of policy options that can support the deployment of renewable heat technologies. Masini and Menichetti [31] 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 financing investment incentives. Public (financial) incentives are often seen as the most appropriate and efficient measures to fill this gap. Reuter et al. [32] compare different policy instruments, ranging from feed-in tariffs to investment subsidies, tax credits, portfolio requirements, and certificate systems. While focusing on companies and their willingness for renewable energy technology investments in the electricity sector, they conclude that feed-in tariffs are an effective means promoting these investments[2]. Similar results also can be found in the study from Couture and Gagnon [34]. Nevertheless, the two latter studies only investigate the deployment of renewable energy technologies in the electricity sector and not in the heating sector.

Building on these literature findings, however, it is of particular importance to differentiate between renewable energy technology investments from companies and private end-customers and households. In contrast to companies, private households are incentivized more effectively by investment grants to invest in renewable energy technologies [35]. This distinction and targeted adjustment of public financial incentives are important since private investment is a key driver of the diffusion of renewable energy technologies [36]. Østergaard et al. [37] investigate the investment costs of households to prepare existing buildings for high-efficient and sustainable heating systems. Their results show that customer investments require financial incentives and are required to be motivated eco-

[2]Zhou et al. [33] provide a study dealing with the effectiveness of public financial incentives. The authors define effectiveness/efficiency as the amount of intervention (e.g., taxes collected, subsidies paid, etc.) to achieve a policy goal. Here, it is essentially the electricity sector that is being studied.

nomically[3]. In this context, the role of an increasing CO_2 price should also be interpreted with particular circumspection. Although, in general, the literature sees carbon pricing as the most important measure speeding up the sustainable energy system transition (see, for example, Nägeli et al. [38] focusing on the impact of carbon pricing on the residential building sector). However, this does not solve the inherent problem of differential ownership in the residential sector (i.e., landlords and tenants/renters). It is, therefore, only logical that Hecher et al. [39] focus in their work on the decision-making processes regarding sustainable heating system investments of homeowners. Therefore, there is a gap in the literature dedicated precisely to a heating system change in the residential sector, not neglecting the different ownerships.

We conclude this section with the topic of energy and heat contracting business models and explicitly aim to give only a small overview, as contracting business models themselves are not part of the paper's main scope. A comparative review of municipal energy business models in different countries is given by Brinker and Satchwell [40]. Kindström and Ottosson [41] analyze local and regional energy companies offering energy services and conclude that most many of these are experiencing difficulties on the market. One reason is, as Fine et al. state, that the contracting framework itself decreases the economic viability since the contractor business companies (third party) aim to gain profit (i.e., contractor's interest rate). Suhonen and Okkonen [42] conduct an analysis of energy service companies in the residential heating sector and show a wide-ranging set of barriers of such business models. Moreover, the results of their Finnish case study reveal that this kind of contracting business model is unattractive and not profitable. Brown [43] investigates business models for residential retrofit in

[3] In particular, Østergaard et al. [37] 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.

the United Kingdom and the European Union. Fina et al. [44] study the profitability of contracting business cases for shared photovoltaic generation and renovation measures in a residential multi-apartment building. Their results indicate that the profitability of (passive) building renovation measures significantly depends on the carbon price. However, the difficulties of high carbon prices are already addressed above and in the novelties of this work in the next section. Furthermore, Fina et al. focus explicitly in their study on building owners and neglect different ownership relationships.

2.4. Progress beyond state-of-the-art

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

- A sustainable heating system change with a focus on the efficient provision of heat service needs at the multi-apartment building is carried out, emphasizing the ownership structure of the building and related financial interests of the building owner and the different tenants/renters. In particular, this addresses one of the hot potatoes of deep decarbonization strategies, namely, the residential heating sector with tenants who cannot change the heating system on their own due to missing ownership, and therefore extra attention need. The sustainable heating system alternative is financially incentivized by a federal subsidy strategy considering monetary justice between the landlord and the tenants.

- The developed analytical framework determines a cost-optimal and socially balanced subsidization strategy from the governance incentivzing a just heating system decarbonization at the building level. Especially, the optimization model allows a quantitative analysis of justice in low-carbon residential heating sector including the agent's specific monetary interests and the ownership structure within a building. Thus, this work focus on the trade-off analysis between the governance, landlord and tenants.

- The sensitivity analysis of sharing carbon-related energy costs between the building owner and tenants on the one hand, and linking the governance's strategy directly to building retrofitting measures, on the other hand, represent substantial innovations in the field of research for decarbonizing the existing building stock with landlord and tenants relations. The obtained insights can help build a more reliable understanding of decarbonizing the existing (rented) building stock. Even more, this work may contribute to rapidly increasing the renovation rate, often seen as a key for a high-efficient and decarbonized residential sector.

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.

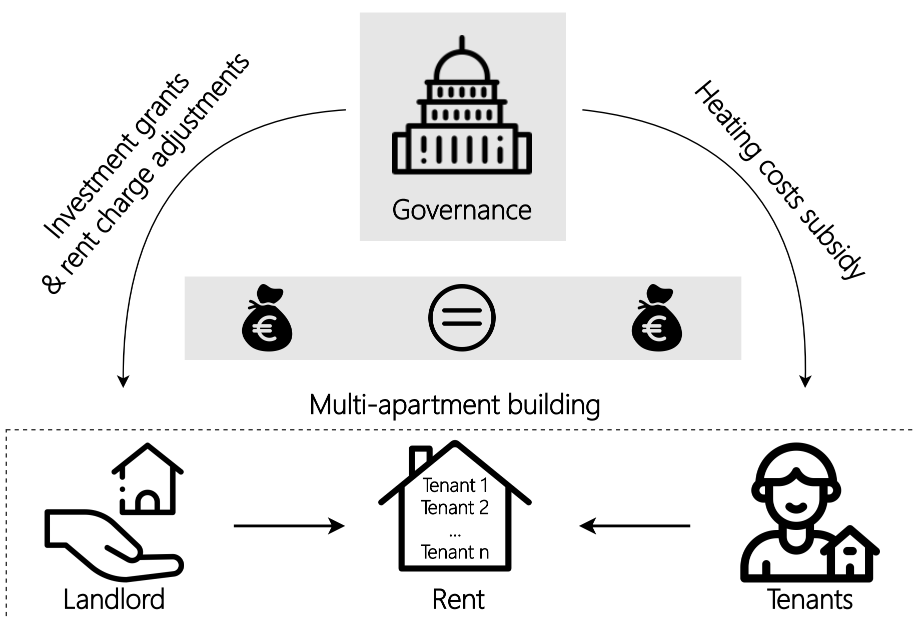


Figure 1: Sketch of the model illustrating the iterrelations between the governance, landlord, and tenants. Financial support from the governance is socially balanced at the multi-apartment building.

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[4]. 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 to the 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[5] 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

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

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

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) [45]. 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[6].

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

[6]For example, there are more than 600 000 natural gas-based heat dwellings in Berlin, Germany in 2020 [46].

to the district heating network and a installation of a air-sourced heat pump[7]. 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[8]. 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 [47] and [48]. For the reader with a particular interest in the openENTRANCE scenarios, we refer to the work in [49], 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.

[7]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.
[8]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.).

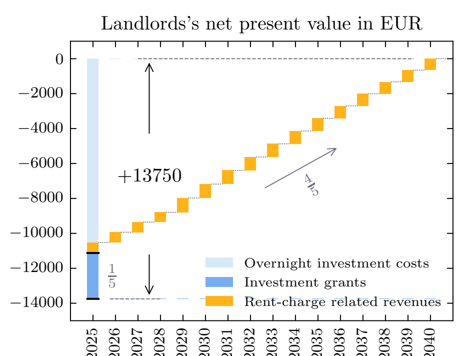
Scenario	Variable	Unit	2020	2025 − 30	2030 − 35	2035 − 40
DT	CO_2 price	EUR/tCO_2	30	196	357	510
SC	CO_2 price	EUR/tCO_2	30	62	137	273
GD	CO_2 price	EUR/tCO_2	30	83	128	183
LP	CO_2 price	EUR/tCO_2	30	60	70	80

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

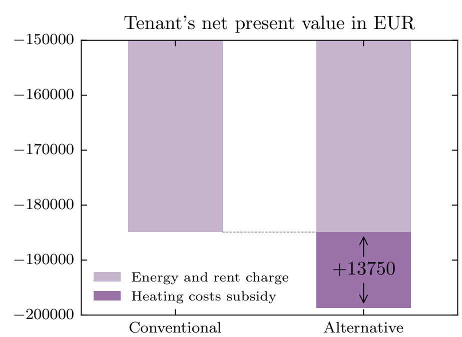
Further empirical settings can be found in Appendix A.

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 [50]. 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 [51]. Note that all materials used in this study are disclosed as part of the publication at GitHub [9]. 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

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

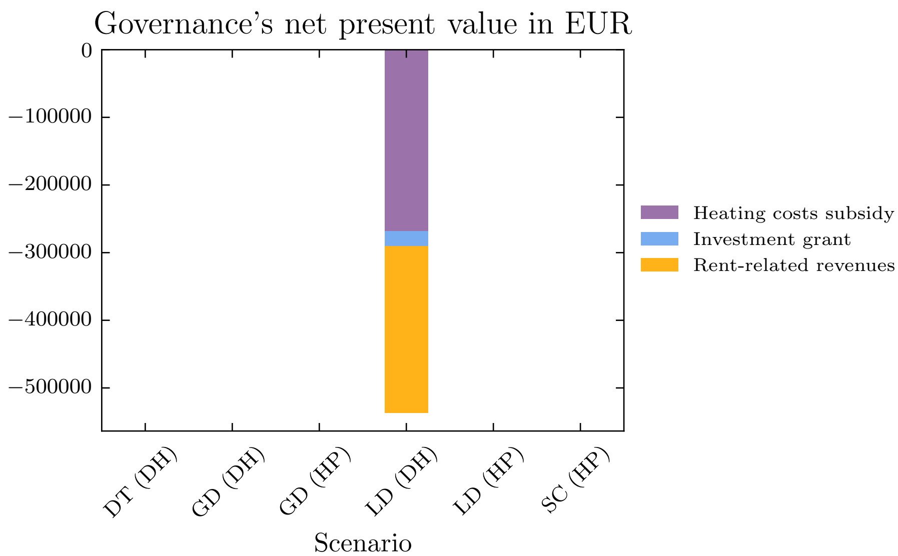


Figure 3

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 These insights will help engineers and policy-makers to decarbonise domestic heat using heat pumps.

Declaration of interests

None.

Declaration of Competing Interest

The authors report no declarations of interest.

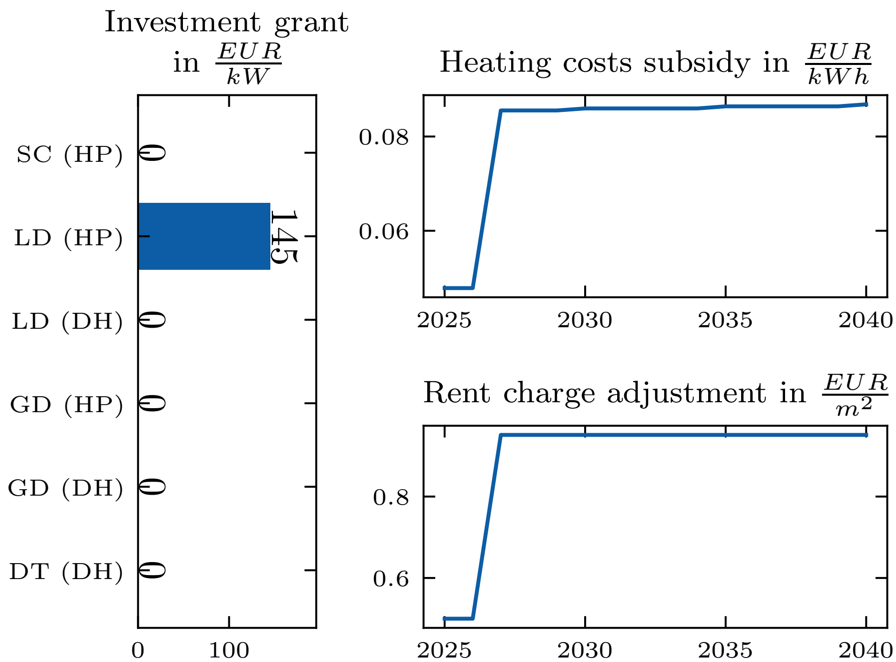


Figure 4

Acknowledgments

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 835896. The authors acknowledge TU Wien Bibliothek for financial support through its Open Access Funding Programme.

References

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

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

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

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

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

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

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

[8] E. Popovski, T. Fleiter, H. Santos, V. Leal, E. O. Fernandes, Technical and economic feasibility of sustainable heating and cooling supply options in southern european municipalities-a case study for matosinhos, portugal,

Energy 153 (2018) 311–323. doi:https://doi.org/10.1016/j.energy.2018.04.036.

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

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

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

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

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

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

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

[16] G. Weinberger, S. Amiri, B. Moshfegh, Investigating techno-economic effects and environmental impacts of energy renovation of residential building clusters on a district heating system, Energy and Buildings 251 (2021) 111327. doi:https://doi.org/10.1016/j.enbuild.2021.111327.

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

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

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

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

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

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

[23] R. Hiteva, B. Sovacool, Harnessing social innovation for energy justice: A business model perspective, Energy Policy 107 (2017) 631–639. doi:https://doi.org/10.1016/j.enpol.2017.03.056.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

[38] C. Nägeli, M. Jakob, G. Catenazzi, Y. Ostermeyer, Policies to decarbonize the swiss residential building stock: An agent-based building stock model-

ing assessment, Energy Policy 146 (2020) 111814. doi:https://doi.org/10.1016/j.enpol.2020.111814.

[39] M. Hecher, S. Hatzl, C. Knoeri, A. Posch, The trigger matters: The decision-making process for heating systems in the residential building sector, Energy Policy 102 (2017) 288–306. doi:https://doi.org/10.1016/j.enpol.2016.12.004.

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

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

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

[43] D. Brown, Business models for residential retrofit in the uk: a critical assessment of five key archetypes, Energy Efficiency 11 (6) (2018) 1497–1517. doi:https://doi.org/10.1007/s12053-018-9629-5.

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

[45] Statistik Austria, Heizungen 2003 bis 2020 nach Bundesländern, verwendetem Energieträger und Art der Heizung, retrieved on

18.10.2021, https://www.statistik.at/web_de/statistiken/energie_umwelt_innovation_mobilitaet/energie_und_umwelt/energie/energieeinsatz_der_haushalte/index.html (2020).

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

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

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

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

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

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

Appendix A. 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