Dissertation

Towards carbon neutrality of energy systems: insights from modeling energy networks at the regional down to the building level

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by

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Abstract

The main objective of this dissertation is to comprehensively analyze selected aspects of phasing out the use of fossil natural gas in the course of decarbonizing energy systems. Four different scientific approaches that are based on optimization form the basis of this work, with a focus on energy network modeling. Three of these approaches focus on the development of a sustainable heat supply and offer insights into sustainable heat supply from the European level via the distribution networks to the end user or building level. In particular, not only district heating, its networks and the development of heat densities play an important role, but also the question of social justice and who has to bear the costs of inaction. The remaining approach deals with the trajectory of gas networks against the background of overall strongly declining transport volumes. The possibilities of decommissioning or refurbishment investments are discussed with regard to the aging of existing pipelines and the taboo of no longer supplying existing gas consumers with pipelines is critically questioned. Last but not least, it is shown that if an area-wide gas network is maintained, it will be necessary to socialize the network costs to the remaining gas customers. Overall, the four papers draw a clear picture from different perspectives of the tendency that the question of cost-efficient and sustainable energy supply in future energy systems will have to be answered not only at the sectoral level but also at the regional or local level.

Kurzfassung

Das Hauptziel dieser Dissertation ist die umfassende Analyse ausgewählter Aspekte des Ausstiegs aus der Nutzung von fossilem Erdgas im Zuge der Dekarbonisierung der Energiesysteme. Vier verschiedene wissenschaftliche Optimierungsansätze bilden die Grundlage dieser Arbeit, wobei der Schwerpunkt auf der Modellierung der Energienetze liegt. Drei dieser Ansätze konzentrieren sich auf die Entwicklung einer nachhaltigen Wärmeversorgung und bieten Einblicke in die gasfreie Wärmebereitstellung von der europäischen Ebene über die Verteilnetze bis hin zur Endkunden- bzw. Gebäudeebene. Insbesondere spielen dabei nicht nur die Themen Fernwärme, deren Netze und die Entwicklung der Wärmedichten eine wichtige Rolle, sondern auch die Frage der sozialen Gerechtigkeit und wer die Kosten des Nichthandelns zu tragen hat. Der verbleibende Ansatz befasst sich mit dem Entwicklungspfad der Gasnetze vor dem Hintergrund insgesamt stark rückläufiger Transportmengen. Dabei werden die Möglichkeiten von Stilllegungen oder Erneuerungsinvestitionen im Hinblick auf die Alterung bestehender Leitungen diskutiert und das Tabu, bestehende Gasverbraucher nicht mehr leitungsgebunden zu versorgen, kritisch hinterfragt. Nicht zuletzt wird aufgezeigt, dass bei Aufrechterhaltung eines flächendeckenden Gasnetzes eine Sozialisierung der Netzkosten auf die verbleibenden Kunden notwendig wird. Insgesamt zeichnen die vier Arbeiten aus unterschiedlichen Perspektiven ein klares Bild von der Tendenz, dass die Frage nach einer kosteneffizienten und nachhaltigen Energiebereitstellung in zukünftigen Energiesystemen nicht nur auf sektoraler, sondern auch auf regionaler bzw. lokaler Ebene zu beantworten sein wird.

Contents

1. Introduction

1.1. Motivation

By 2023, the transition from a predominantly fossil fuel-based energy system to a carbon-neutral one is well underway for some, while many others believe it is progressing too slowly or may be too late altogether (Rogelj et al., 2015). In particular, energy systems' dependence on fossil natural gas plays a significant role. In the European Union, for example, almost a quarter of the gross available energy is natural gas (Eurostat, 2023). Regardless of one's individual perspective, which may be influenced by personal optimism or pessimism, the scientific community agrees that despite the vast number of publications on the subject of climate-neutral energy systems, many questions remain unanswered (Pfenninger et al., 2014). In particular, this work aims to contribute to a better understanding of some of these unresolved issues associated with the face-out of natural gas, which is essential to achieve climate neutrality of energy systems, focusing on the heating of buildings.

Specifically, this thesis presents a comprehensive analysis of the impact of the phase-out of fossil natural gas on energy networks. It spans the bow from the distribution grid level down to the end-user investment decision. The focus is on modeling energy systems and networks at different spatial scales and from different perspectives, under scenarios that comply with climate neutrality by mid-century. Four cases of integrated energy system planning are examined. In addition to analyzing the impact of natural gas phase-out on heating systems and district heating networks at the energy system and building level, the study also examines the economic viability of gas distribution networks in the face of declining gas demand from the perspective of the network operator. Furthermore, the study analyzes also the changing needs of local distribution grids for electricity and district heating in a neighborhood once a gas-free heat supply is implemented. Figure 1.1 illustrates the focus of the thesis in three dimensions.

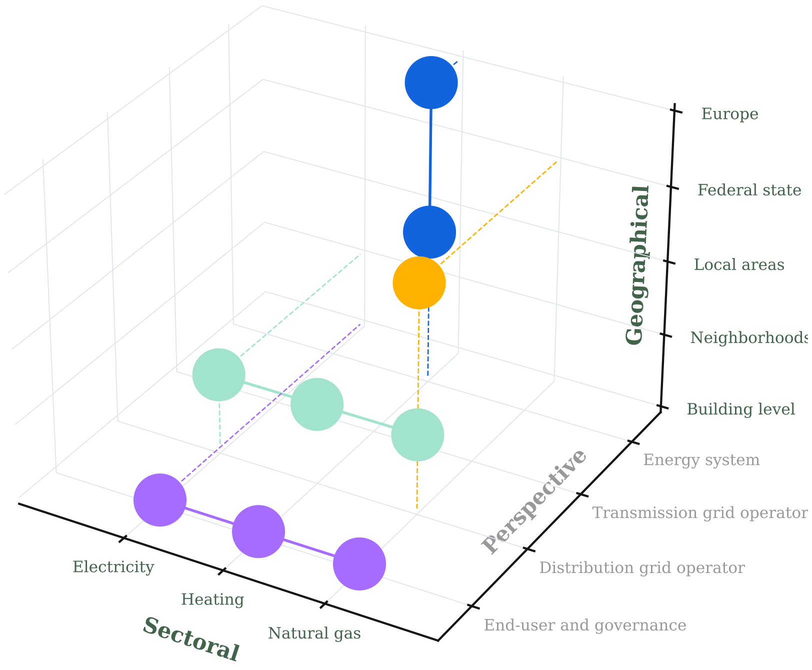

Figure 1.1.: Illustration of the scope of the thesis in three dimensions. Each of the four cases of the thesis is represented by a color and one or more spheres, indicating its scope in each dimension.

The first dimension is sectoral and has electricity, heating, and natural gas as elements. The second dimension is the perspective. It ranges from the perspective of the energy system to that of the end user. The third dimension is geographical. It ranges from the European down to the building level. Here is just one example to help understand the figure. One of the cases, as mentioned above, looks in detail at the heating sector from an energy system perspective. It uses downscaling to disaggregate values from the European to the local level to examine district heating networks in the context of decarbonizing the European energy system. This case is represented by the two blue spheres (at the top in Figure 1.1). As the main scope of the thesis is now given, the four cases, and in particular their underlying research questions, are described in more detail.

1.2. Research questions (RQ 1-4)

This thesis addresses four research questions about a natural gas face-out reaching carbon-neutral energy systems. Each research question is answered in a peer-reviewed article published by the author of this thesis as the main author. In the following, each research question along with a brief overview of its motivation and topic is presented.

The first contribution (Zwickl-Bernhard et al., 2022b) elaborates on the implications of the face-out of natural gas on the heating sector. In particular, it focuses on the role of district heating networks supplying low-temperature building heat demand (blue spheres in Figure 1.1). The first research question, defined from the energy system perspective, is as follows.

Research question 1: *What would a deep decarbonization of building heat demands in Austria by 2050 look like, and what are the implications of this sustainable energy mix for district heating?*

It bridges the gap between decarbonization plans/pathways at the European and country level with energy planning at the community and, thus, network levels. For this purpose, cost-effective heat supply of different European decarbonization scenarios generated by the aggregate large-scale energy system model GENeSYS-MOD (The Global Energy System Model)[1] from the na-

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[1] `https://git.tu-berlin.de/genesysmod/genesys-mod-public/-/releases/`

tional to the community level in Austria is downscaled. The main idea is to test whether or not large-scale energy system models (such as GENeSYS-MOD) are capable of covering local trends in district heating and its economic viability at the local levels and how locally determined district heating and heat densities could be returned into the aggregate models in the sense of a feedback loop. That would allow refining assumptions in the large-scale upper-level models, which in turn will increase the plausibility and realism of pathways at the European level.

The second contribution (Zwickl-Bernhard et al., forthcoming) deals with the future development and trajectory of gas networks and their infrastructure under the expectation of declining natural gas demands and the increasing integration of green gases, such as synthetic gas and hydrogen. The second research question, defined from the perspective of the gas network operator, is as follows.

Research question 2: *Which decommissioning and refurbishment investment decisions result in a cost-effective gas network infrastructure by 2050?*

The focus lies on gas network infrastructure that ensures the coverage of various energy service needs (e.g., residential building heat, industrial process heat). Associated with this is the question of which gas network infrastructure is needed to supply the non-substitutable natural gas demands under consideration of possible stand-alone natural gas supply options (delivery of liquified natural gas by truck, etc.). In this case, the gas network infrastructure of a federal state in Austria is modeled.

The third contribution (Zwickl-Bernhard and Auer, 2022) elaborates on deep decarbonization in an urban neighborhood in Vienna, Austria. The focus is on decommissioning the gas distribution grid for heat supply rather than trying to feed in "green" gas in the future. The third research question, defined from the perspective of the distribution network operator, is as follows.

Research question 3: *Which alternative distribution grid capacities and sector coupling technologies are required to ensure adequate, but sustainable*

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development in the provision of local heat energy services (e.g., space heating and hot water)?

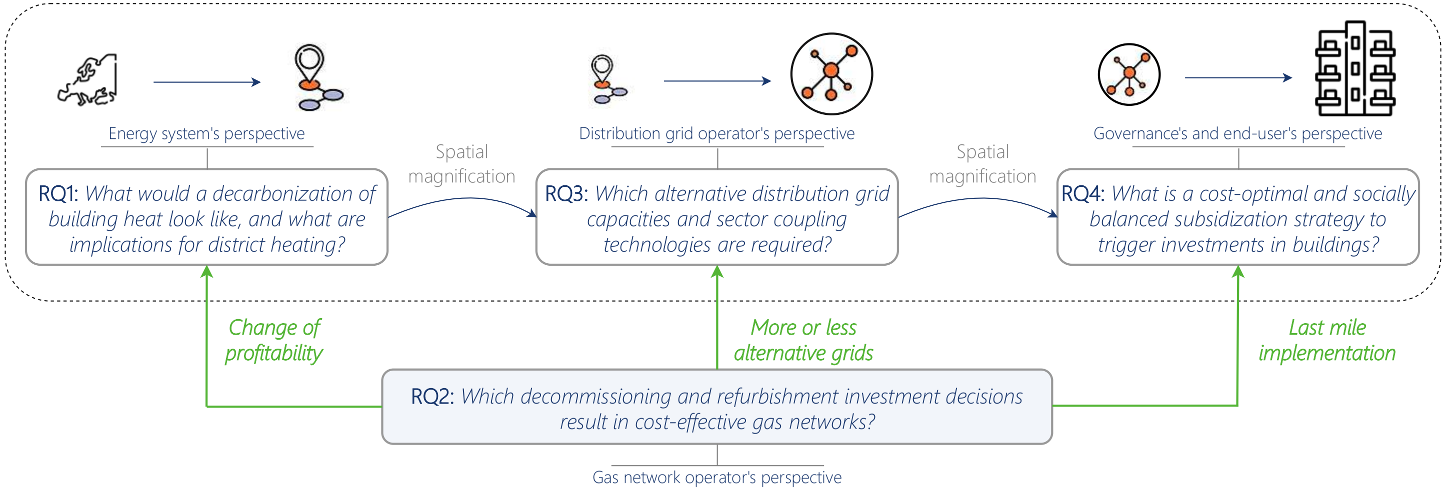
The core objective is to demonstrate that alternative network infrastructures and energy technologies ensure not only an adequate but also an even superior provision of local heat energy services.

The fourth and last contribution (Zwickl-Bernhard et al., 2022a) aims to demonstrate equitable decarbonization of heat supply in residential multi-apartment rental buildings. A modeling framework is developed to determine a socially balanced financial governance support strategy between the property owner and tenants to trigger a heating system change from a natural gas-based heating system towards a sustainable alternative. The fourth research question, defined from the governance's perspective, is as follows.

Research question 4: *What is a cost-optimal and socially balanced subsidization strategy for a multi-apartment building to trigger investments in a sustainable heat supply?*

The scope of this paper aims at exploring how to deal with one of the "hot potatoes" on the road to a sustainable society: to trigger investments for deep decarbonization of the rented residential building sector in terms of heating system change and passive retrofitting. The focus is put on multi-apartment buildings in urban areas that are often heated by natural gas-based heating systems. Moreover, the frequently occurring ownership structure within the building with a single property owner (building or at least apartment owner) and numerous tenants plays a key role in the analysis as this is a generally crucial relationship.

Figure 1.2 aims to illustrate the connection between the four distinct research questions. The figure builds on the three dimensions (sectoral, perspective, geographical) introduced in Figure 1.1. In principle, Figure 1.2 is divided into two parts. One part, at the top of the figure, shows the three research questions 1, 3, and 4 that focus on the heating sector in detail. The other part, at the bottom of the figure, relates to research question 2 which focuses on the natural gas in detail. The link between the three research questions



RQ1: *What would a decarbonization of building heat look like, and what are implications for district heating?*

RQ3: *Which alternative distribution grid capacities and sector coupling technologies are required?*

RQ4: *What is a cost-optimal and socially balanced subsidization strategy to trigger investments in buildings?*

RQ2: *Which decommissioning and refurbishment investment decisions result in cost-effective gas networks?*

Figure 1.2.: Graphic illustration of the four different research questions and how they relate to each other

of the heating sector is spatial magnification. It starts on the far left with research question 1 at the European and national level and ends on the far right at the building level. However, the link between these three is more than that. Research question 3 essentially takes the "where" (i.e. localization of district heating networks) of research question 1 and asks the "what" (i.e., what distribution grids in one district heating network). Research question 4 goes even one step further, essentially taking the "what" of research question 3, and asking "how" buildings implement sustainable heating. The link from research question 2 to the other research questions is shown in green. The question of how the profitability of alternative heat supply options to natural gas, such as district heating, changes is the link between research questions 1 and 2. The extent to which alternative distribution grids are needed to provide sustainable heat to buildings is also influenced by the decision to decommission parts of the gas networks. The latter aspect thus links research questions 2 and 3. Whether the decommissioning of parts of the gas network is at all possible and can be considered depends on whether it is possible to realize the "last mile" and substitute gas demand in buildings. This is less a technical-economic question than a question of implementation.

1.3. Structure of the thesis

The remainder of this thesis is organized as follows:

In Chapter 2, the literature review is presented. The review begins with a selection of studies related to deep decarbonization pathways of energy systems on different scales. Then, it discusses the implications of large-scale numerical model results at the local level, forming the basis of the discussion on the effects of decarbonization on the heating sector. This discussion focuses on the building and end-user perspectives. The chapter also examines justice in energy systems, considering the socially balanced aspects of a sustainable energy transition. Finally, the chapter concludes by summarizing the progress beyond the state of the art of this thesis.

In Chapter 3, the methodologies employed to address the research questions are presented in detail. Each method answering one of the research questions is described in a dedicated section (Sections 3.1 to 3.4), beginning with an overview of the problem, followed by a comprehensive explanation of the mathematical formulation and nomenclature used. This ensures a clear and systematic presentation of the methods and facilitates a better understanding of their application in addressing the research questions.

In Chapter 4, the results are presented. Each section (Sections 4.1 to 4.4) focuses on one of the four research questions. In Section 4.1, the results of downscaling the European cost-optimal heat supply to the level of district heating networks are presented. Section 4.2 examines the cost-optimal decommissioning and refurbishing investments of gas networks at the federal-state level. The results of local deep decarbonization of urban neighborhoods are presented in Section 4.3, while Section 4.4 shows the findings on equitable decarbonization in multi-apartment residential buildings.

Chapter 5 provides a broad synthesis of the key findings presented in the previous chapters. It discusses the findings of the thesis and describes the conditions for the transferability of the present results. In addition, the limitations of the methods are critically discussed.

Chapter 6, concludes the thesis by summarizing the main conclusions drawn from the research, while the final Chapter 7 outlines future work based on the thesis work.

2. State of the art and progress beyond

In this chapter, the reader will find relevant background information related to the scope of this thesis. The first four Sections 2.1 to 2.4 are dedicated to the existing literature. The last section 2.5 presents the contribution of this thesis and discusses its progress beyond the state of the art. Section 2.1 starts with the literature about deep decarbonization pathways on energy systems on different scales. This is followed by a discussion related to the implications of large-scale numerical model results at the local levels in Section 2.2. Then, Section 2.3 deals particularly with the implications of decarbonization on the heating sector, while Section 2.4 presents selected literature on the crucial question of justice in future energy systems and socially balanced sustainable energy transitions.

2.1. Deep decarbonization pathways of energy systems on different scales

In light of the energy system transition, deep decarbonization is of paramount importance and determines key priority challenges toward sustainable energy provision (Wesseling et al., 2017). For this reason, many scientific contributions provide comprehensive studies dealing with (i) sustainable energy provision (Zhang et al., 2010), (ii) efficiency-enhancements (Vaillancourt et al., 2017), and (iii) measures for energy demand reduction (Sorrell, 2015). Generally, these studies carry out analyses with different emphases and on various scales (such as global, regional, or national levels (Kueppers et al., 2021)).

The high-level goals are important cornerstones from an energy planning perspective and give guidance and future orientation. In this context, the work in (Loftus et al., 2015) provides a critical review of global decarbonization scenarios covering several sectors. The authors in (Victor et al., 2018) and (Brown and Botterud, 2021) conduct studies, in particular, for the decarbonization of the U.S. power sector. The trends of power system decarbonization in Europe (Haller et al., 2012), China (Khanna et al., 2019), and other regions (see exemplarily in (Dranka and Ferreira, 2018)) also head in a similar direction similar to those outlined in the U.S. studies. The decarbonization study in (Auer et al., 2020b) targeting climate neutrality in Europe in 2040 and 2050 is more comprehensive and covers several important sectors as there are energy, industry, building, and transport. Examples of in-depth analyses on decarbonization pathways in the transport sector and heavy industry can be found in (Göhlich et al., 2021) and (Obrist et al., 2021), respectively.

Furthermore, there exist already studies attempting to downscale global/high-level studies to fine-granulated structures or local levels (Benestad, 2004). Moreover, there is an increasing need for comprehensive down- and upscaling measures and tools, engaging the possibilities to map higher-level energy system goals on a local level (Tlili et al., 2020). For example, in (Chen et al., 2020), it is identified that the implementation of aligned and sustainable energy planning is also important on the province, district, or neighborhood level. Consequently, comprehensive studies work on the disaggregation (or mapping) of superior/generalized decarbonization pathways on higher resolved spatial levels. The implementation of decarbonization pathways for whole cities is shown in Ibrahim (2017) (and also in (Echeverri, 2018) focusing on investment needs on city levels). The studies in (Leibowicz et al., 2018) and (Zhang et al., 2020) decompose decarbonization pathways on an even higher resolution, such as on the building level. Thereby, the first study focuses on building thermal efficiency improvements, and the latter one, in particular, focuses on achieving the predefined national climate goals. Finally, it is important to note that spatial characteristics of the particular area need to be taken into account when developing the local decarbonization pathways. Different local areas or settlement patterns require different efforts. However, the scope of this work is densely populated and urban areas. Hence, it is exemplarily referred to the work in (Zhao et al., 2020) which detects a clear decarbonization trend in urban areas and considers the unique characteristics of highly populated neighborhoods.

2.1.1. Trade-Offs in energy system planning and key performance indicators

A vast number of scientific contributions have already dealt with trade-off analyses in energy systems (see, e.g., (Nerini et al., 2018)). In general, these kinds of analyses are caused by the fact that energy systems often have to meet different contradictory requirements (Jing et al., 2021). The bandwidth of energy supply needs and objectives concerns, among others, techno-economic, security/reliability, and sustainability/environmental related goals. Therefore, energy system analyses accept the challenges to address multiple objectives (Gracceva and Zeniewski, 2014). This is achieved by integrated (Mirakyan and De Guio, 2013), holistic (Sperling et al., 2011), and multi-criteria (Tsoutsos et al., 2009) energy planning approaches.

At the same time, further works depict that solutions optimized with respect to one specific objective are distant from each other keeping in mind the solutions of all possible objectives. Therefore, studies often analyze the so-called Pareto Front (describing a set of optimal solutions) (Ganjehkaviri et al., 2017). For example, the work in (Fleischhacker et al., 2019) shows that the optimal cost-minimizing and emission-minimizing solutions lie on the extreme points of the Pareto Front. Therefore, it is likely that optimizing one objective leads to producing a suboptimal result related to another (compare, e.g., the ambivalence between cost-optimal and security-optimal solutions (Wang and Singh, 2006)). Notwithstanding, in most energy system planning analyses predominantly cost-minimal solution has been mainly addressed so far (see, e.g., (Krishnan and Das, 2015)).

Nevertheless, climate change-related measures can no longer be placed behind the question of myopic economic viability considerations (Santoyo-Castelazo and Azapagic, 2014). Hence, several works suggest that strategic energy system-related decisions should strive to be subjected to the principle of sustainability and environmental-friendliness (Vuuren et al., 2020). This takes into account binding agreements of climate and sustainable development goals (Tanasa et al., 2020) (see also, e.g., in (Bosetti et al., 2009)). In addition, there are strong efforts to take increased account of still scarcely adopted cost components, such as externality and greenhouse gas emission costs.

In particular, long-term strategic decisions governing sustainable energy system transition require further benefit evaluation criteria. In scientific contributions and real-life applications, benefit/performance indicators enable a fundamentally enhanced assessment and supersede high-complex or rather academic multi-criteria analysis approaches. The fundamental work conducted in (Afgan and Graça Carvalho, 2000) develops sustainability indicators for the assessment of energy systems. The studies in (Vera and Langlois, 2007) and (Kemmler and Spreng, 2007) are heading in a similar direction and conduct energy indicators for sustainable developments. Looking rather from a more general/global perspective, the work in (Reuter et al., 2020) carries out a comprehensive indicator set for measuring energy efficiency benefits.

2.1.2. Aggregation and flexibility responses with different objective

Flexibility options for energy systems are manifold. Lund et al. (2015) list grid reinforcement and expansion, flexible dispatchable power plants, energy storage, sector coupling, energy markets, and demand side management. Demand- and supply-side flexibility, sector coupling through power-to-gas or power-to-heat, and energy storage can be provided centrally with large-scale technologies or by distributed small-scale applications. Large-scale flexibility options are already included in large-scale energy system models (such as exemplarily the EMPIRE model Marañón-Ledesma and Tomasgard (2019) and Backe et al. (2021)) and similar tools to investigate the future development of energy systems with a high penetration of variable renewable energy sources.

Although the potential for distributed flexibility is significant, it is yet unclear for what purpose the flexibility should be utilized and how flexibility responses differ with different objectives (Backe et al., 2022).

In a perfectly competitive electricity market, profit-maximizing decisions in smaller firms will also maximize social welfare given complete and correct price signals (Green, 2000). This is also true in electricity systems with variable renewable energy sources and electricity storage (Korpås and Botterud, 2020). In reality, the challenge is to ensure that flexibility providers are faced with complete and correct price signals, including production prices, grid prices, and pollution prices. Eid et al. (2016) review different applications, incentives, and market designs for the flexibility management of distributed energy resources. Schwabeneder et al. (2019) provide a classification for demand response and investigate the impact of different general flexibility characteristics on the profitability of load shifting. They highlight that market-driven flexibility optimization does not necessarily yield a reduction in carbon emissions of the electricity system. Nolting and Praktiknjo (2019) conduct a techno-economic analysis of flexible heat pump controls and find that the economic efficiency and the environmental efficiency are in conflict. This is supported by Fleischhacker et al. (2019) who optimize the portfolios of ECs with different objectives. They conclude that solutions for minimum cost and minimum carbon emissions are contrary to each other. Schwabeneder et al. (2021) investigate business cases for aggregators of residential customers with flexible technologies in different European electricity markets. They show that neglecting household-specific costs in the optimization of an aggregator's portfolio can yield sub-optimal results.

These findings suggest that individual objectives from a private perspective and the objectives from a system perspective may not always coincide without complete and correct prices. This poses a challenge for the integration of distributed flexibilities in a system analysis framework. The computational complexity of a capacity expansion planning model for multiple European countries that considers a high number of distributed small-scale flexibility options represents another challenge. It can be tackled by aggregating all flexibilities at a country or node level and simplifying their representation in the optimization model. Müller et al. (2019b) provide a generic approach for this purpose using zonotopic sets: The feasible region of a flexibility option in a linear optimization problem describes a convex polytope. In their approach, they inner-approximate this region by a subclass of polytopes, known as zonotopes, and they show how zonotopes can be aggregated and disaggregated efficiently.

2.2. Implications of large-scale energy system model results at the local levels

For quantifying solutions for complex energy system planning problems, researchers use numerical models. In general, these models strike a balance between complexity and aggregation. Integrated assessment models (IAMs) are large numerical models covering complex interrelationships between climate, society, economics, policy, and technology (Dowlatabadi, 1995). Particularly, IAMs contribute to the understanding of global energy decarbonization pathways (Wilkerson et al., 2015). Evaluating and discussing IAM involves, among others, the appropriate level of regional (spatial) aggregation of countries in the modeling analysis (Schwanitz, 2013). Generalizing this aspect reveals an aspect already known but essential in the context of large numerical models. Setting priorities regarding the level of detail becomes necessary for modelers, which inevitably creates trade-offs in the analysis regarding the granularity of temporal, spatial, and other dimensions (Gargiulo and Gallachóir, 2013). Accordingly, IAMs should increasingly be supplemented with other models and analytical approaches (Gambhir et al., 2019). Not least for this reason, large-scale detailed energy systems models also play a significant role in the analysis of energy systems in the context of climate change. Compared to IAMs, they more strongly emphasize the level of detail in terms of techno-economic characteristics. However, the lack of granularity remains; these global systems models consider only a highly aggregated spatial resolution. To name just two selected approaches, PRIMES (Capros et al., 2012) and GENeSYS-MOD (Löffler et al., 2017) are aggregate energy system models focusing on the European energy system with a spatial resolution at the country level. Further approaches are needed to disaggregate results obtained at the country level to finer scales, such as districts, neighborhoods, and other local levels. In this context, a novel approach in the context of merging local activities/behavior in sustainable local communities into a large energy system model (bottom-up linkage) is presented in (Backe et al., 2021). In this study, local flexibility options are integrated into the large-scale energy system model EMPIRE, which provides, in principle, only country-level resolution. This and other work confirms the emerging trend of making top-down and bottom-up linkages between different spatial-temporal levels of resolution to drive decarbonization across all sectors.

2.3. Implications of decarbonization on the heating sector

The scope of changes required by 2030/2050 in the heating sector becomes even clearer at the national level. In Europe, the share of renewable energies in the heating and cooling sector in 2018 is only just above 20 % on average (Eurostat, 2021). In Austria, it reaches 34%. However, fossil fuels continue to dominate there as well. In 2015, the heat demand for low-temperature heat services in Austria was around 96 TWh. This heat volume encompasses low-temperature heat demand of residential buildings (domestic spacial heating demand, calculated on the basis of the outdoor temperature), industrial heat demand below 100°C (e.g., food sector, machinery, and wood), and process heat demand (Burandt et al., 2018). In the residential building sector, natural gas, oil, and coal account for almost 45% of space heating and hot water demand (Öesterreichs Energie, 2018). The share of district heating reaches almost 15%, and more than one million households are connected to district heating networks. According to (Statistik Austria, 2016), the total heat production from district heating was around 24 TWh in 2016. Thereby, the share of renewable energy was 45%. Besides, the share of waste sources was 9%. In 2018, district heating supplied 18% of the total heat demand in the residential building and service sector with a share of 48% renewable heat sources. Thereby, the amount of district heating was 20 TWh.

Nevertheless, of the nearly 4,000,000 residential dwellings in Austria, more than one million are heated with natural gas, and more than 500,000 are heated with oil (Statistik Austria, 2020a). If these heating systems are converted to renewable energy supply by 2040, this corresponds to a retrofitting of more than 80,000 units per year or more than 225 per day - only in Austria. To achieve this goal, measures that go beyond the electrification of the heat supply are necessary, which may require an expansion of district heating networks. This holds true even when substantial heat-saving measures are implemented (Jalil-Vega and Hawkes, 2018).

In Europe, good conditions for district heating exist (Persson et al., 2019), especially in the provision of heat services in densely populated or urban areas (Inage and Uchino, 2020) because of the high heat densities that are found there. In addition to heat density, the connection rate is a key factor determining the efficiency of district heating/cooling networks and thus their implementation. In Austria, a benchmark of 10 GWh/km^2 at a connection rate of 90 % is currently used when deciding whether to supply an area with district heating[1]. This reference value considers the area effectively supplied by district heating and not the total area. Thus, the exclusion of land areas that contain woodland, mountain, agricultural, and other low heat-density areas is crucial. The reference/benchmark value is in line with findings regarding district heating networks also from the Scandinavian region (Denmark, Sweden, and Finland) (Zinko et al., 2008). These are rough estimates, but they do allow an initial assessment of the economic viability or feasibility of a district heating network. In a detailed consideration and evaluation of district heating networks, numerous factors play a decisive role. For example, the design and topology of district heating networks demonstrate a significant impact on their cost-effectiveness (Nussbaumer and Thalmann, 2016; Zvoleff et al., 2009). In addition, the cost-optimized heat supply is also influenced by the location of heat generation units/sources within the networks (Laasasenaho et al., 2019). The influence of the connection rate and linearly decreasing heat densities on the profitability of district heating networks is investigated in (Nilsson et al., 2008) and (Dochev et al., 2018). The study in (Bordin et al., 2016) presents an optimization approach for

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[1] `http://www.austrian-heatmap.gv.at/ergebnisse/`

district heating strategic network design. Further works also evaluate the impact of the heating system topology on energy savings (Allen et al., 2020). When examining the economic viability of district heating networks, building renovation measures must also be taken into account (Andrić et al., 2018). Recently, the results in (Hietaharju et al., 2021) show that a $2-3\%$ building renovation rate per year results in a $19-28\%$ decrease of the long-term district heating demand, which consequently also reduces the heat densities of district heating networks. However, studies show that a reduction in heat density is not necessarily a barrier to district heating networks (Persson and Werner, 2011). For example, energy taxes which can certainly be expected in the future (e.g., higher taxes on fossil fuels) can improve the profitability of sparse district heating networks (Reidhav and Werner, 2008). Following these considerations and in light of ambitious CO_2 reduction targets assumptions exist that rising CO_2 prices exhibit a similar effect. However, this is valid only in the case of deep decarbonization of the generation mix feeding into district heating networks. In general, a variety of alternatives to decarbonize the energy mix of district heating networks exists. Among others, geothermal (Kyriakis and Younger, 2016), biomass (Di Lucia and Ericsson, 2014), waste (Hiltunen and Syri, 2020), and heat recovery from industrial excess heat (Bühler et al., 2017) are likely to be the primary heat sources in sustainable district heating networks. Eventually, the increasing cooling demand and the co-design of district heating and cooling networks can also increase the economic viability of these and counteract the reduction of heat density from an economic point of view (Zhang et al., 2021).

2.3.1. Natural and green gases in sustainable energy systems

It is debatable whether natural gas will play a significant role in the energy transition over the next few decades, and if so, under what conditions. Gürsan and Gooyert (2021) provide a recent and concise review of the state of the art of natural gas in reducing CO_2 emissions from energy systems. Kotek et al. (2019) conduct a study on the European natural gas infrastructure in the context of the energy transition. Already in 2012, Stephenson et al. (2012) discuss natural gas as a transition fuel in the sustainable transformation of energy systems. They concluded that a natural gas climate solution is unsubstantiated. This is also reflected in a large number of studies on cost-optimal energy supply until 2050. Auer et al. (2020b), for example, investigate the European energy supply until 2050 for various decarbonization scenarios under the remaining European fraction of the CO_2 budget and discover that natural gas is almost completely replaced in the primary energy demand in 2040.

Green gases are becoming increasingly important, as evidenced by not only the results of Auer et al. for Europe but also, those of Zhang et al. (2022) for China. Against this background, it is certainly possible to see existing natural gas networks as a crucial part of the energy transition to transport and deliver green gases. Recently, Quintino et al. (2021) elaborate on aspects of green gas introduction in natural gas networks. Dodds and McDowall (2013) examine the long-term future of gas networks and state that the most cost-effective strategy might be to convert the networks to deliver green gases[2]. Similarly, Mac Kinnon et al. (2018) investigate the role of natural gas networks in mitigating greenhouse gas emissions. Gillessen et al. (2019) elaborate on the role of natural gas as a bridge to sustainable energy systems and related infrastructure expansion of gas networks. Gondal (2019) studies hydrogen integration into gas transmission networks.[3]

Nonetheless, although the expected potential of green gases exists, it is nowhere large enough to replace the current amount of natural gas in the energy supply. Accordingly, the discussion of existing natural gas networks may and should include decommissioning as part of the solution space. Furthermore, this possibility should no longer be seen as a taboo subject but rather as a real decision option that can even be argued from a techno-economic point of view. Giehl et al. (2021) examine cost-optimal gas networks and focus particularly on the distribution network level, finding a declining need for gas

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[2] Interestingly, Dodds and McDowall find in their scenarios that hydrogen injection into gas networks has only a small role and low impact on gas networks.

[3] Particularly, Gondal states that (i) at the transmission network level, compressors are the determinant element and limit the value of hydrogen by 10%; (ii) at the distribution network level, pipelines and storage elements allow shares up to 50% of hydrogen; and (iii) at the level of end-use appliances, a tolerant range and share of 20-50% of hydrogen is possible.

distribution networks in their future scenarios. Feijoo et al. (2018) find risks of underutilization of gas networks (i.e., pipeline capacities) in a low-carbon future economy even at the interstate and transmission level. Brosig et al. (2017) compare the cost-effectiveness of different future pathways between the expansion and decommissioning of the gas grid network.

In this context, local renewable energy sources and technologies are becoming increasingly important. For example, district heating contributes in densely populated and urban areas to the decrease of natural gas in the supply of energy service needs. Möller and Lund (2010) examine the conversion of individual natural gas heating units to district heating. Hofmann et al. (2014) show the use of geothermal sources for heat generation for both residential and industrial. At the national level, Geyer et al. (2021) present scenarios, energy carriers, and infrastructure requirements for a completely renewable energy-based industry sector. Rahnama Mobarakeh et al. (2021) show, particularly the reduction of gas demands and associated CO_2 emission for the pulp and paper industry by electrification of energy service needs. Bachner et al. (2020) focus on the replacement of gas and other fossil fuels in the steel and electricity sector from a macroeconomic perspective[4].

Findings of the literature in the previous paragraph indicate that large portions of natural gas demands can, in principle, be substituted by sustainable alternatives. Against this background and considering that natural gas networks are regulated entities of the energy system, are capital intensive, and therefore require long-term strategies or planning, avoidance of stop-and-go policy is crucial. Exemplarily, Then et al. (2020b) study the operator strategy and economic viability of gas networks in the face of decreasing gas demands. Hickey et al. (2019) identify significant challenges and risks to policymakers and investors in using gas networks in sustainable energy systems encompassing the risk of stranded assets resulting not only from declining gas demand but also from changes in regulation and how tariffs are allocated. Hausfather (2015) focuses on the policy decisions for natural gas and its network

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[4] In the context of a decarbonized electricity supply, Qadrdan et al. (2015) investigate the impact of transitioning to a low-carbon electricity sector on gas network infrastructure. Particularly, the authors focus on the gas network in Great Britain and find that despite the declining gas demand, the peak gas demand remains unchanged.

infrastructure until 2030 as they irreversibly impact the future of natural and synthetic gas in the period 2030 to 2050[5]. Glachant et al. (2014) study and identify the fundamental reasons for diverging gas network and market developments. Mosácula et al. (2018) propose a novel methodology for gas network charges design, which builds on economic efficiency as the main principle. Hutagalung et al. (2017) deal with the economic implications of natural gas infrastructure investments. Tata and DeCotis (2019) focus on risks and responsibilities associated with natural gas infrastructure development. Capece et al. (2021) benchmark and analyze the efficiency of natural gas distribution utilities. Sacco et al. (2019) analyze maintenance risks associated with gas networks. Sesini et al. (2020) assess resilience and security in gas network systems. The key findings can be summarized since decisions on natural gas infrastructure development should not be made through a single-lens view.

2.3.2. Distribution grid planning and energy infrastructure decommissioning

Energy technology infrastructures are undergoing rapid changes. It is the consequence of various factors, such as the already mentioned ongoing decarbonization, but also decentralization, digitalization (Di Silvestre et al., 2018) and, ultimately "democratization" of the energy systems. Thus, in particular, energy distribution grid planning faces enormous challenges (i.e., incorporation of flexibility options (Klyapovskiy et al., 2019), energy demand response (Medina et al., 2010), or providing the interface for charging high shares of electric vehicles (Yang et al., 2014)). In either case, distribution grid planning analyses require more than ever integrated/holistic approaches (Müller et al., 2019a). This includes, among others, sector coupling (Fridgen et al., 2020). Since a large number of scientific contributions already comprehensively dealt with sector coupling, it is referred to the literature in this context (see, e.g., in (Brown et al., 2018), many further contributions, and additionally in the recently published review in (Ramsebner et al., 2021)).

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[5] Moreover, Hausfather concludes that policy decisions are needed leading to the decarbonization of natural gas no later than 2030.

In addition to energy network infrastructures and facilities, also innovations in the energy technology supply portfolio develop very fast (see in (Fleischhacker et al., 2019) and especially related to energy storage deployment in (Ziegler et al., 2019)). This is the main driver for the already partial phase-out and decommissioning of selected energy technologies and related infrastructures, respectively (Hansen et al., 2019). In particular, the work in (Fowler et al., 2014) focuses on decommissioning of natural gas infrastructure in the upstream energy sector. However, these actions led to profound changes and enabled the linkage and interaction of different energy technologies and carriers in energy systems. Considering this work's scope, the relevant study in (Then et al., 2020a) analyzes interrelationships in the downstream sector between gas and electricity distribution grid planning (as well as building energy retrofit decisions). In this regard, the authors also explicitly want to cite the study in (Weidenaar et al., 2011) that develops options for the Dutch gas distribution grid in a changing natural gas market.

Complementing the scientific literature review above, the following paragraph should provide a few insights into the practical relevance of gas distribution grid decommissioning considerations. Thus, the real-world applicability of this work's study is visible. In this context, the Netherlands can be cited as a role model to discuss the future of gas without taboos. Although the Netherlands is considered a European country with one of the highest natural gas reserves, they have committed themselves to consider a gas-free energy system in 2050[6] that would fundamentally change the heat supply of new buildings and the existing building stock. This discussion also includes the related meaninglessness of green gas (but not, of course, those of hydrogen to supply higher-priority energy services in other sectors). Moreover, individual cities in the Netherlands (e.g., Utrecht) have set even more ambitious targets and aim for a gas-free energy supply in 2030[7]. Furthermore, the city of Zürich in Switzerland with its 400 thousand inhabitants is pursuing a pioneering attempt[8]. The planned phase-out of the gas-based heat supply in

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[6] `https://www.oxfordenergy.org/publications/the-great-dutch-gas-transition/`

[7] `https://www.german-energy-solutions.de/GES/Redaktion/DE/Publikationen/Marktanalysen/2021/zma-niederlande-2021-energieeffizienz-gebaeude.html`

[8] `https://www.ebp.ch/sites/default/files/2020-12/2019_EBP_Fachbericht_Zukunft_Gasinfrastruktur.pdf`

the next years in two districts explicitly includes "stranded costs" considerations of end-users gas supply infrastructure and appliances. Consequently, compensation payments for non-depreciated end-user investments associated with a gas supply are granted.

This real-world example in Zürich is a first indication that in the energy transition, it is increasingly important to compare both the costs of removing "stranded assets" (including compensation payments to those who are affected) and the costs of inaction (including the costs of possible future penalties for failing to meet climate targets). Even more, business models and economic viability analyses in the energy transition must increasingly address these kinds of opportunity costs alongside the prices of energy carriers and their externalities. This casts already a different light on the attractiveness of gas-based business models both now and in the future.

2.3.3. Modeling gas networks

Particularly, the previous paragraph regarding the challenges and risks of long-term planning of gas networks provides the starting point for this section dedicated to modeling and simulation of gas networks. Ríos-Mercado and Borraz-Sánchez (2015) present a comprehensive state of the art review on the optimization of natural gas networks encompassing both the transmission and distribution network level. Osiadacz and Gorecki (1995) provide an even broader summary of gas network optimization modeling approaches. Particularly, they mention heuristic, continuous, and discrete methods of the optimal design of gas networks. Feijoo et al. (2016) propose a long-term partial equilibrium model that allows for endogenous gas network infrastructure expansion and nonlinear cost functions. Fügenschuh et al. (2011) develop an optimization model with a quadratic formulation. Fodstad et al. (2016) and Aßmann et al. (2019) use stochastic optimization including gas demand uncertainties in the optimization of gas networks. Latter use a decomposable robust two-stage optimization model. Von Wald et al. (2022) propose a multiperiod planning framework for the decarbonization of integrated gas and electric energy systems.

The long-term planning of gas networks is exemplarily shown by Hubner and Haubrich (2008) and Giehl et al. (2021). The latter proposes a greenfield approach and optimization model for gas networks without considering the existing network infrastructure (i.e., from scratch). Mikolajková et al. (2017) show the optimization of a natural gas distribution network with the potential future extension of the transmission network level. Kashani and Molaei (2014) present the techno-economical and environmental optimization of natural gas network operation. Farsi et al. (2007) show a national case study regarding the cost efficiency of gas distribution networks. Particularly, they emphasize the impact of customer density and network size in the Swiss gas distribution sector. Odetayo et al. (2018) show the modeling flexibilities of gas networks for energy system operation. Diéguez et al. (2021) show the modeling of decarbonization transition in a national integrated energy system including hourly operational resolution of gas networks. Yusta and Beyza (2021) emphasize the modeling of large-scale gas storage facilities by a dynamic approach. Kerdan et al. (2019) link a spatially resolved gas infrastructure optimization model with an energy system model.

2.4. Justice in energy systems and a socially balanced sustainable energy transitions

The aspect 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 climate action. More generally, the three energy justice tenets are distributional, recognition, and procedural[9]. Recently, they are comprehensively discussed and reviewed by Pellegrini-Masini et al. (2020). Considering this work's scope, focus is put on procedural justice, as it represents measures that reduce potential barriers to new clean energy investments Oxford Institute for Energy Studies (2021).

Dealing with sustainable energy systems is a monumental task and seems to

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[9] In some works, restorative and cosmopolitan justice are also mentioned in this context; see exemplarily in Oxford Institute for Energy Studies (2021).

be very challenging to be generalized. However, studies focusing on certain local areas are likely to be the most promising approach. Recently, Bommel and Höffken (2021) conducted a review study focusing on energy justice at the European community level. Besides that, Lacey-Barnacle et al. (2020) elaborate on energy justice in developing countries. Coming back to this paper's content and spatial scope, Mundaca et al. (2018) present two local European case studies in Germany and Denmark assessing local energy transition from an energy justice perspective. Their findings are in line with those from Jenkins et al. (2018) showing that energy justice and transition frameworks can be combined and achieved simultaneously. However, Hiteva and Sovacool (2017) conclude from a business model perspective that energy justice may be realized through market principles but not through the market alone.

Recently, Hanke et al. (2021) have investigated 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 this regard on low-income households. Exemplarily, Xu and Chen (2019) propose on the basis of their results that low-income households need tailored assistance to ensure energy justice. In particular, they demonstrate that low-income households are renters and thus have low energy-efficient appliances. Sovacool et al. (2019a) point in the same direction and discuss the difficulties for households who lack the capital for sustainable energy investments and are predominantly tenants and not owners of their homes. Moreover, renters also often have higher residential heating energy consumption; an indicator for energy efficiency Reames (2016). In this context, Greene (2011) discusses the so-called “efficiency gap” or “energy paradox", showing that consumers have a bias to undervaluation of future energy savings in relation to their expected value. The main reasons are a combination of two aspects, namely, uncertainty regarding the net value of future fuel savings and the loss aversion of typical consumers. Filling the abovementioned efficiency gap is crucial in order to achieve both energy transition and energy justice. Sovacool et al. (2019b) show that unfolding the energy transition results in deeper injustices.

2.5. Contribution to the progress beyond the state of the art

Based on the research questions presented earlier and the literature review conducted, this study has identified four distinct areas of novelty and contribution to the scientific literature. Each of these areas is closely linked to one of the published papers.

With respect to research question 1, a simplified optimization model is developed for downscaling European decarbonization scenarios of the heating sector to the community levels serving end-users in 2050. Compared to the existing literature presented, this thesis includes the following novelties:

- The topography of district heating networks is of particular importance and plays a crucial role in applied downscaling. This allows estimates of realistic decarbonized district heating networks in 2050 to be obtained, which can be compared with existing networks. Thereby, the heat density of district heating networks serves as a comparative indicator and permits a rough estimation of the changes needed for district heating networks considering the 1.5 °C and 2.0 °C climate targets.
- In particular, downscaling considers the highly efficient and local use of sustainable heat sources in district heating (e.g., geothermal, co-firing synthetic gas and hydrogen, and large-scale waste utilization)
- An Austrian case study is conducted, downscaling the cost-effective results of the heating sector in 2050 from the large numerical energy system model GENeSYS-MOD, from the country to the community level. In general, GENeSYS-MOD exhibits a focus on generic heat supply options based on primary energy sources, rather than local heat sources which is in general the fundamental idea of district heating.
- Accordingly, this study can be seen as an attempt for a stress test applying GENeSYS-MOD's heat supply in the context of district heating. The GENeSYS-MOD results, and thus the values to be downscaled implicitly, include the remaining European carbon budget in line with the 1.5 °C and 2.0 °C climate targets.

With respect to research question 2, a linear optimization model is developed with the objective to minimize the network operator's net present value over time. Compared to the existing literature presented, this thesis includes the following novelties:

- A cost-effective trajectory of existing gas network infrastructure is modeled considering the expectation of both declining gas demands resulting from the defossilization of energy services and the increasing but limited integration of green gases, such as synthetic gas and hydrogen.
- Since existing gas network infrastructure requires the refurbishment of its gas pipelines due to the expiration of the technical lifetime, it is shown how the gas network operator decides from a techno-economic point of view between decommissioning and refurbishment investment of gas pipelines at different network and pressure levels (transmission, high-pressure and mid-pressure).
- The optimization of a cost-effective trajectory of existing gas network infrastructure includes the gas network operator's decision between supplying or not supplying available gas demand (i.e., disconnection from the gas network by decommissioning gas pipelines and implicitly implementing stand-alone gas supply alternatives). Particularly, the long-term planning horizon of the model allows for investigating this trade-off decision between investment/capital costs, related book values, and expected revenue and purchase streams for individual gas pipelines.
- The application of the proposed model on a real test bed in a federal state region in Austria until 2050 provides useful insights that can be used directly by decision and policymakers. The investigated test bed is representative of other gas networks since it comprises, on the one hand, gas demands that are supplied in different end-user sectors, and, on the other hand, encompasses different gas network/pressure levels.

With respect to research question 3, the extension and coupling of two verified open-source models enable high-spatially resolved modeling exercises that focus on the distribution network of electricity, natural gas, and district heating. Compared to the existing literature presented, this thesis includes the following novelties:

- A deep decarbonization analysis of a multiple-energy carrier energy system of a local urban neighborhood is carried out by focusing on decommissioning the natural gas distribution grid rather than trying to supply the gas grid with green gas in the future. This is motivated by the energy policy decision to no longer allow natural gas connections for future new building areas. The demonstration of sustainable supply alternatives and thus the demystification of the necessity of sticking to the existing gas distribution grid is one of the main novelties.

- The case study of the spatially limited urban neighborhood clearly shows that high-level decarbonization goals are not something abstract or intangible, but can be implemented locally, taking into account several specific characteristics on-site. This includes mapping the local energy supply alternatives and network infrastructures as well as the building stock to enable detailed decarbonization scenario studies and assessment of its economic viability. Even more, high-resolution local mapping also allows for the quantification of possible synergies by achieving economies of scale and estimating the opportunity costs of alternative energy supply compared with inactivity (e.g., persisting with the current natural gas distribution grid and end-user devices).
- The extension and application of the two open-source models can be seen as a significant contribution not only to the open-source scientific community but also to a wider public interested in transparent and comprehensive energy transition analysis tools. The functionality extension with regard to economies of scale in the modeling framework covers non-linearities describing not only the optimal local district heating/cooling expansion path but also implicitly the opportunity costs and penalties in light of unachievable climate targets as a result of inaction or inertia in the energy system transition.
- Tailor-made benefit/performance indicators enhance benchmarking of the distinct local deep decarbonization pathways and make related energy system achievements and efforts measurable. They enable monitoring of long-term sustainable or even net-zero emission energy supply pathways, such as those that are aimed at the climate target years 2040 and 2050. In particular, the introduced indicators serve to quantify the relative differences between the various energy system planning decisions of the respective decarbonization scenarios from a technical and

economic perspective.

With respect to research question 4, the development of a linear optimization model with the aim of minimizing the net present value of the government's financial support over time, in order to achieve a socially balanced subsidy strategy for an apartment building to trigger investment in a sustainable heat supply. Compared to the existing literature presented, this thesis includes the following novelties:

- An equitable and socially balanced change of a currently gas-based heating system toward a sustainable alternative in a rented multi-apartment old building is modeled considering the complex ownership structure and relations between the property owner and tenants to "take action".
- Since the governance's first and foremost aim is that the heat system exchange in the multi-apartment building takes place, it is shown how the governance incentivizes sustainable investment through monetary and regulative support for both the property owner and tenants. While respecting the property owner's and tenants' individual financial interests, the governance's optimal financial support strategy puts particular emphasis on the highly efficient provision of the residential heat service needs, heat demand reduction, and building efficiency improvements.
- The developed analytical framework determines a cost-optimal and socially balanced governance's subsidization strategy for the decarbonization of the heat demand at the building level. That includes, among others, the profit-oriented behavior of the property owner and the tenants, as well as the abovementioned financial support parity among both sides. Especially, the proposed optimization model allows detailed quantitative analyses of justice in low-carbon residential buildings and the heating sector with an eye on the complex ownership structure within buildings. Moreover, this work focuses on the economic trade-offs between different agents in the energy transition, particularly the government's role in triggering private investments and social balance with an eye on the costs of inaction (opportunity costs) and increasing carbon prices.
- Different sensitivity analyses play a key role in this paper, understand-

ing that the impact of varying allocations of the costs of inaction among the governance, the property owner, and the tenants can be seen as one of the main novelties of this work. Moreover, the importance of building stock renovation in the context of public monetary payments is critically discussed. Insights in that respect can help build a more reliable understanding of a sustainable future urban society predominantly living in highly efficient rental apartments.

3. Methods

This chapter introduces the four methods used in this thesis to address the research questions. The first method, described in Section 3.1, is the *downscaling model*, which links European decarbonization scenarios with district heating networks to answer research question 1. Section 3.2 presents the *decommissioning model*, which is related to natural gas networks and used to address research question 2. In Section 3.3, the distribution grid model is presented, which is associated with electricity and district heating networks and used to answer research question 3. Finally, Section 3.4 outlines the *equitable model* for a sustainable heating switch of buildings, which is used to address research question 4.

3.1. *Downscaling model* to link European decarbonization scenarios and district heating networks

The detailed description of the *downscaling model* is divided into three parts. First, Section 3.1.1 presents the output from the European Horizon 2020 project openENTRANCE (incl. GENeSYS-MOD results), since this is the main input for the downscaling. Therein, information about the different heat sources/generation technologies that are downscaled is provided. Section 3.1.2 explains the mathematical formulation of the optimization model in detail. Then, Section 3.1.3 shows the workflow that is used to determine the implemented shares of district heating. Finally, Section 3.1.4 presents the nomenclature of the model's variables and parameters. Further information can be also found in Appendix A.

3.1.1. Heat supply of the Austrian residential and commercial sector in four decarbonization scenarios 2050

This section presents the heat generation mix covering the Austrian residential and commercial heat demand in 2050 for four different scenarios, which have been developed within the European Horizon 2020 openENTRANCE project. They are named as follows: *Directed Transition*, *Societal Commitment*, *Techno-Friendly*, and *Gradual Development*. Within each of them, specific fundamental development of the energy systems is described while aiming for a sustainable transition of the provision of energy services. The first three scenarios assume different approaches to limit global warming to around 1.5 °C as laid out in the Paris Agreement. Particularly, the results of these scenarios implicitly consider the remaining European fraction of the CO_2 budget of the 1.5°C climate target. The last scenario (*Gradual Development*) can be interpreted as a less ambitious scenario, limiting global warming to around 2.0 °C climate target. Accordingly, the results of this scenario consider the remaining European fraction of the CO_2 budget of the 2.0°C climate target. Below, the scenarios are described briefly, before the quantitative results at the country level are presented. For a more detailed description of the scenarios, refer to (Auer et al., 2020a; Auer et al., 2020b; Hainsch et al., 2022). Further information is also available on the website of the project[1] and on GitHub[2].

The underlying concept of the four scenarios is a three-dimensional space consisting of the following parameters: technology, policy, and society. Each scenario describes a specific pathway to reach a decarbonized energy system taking into account a pronounced contribution of two dimensions. Regarding the third dimension, a development is assumed that leads to no significant contribution to the decarbonization of the energy system.

- *Directed Transition* looks at a sustainable provision of energy services through strong policy incentives. This bundle of actions becomes necessary because neither the markets nor the society adequately pushes

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[1] `https://openentrance.eu/`

[2] `https://github.com/openENTRANCE`

sustainable energy technologies.

- *Societal Commitment* achieves deep decarbonization of the energy system by a strong societal acceptance of the sustainable energy transition and shifts in energy demand patterns. Thereby, decentralized renewable energy technologies together with policy incentives facilitate a sustainable satisfaction of energy service needs. Due to the shift in energy demand, no fundamental breakthroughs of new clean technologies are required.

- *Techno-Friendly* describes a development of the energy system where a significant market-driven breakthrough of renewable energy technologies gives rise to the decarbonization of the energy service supply. Additionally, society's acceptance supports the penetration of clean energy technologies and the sustainable transition.

- *Gradual Development* differs from the other scenarios; it assumes emissions reductions that (only) stabilize the global temperature increase at 2.0 °C. At the same time, a combination of each possible sustainable development initiative of the energy system is realized in this scenario. Although the other three dimensions contribute to decarbonization, they do not push it sufficiently, and this results in a more conservative scenario than the others.

Table 3.1 shows the heat generation by source/technology in Austria in 2050 for the four scenarios. These values were obtained during the course of the openENTRANCE project and are generated by the open-source aggregate model GENeSYS-MOD (Burandt et al., 2018).

In this work, the naming convention of heat sources/generation technologies from GENeSYS-MOD is essentially followed to ensure consistency between aggregated (i.e., downscaling input values) and local (i.e., downscaling output values) levels. However, waste and geothermal heat sources were not initially included in the list of heat sources from the openENTRANCE results and have therefore been added. To complement the GENeSYS-MOD results, waste has been separated from biomass and geothermal from heat

	obtained from GENeSYS-MOD				
	2020	2050			
Generation by source in TWh	-	DT	SC	TF	GD
Biomass	13.00	3.37	3.37	3.37	3.37
Direct electric	4.10	2.13	1.98	1.53	1.81
Geothermal	0	2	2	2	2
Natural gas (fossil)	43.67	0	0	0	0
Heat pump (air)	11.37	22.73	15.71	25.96	9.68
Heat pump (ground)	0	17.50	19.47	4.69	19.21
Hydrogen	0	1.03	2.18	7.43	8.65
Oil	0.66	0	0	0	0
Synthetic gas	0	0.36	1.35	2.79	5.35
Waste	1.2	2	2	2	2
Total	74.0	51.12	48.06	49.77	52.07
Rel. reduction compared to 2020	-	-31%	-35%	-33%	-30%
District heating (Q^{dh}_{GENe} in Sec. 3.1.2)		16.75	15.38	27.20	22.84

Table 3.1.: Heat generation by source in Austria in 2020 and the four different decarbonization scenarios in 2050 obtained from GENeSYS-MOD. Geothermal, hydrogen, synthetic gas, waste, and half of the heat pump (air-sourced) generation are used in district heating. Sources: Auer et al. (2020b), Könighofer et al. (2014), and Büchele et al. (2015)

pump (ground-sourced) heat generation, respectively, using estimates from Austrian national studies in (Könighofer et al., 2014) and (Büchele et al., 2015). Note that the values obtained from GENeSYS-MOD do not explicitly include district heating, which is why its 2020's value in Table 3.1 cannot be specified. The total heat generation (and thus total heat demand) is significantly reduced when comparing the values of 2020 and 2050. The heat demand reduction varies between -30% and -35% and is highest in the *Societal Commitment* scenario. District heating (bottom row in Table 3.1) describes the amount of heat generation used for district heating. In this work, the assumption is made that geothermal, hydrogen, synthetic gas, waste, and half of the total heat generation by heat pumps (air-sourced) are used in district heating. Therefore, it is claimed that

- geothermal (Weinand et al., 2019) and waste (Fruergaard et al., 2010) as renewable heat sources contribute to the decarbonization of heat supply by the integration into district heating.
- the limited amounts of synthetic gas and hydrogen are preferably used in district heating (i.e., co-firing in cogeneration plants (Zwickl-Bernhard and Auer, 2022)) if they supply (residential and commercial or low-temperature) heat demands (Gerhardt et al., 2020; Jensen et al., 2020; Dodds et al., 2015).
- half of the cost-optimal heat supply of heat pumps (air-sourced) of the aggregate model GENeSYS-MOD are used in district heating through the implementation of large-scale heat pumps. Accordingly, heat pumps (air-sourced) significantly contribute to supplying decarbonized district heating networks (Bach et al., 2016).

3.1.2. Mathematical formulation of the *downscaling model*

Building upon the amount of district heating obtained by the aggregate model GENeSYS-MOD, this section explains the optimization model used to downscale heat supply to the LAU level in detail. In Appendix A, Table A.1 shows the spatial nomenclature of this work based on the NUTS nomenclature. Particularly, this includes representative examples for the LAU level. Against this background, Equation 3.1 shows the objective function of the model that is used for the downscaling.

$$\max_{q_l^{dh}, q_l^{dec}} \sum_l \underbrace{\frac{q_l^{dh}}{\phi_l \cdot A_l}}_{\text{within LAU } l} + \underbrace{\frac{q_l^{sur}}{A_l^{sur}}}_{\text{around LAU } l} \tag{3.1}$$

Therein, q_l^{dh} is the amount of district heating supply per LAU, q_l^{dec} the amount of heat demand supply decentralized/on-site, ϕ_l a scaling factor to obtain the effective supplied area of district heating based on the permanent settlement area A_l per LAU l. This becomes necessary since A_l includes the space available for agriculture, settlement, and transport facilities. q_l^{sur} is the amount of district heating in the surrounding LAUs of l. A_l^{sur} is the effective area of the surrounding LAUs. Equation 3.2 links the aggregate model GENeSYS-MOD with the developed optimization for the downscaling since the upper bound of district heating is set to the amount of district heating from GENeSYS-MOD's cost-optimal solution Q_{GENe}^{dh}.

$$\sum_l q_l^{dh} \leq Q_{GENe}^{dh} \tag{3.2}$$

Equation 3.3 is the demand constraint per l, ensuring that the total heat demand q_l^{total} is covered either by district heating or decentralized/on-site at l.

$$q_l^{dh} + q_l^{dec} = q_l^{total} \quad : \forall l \tag{3.3}$$

Equation 3.4 calculates the amount of district heating in surrounding areas of l, which is expressed by the subset L_l^{sur} containing all LAUs bordering l and the effective area A_l^{sur}. Latter is performed similarly to the first term (within LAU) in the objective function in Equation 3.39.

$$q_l^{sur} = \sum_{l \in L_l^{sur}} q_l^{dh} \quad \text{and} \quad A_l^{sur} = \sum_{l \in L_l^{sur}} \phi_l \cdot A_l \quad : \forall l \tag{3.4}$$

Equation 3.5 ensures non-negativity of the decision variables q_l^{dh} and q_l^{dec}.

$$q_l^{dh}, q_l^{dec} \geq 0 \quad : \forall l \tag{3.5}$$

3.1.3. Workflow to obtain implemented shares of district heating and their networks

In order to maximize the objective function value, the described mathematical formulation of the optimization model allocates the amount of district heating to the LAU level. However, this does not necessarily ensure that obtained heat densities of district heating networks reach the benchmark of 10 GWh/km^2 being assumed in this work. Consequently, this section explains in detail how the optimal values of q_l^{dh} (i.e., district heating at the LAU level) are further processed resulting in heat densities of district heating higher than the benchmark value. The developed workflow is as follows:

1. Starting with the optimal amount of district heating q_l^{dh} at the LAU level obtained from the optimization model.

2. Identification all LAUs that do not achieve the required heat density benchmark value of 10 GWh/km^2.

3. For each of those LAUs, the heat density of district heating within the corresponding NUTS3 region and thus network level is calculated.

4. In case the heat density reaches values higher than the benchmark at the NUTS3 level, the supply using district heating remains since LAUs are then connected to or in the surrounding area of high heat density areas.

5. Otherwise, q_l^{dh} is set to zero as no economic viability can be expected there due to lower achieved heat densities than the benchmark.

Finally, steps 1 to 5 allow us to calculate implemented district heating under the condition that either the local heat density at the LAU or the network heat density at the NUTS3 level achieves the assumed heat density benchmark value of 10 GWh/km^2.

3.1.4. Nomenclature *downscaling model*

Type	Description	Unit
Set and index		
$l \in \mathcal{L} = \{1, \ldots, L\}$	Local administrative unit / community, index by l	
Variables		
q_l^{dh}	Amount of district heating supply per l	MWh, GWh, TWh
q_l^{dec}	Amount of decentralized / on-site heat supply per l	MWh, GWh, TWh
q_l^{sur}	Amount of district heating in the surrounding of l	MWh, GWh, TWh
Parameters		
Q_{GENe}^{dh}	District heating in GENeSYS-MOD's results	MWh, GWh, TWh
q_l^{total}	Total heat demand per l	MWh, GWh, TWh
ϕ_l	Scaling factor to obtain effectively supplied area per l	1
A_l	Permanent settlement area per l	km^2
A_l^{sur}	Effectively supply area in surrounding communities per l	km^2

3.2. *Decommissioning model* to determine future gas network trajectory

This section explains the proposed methodology of the *decommissioning model*. First, Section 3.2.1 introduces the model. Then, Section 3.2.2 presents the mathematical formulation in detail. Section 3.2.3 explains the different model runs and defined scenarios. In Appendix B a detailed description of the test bed is provided. In the end, in Section 3.2.4, an outline of the latest version of the model which is an extension of the previously described model is given. It adds further functionality to the model in terms of how to deal with available gas demand and how to decommission economically inefficient gas pipelines before they reach their technical lifetime. Finally, the nomenclature of the model's variables and parameters is shown in Section 3.2.5.

3.2.1. Introduction to the main idea of the optimization problem

Figure 3.1 provides an overview of the method, including the interrelationships between the inputs (left), the modeling framework (middle), and the outputs (right). Generally, the inputs (and thus parameters) can be divided into three different categories, namely, technical parameters (e.g., existing pipeline capacity per network/pressure level and the year of construction), economic parameters (e.g., refurbishment investment costs per pipeline), and further empirical data needs (e.g., gas demand and supply at the local community level and seasonal gas storage capacities). The modeling framework (CANCEL) is developed as a linear program and is based on graph theory. It emphasizes the high spatial resolution in modeling. Particularly, a single node in the gas network graph corresponds to a community and covers an area of approximately 40 km^2 on average. The temporal resolution and thus investment planning horizon are until 2050, whereas an individual year is monthly resolved. Since the modeling framework is an investment and dispatch model, the outputs can also be divided into these categories. The outputs related to the investment decision are particularly the decommissioning and refurbishment investment decision per pipeline and gas network level. Additionally, the outputs encompass the dispatch of the gas networks on a monthly resolution. This includes the utilization of pipelines and particularly the gas demand and gas demand not supplied per community.

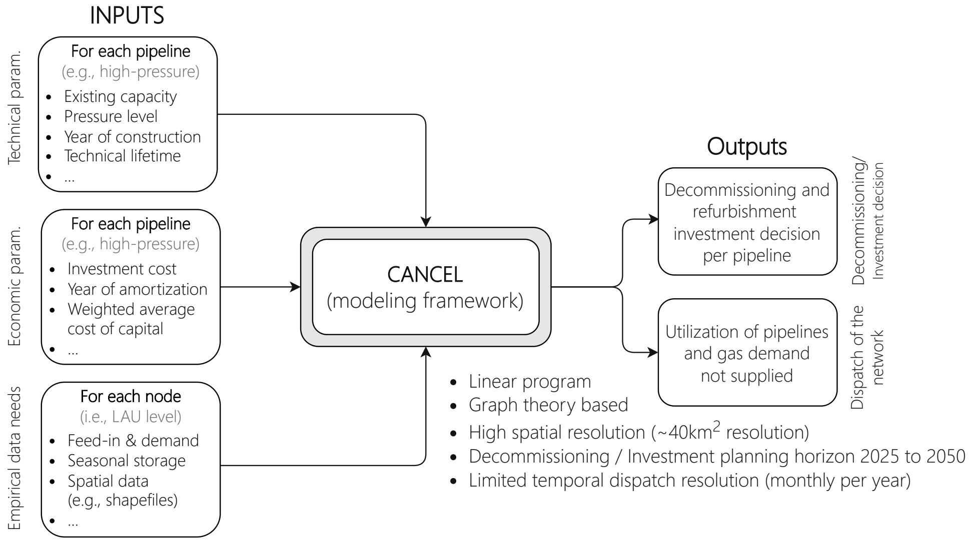

Figure 3.1.: Overview of the method

3.2.2. Mathematical formulation

This section is dedicated to providing a detailed mathematical formulation of the modeling framework. It starts with the objective function and has deliberately chosen the further order of equations so that the following equation builds on the previous one as far as possible.

Equation 3.6 shows the objective function of the model where $Capex$ is the net present value of the capital expenditures, $Opex$ of the operational expenditures, Rev of the revenues from the supply of gas demands, and $Purch$ of purchasing gas. $Capex$ and $Opex$ represent the decommissioning and investment decision, whereas Rev and $Purch$ the dispatch of the gas networks.

$$\min_{x} Capex + Opex - Rev + Purch \tag{3.6}$$

Additionally, x represents the decision variables of the model. Equation 3.7 shows the calculation of the discount factor per year y (α_y), where i is the interest rate and y_0 is the reference year.

$$\alpha_y = \frac{1}{(1+i)^{y-y_0}} \tag{3.7}$$

Building upon, $Capex$ is calculated as shown in Equation 3.8 where ω is the weighted average cost of capital and Π_y is the book value of the pipelines in y.

$$Capex = \sum_{y}^{y_{end}-1} \alpha_y \cdot \omega \cdot \Pi_y + \underbrace{\alpha_{y_{end}} \cdot \Pi_{y_{end}}}_{\text{early depreciation}} \tag{3.8}$$

Similarly, $Opex$ is calculated as shown in Equation 3.9 where λ_y is the fixed (operating) costs of the pipelines in y.

$$Opex = \sum_{y} \alpha_y \cdot \lambda_y \tag{3.9}$$

Equation 3.10 shows the calculation of the λ_y where c_l^{fix} is the specific fixed (operating) costs per l and $\gamma_{l,y}$ is the installed pipeline capacity per l in y.

$$\lambda_y = \sum_{l} c_l^{fix} \cdot \gamma_{l,y} \tag{3.10}$$

Equation 3.11 shows the calculation of $\gamma_{l,y}$ where $\gamma_{p,l,y}$ is the installed pipeline capacity at p and l in y and P_l the subset of all pipelines at l.

$$\gamma_{l,y} = \sum_{p \in P_l} \gamma_{l,y,p} \tag{3.11}$$

Equation 3.12 defines the capacity of a pipeline p at l in y where $\gamma_{p,l,y}^{pre}$ is the preexisting capacity and $\gamma_{p,l,y}^{ref}$ is the refurbished capacity of p at l in y.

$$\gamma_{p,l,y} = \gamma_{p,l,y}^{pre} + \gamma_{p,l,y}^{ref} \tag{3.12}$$

Similarly, Equation 3.13 defines the book value of a pipeline p at l in y, where $\Pi_{p,l,y}^{pre}$ is the book value of the preexisting pipeline (capacity), $\Pi_{p,l,y}^{ref}$ of the refurbished capacity of p at l in y, and $f^{ref}_{p,l}$ the discount factor at p and l.

$$\Pi_{p,l,y} = \Pi^{pre}_{p,l,y} + f^{ref}_{p,l} \cdot \Pi^{ref}_{p,l,y^{inv}_{p,l}} \tag{3.13}$$

Equation 3.14 sums the book values of all pipelines and network levels to obtain the total book value per y (Π_y).

$$\Pi_y = \sum_p \sum_l \Pi_{p,l,y} \tag{3.14}$$

The following equation defines the refurbished installed capacity per p at l in y resulting from the refurbishment (or decommissioning) decision in the year of the decision ($y^{inv}_{p,l}$).

$$\gamma^{ref}_{p,l,y} = \begin{cases} 0 & : \forall y \mid y < y^{inv}_{p,l} \\ \gamma^{ref}_{p,l,y-1} & : \forall y \mid y > y^{inv}_{p,l} \end{cases} \tag{3.15}$$

Equation 3.16 calculates the book value of the refurbishment investment at p and l in $y^{inv}_{p,l}$.

$$\Pi^{ref}_{p,l,y^{inv}_{p,l}} = c^{inv}_l \cdot \gamma^{ref}_{p,l,y^{inv}_{p,l}} \tag{3.16}$$

Equations 3.17 and 3.18 define the total gas export and import from n at l in y and m where $q_{p,l,y,m}$ is the amount of gas transported by p at l in y and m. Additionally, $P^{exp}_{n,l}$ and $P^{imp}_{n,l}$ define the subsets containing all pipelines that can export and import gas from n at l.

$$q^{exp}_{n,l,y,m} = \sum_{p \in P^{exp}_{n,l}} q_{p,l,y,m} \tag{3.17}$$

$$q^{imp}_{n,l,y,m} = \sum_{p \in P^{imp}_{n,l}} q_{p,l,y,m} \tag{3.18}$$

Equations 3.19 and 3.20 set the lower and upper bound of the amount of gas transported with respect to the installed pipeline capacity.

$$q_{p,l,y,m} \leq \gamma_{l,y,p} \tag{3.19}$$

$$-q_{p,l,y,m} \leq \gamma_{l,y,p} \tag{3.20}$$

The last two equations underline that a pipeline in the model has a certain direction in which the amount of gas transported is counted positively. Therefore, this direction defines for a node n whether a pipeline p is considered positively in the import or export balance (compare Equations 3.17 and 3.18). Exemplarily, a pipeline p could be considered in the export sum of a node n on the one hand with a positive value if p in fact exports gas from n but on the other hand with a negative value if p imports gas to n in the dispatch of the model decision[3].

Equation 3.21 shows the general formulation of the balance constraint at n where $q^{sto}_{n,l,y,m}$ is the amount of gas from or to storage. Particularly, this equation is defined for each network level l. The coupling of different network levels (e.g., the high- and mid-pressure network levels) is considered implicitly in the definition of the different gas demand variables (see Equation 3.22 below). Additionally, ξ_m is a scaling (or transformation) factor that is defined for each month and is used to couple total values per month (e.g., $q^{dem}_{n,l,y,m}$) and peak values.[4]

$$q^{fed}_{n,l,y,m} - q^{dem}_{n,l,y,m} - \xi_m \cdot \left(q^{exp}_{n,l,y,m} + q^{imp}_{n,l,y,m} \right) + q^{sto}_{n,l,y,m} = 0 \tag{3.21}$$

Exemplarily, Equation 3.22 shows the calculation of the gas demand at network level l, where $q^{del}_{n,l',y,m}$ is the amount of gas delivered from network level l to l' and $q^{dem,loc}_{n,l,y,m}$ is the local gas demand supplied at n. For example, l could correspond to the transmission network level and l' to the high-pressure network level. Note that the pressure in pipelines at l is higher than at l'.

$$q^{dem}_{n,l,y,m} = q^{dem,loc}_{n,l,y,m} + q^{del}_{n,l',y,m} \tag{3.22}$$

---

[3] This approach is used to prevent binary decision variables. Particularly, binary decision variables increase the computation time of graph-theory-based models significantly. For more information, it is referred to (Kotzur et al., 2021) and their comprehensive review on how to handle complexity in energy system optimization.

[4] It reflects the fact that Equation 3.21 encompasses variables that are associated with nodes ($q^{fed}_{n,l,y,m}$, $q^{dem}_{n,l,y,m}$, $q^{sto}_{n,l,y,m}$) modeled at a monthly resolution and with lines ($q^{exp}_{n,l,y,m}$, $q^{imp}_{n,l,y,m}$) modeled at a hourly resolution.

Equation 3.23 is the essential demand constraint and sets the upper bound of the decision variable $q^{dem,loc}_{n,l,y,m}$ to the maximum available gas demand ($d^{max}_{n,l,y,m}$), in which is defined as an input parameter.

$$q^{dem,loc}_{n,l,y,m} \leq d^{max}_{n,l,y,m} \tag{3.23}$$

Particularly, Equation 3.23 allows the model by its mathematical operator with the less than or equal sign ($\leq$) to decide between supplied and not supplied gas demand at the nodal level. This decision is in the foreground of the conducted analysis here, which is why Equation 3.23 is used to define different model runs and thus scenarios. Accordingly, the model runs and scenarios differ by the individual specification of the demand constraint (i.e., $\leq$ or $=$ and $d^{max}_{n,l,y,m}$ as the upper bound of the equation). It is referred to Section 3.2.3 for a detailed description of the model runs and scenarios.

The (total) quantity of gas fed at l' is defined as stated in Equation 3.24 where $q^{fed,local}_{n,l',y,m}$ is the quantity of gas fed directly from n.

$$q^{fed}_{n,l',y,m} = q^{fed,local}_{n,l',y,m} + q^{del}_{n,l',y,m} \tag{3.24}$$

Equation 3.25 defines the balance constraint of a storage unit. Additionally, $q^{sto,soc}_{n,l,y,m}$ is the state of charge. η is the storage efficiency and thus models the losses with respect to the storage of gas between 2 months.

$$q^{sto,soc}_{n,l,y,m} = \eta \cdot q^{sto,soc}_{n,l,y,m-1} + q^{sto}_{n,l,y,m} \tag{3.25}$$

Equation 3.26 calculates the revenues created by the local gas demand supplied where $p^{loc}_{l,y}$ is the price.

$$rev_{n,l,y,m} = p^{loc}_{l,y} \cdot q^{dem,loc}_{n,l,y,m} \tag{3.26}$$

Accordingly, the revenues (Rev from the objective function in Equation 3.39) are calculated as shown in Equation 3.27.

$$Rev = \sum_{y}\sum_{n}\sum_{l}\sum_{m} \alpha_y \cdot rev_{n,l,y,m} \tag{3.27}$$

$Purch$ is calculated as shown in Equation 3.28, where $p^{gas}_{y,m}$ is the gas price in y and m.

$$Purch = \sum_{y}\sum_{n}\sum_{m} \alpha_y \cdot p^{gas}_{y,m} \cdot q^{del}_{n,l,y,m} \quad \text{with } l = \text{high-pressure} \tag{3.28}$$

Particularly, the influence of the gas price in the dispatch of gas networks is considered if gas is delivered from the transmission to the high-pressure network level. This is why Equation 3.28 is only defined for the high-pressure network level. This simplification is quite justified, first, because the gas storage, whose operation is significantly determined by the monthly gas price, are only present at the high-pressure level, and second, because no gas delivery from the high-pressure level to the transmission system is possible in the model.

3.2.3. Model runs and defined scenarios

Three different model runs are conducted, each associated with a scenario. Thereby, the model runs and defined scenarios differ in terms of consideration of the coverage of existing gas demands. Particularly, this is achieved by the modification and tailor-made adaption of the gas demand constraint in Equation 3.23. As mentioned above, this emphasizes the model decision regarding the cost-optimal amount of gas demand supplied and not supplied. Table 3.2 provides information for all model runs and associated scenarios related to the formulation/adaption of Equation 3.23, the obtained gas network design, and the individual results. Note that the cost-optimal gas demand supplied ($\overset{*}{\mathbf{q}}^{dem}_{n,l,y,m}$) without ensured supply (output of model run 1) is used as an input for model run 2 since it allows the tailor-made adaption of Equation 3.23 to assess the shadow price $\lambda^{CO}_{n,l,y,m}$ for the cost-optimal gas network without ensured gas supply. Similarly, model run 3 is used to obtain the shadow price $\lambda^{ES}_{n,l,y,m}$ in case of cost-optimality with an ensured supply of the gas network.

Input			Output
Model run	Formulation of Equation 3.23	Scenario description/gas network design (abbreviation)	Results or further used variable
1	$q^{dem}_{n,l,y,m} \leq d^{max}_{n,l,ym}$	Cost-optimal without ensured supply (CO)	Demand supplied ($\overset{*}{\mathbf{q}}^{dem}_{n,l,y,m}$)
2	$q^{dem}_{n,l,y,m} = \overset{*}{\mathbf{q}}^{dem}_{n,l,y,m}$		Shadow price ($\lambda^{CO}_{n,l,y,m}$)
3	$q^{dem}_{n,l,y,m} = d^{max}_{n,l,ym}$	Cost-optimal with ensured supply (ES)	Shadow price ($\lambda^{ES}_{n,l,y,m}$)

Table 3.2.: Model runs and associated formulation of the gas demand constraint (Equation 3.23), scenarios, and results or further used variables.

3.2.4. Further functionalities and extensions

Selected functionalities that extend the standard model are described below. These have been developed as part of an ongoing national project. At the time of writing, the project is in its final stages. However, the results of the extended model cannot be published until a later date, so only the methodology is presented.

In principle, the extended model includes new functionalities, including how to deal with available gas demand and how to decommission economically inefficient gas pipelines before they reach their technical lifetime. These are explained in more detail below.

3.2.4.1. Dealing with available gas demand

The default model decides whether or not available gas demands are supplied by the network mainly by the trade-off decision between the costs of pipelines (*Capex* and *Opex* in Equation 3.8 and 3.9 respectively) on the one side, and the revenues achieved by transporting gas through the pipeline to meet gas demand (*Ref* in Equation 3.27). In the extended model, decision variables $q^{dem,loc,not}_{n,l,y,m}$ that represent the amount of gas demand that is not met (see Equation 3.29) are added.

$$q_{n,l,y,m}^{dem,loc} + q_{n,l,y,m}^{dem,loc,not} = d_{n,l,y,m}^{max} \tag{3.29}$$

Latter is used to calculate the costs when not meeting gas demand through the network. It is called the "Cost of Alternative Supply" (CoAS). The mathematical formulation for the CoAS is shown in Equation 3.30.

$$CoAS_{n,l,y,m} = q_{n,l,y,m}^{dem,loc,not} \cdot p^{dem,loc,not} \tag{3.30}$$

In particular, the parameter $p^{dem,loc,not}$, given in EUR/MWh, is very interesting here, as it allows us to link investment in gas networks and associated gas pipelines with the option of meeting gas demand not through the gas network but, for example, by using trucks to transport gas to where it is needed. However, this economic comparison is by no means trivial. This is particularly true when considering the flexibility of networks to deliver energy where it is needed. To take into account the flexibility of piped gas, which acts like on-site storage, the cost of transportation, as well as the local investment required in local storage capacity when not supplied by the network, are included. This approach is essential when comparing gas supply through pipelines with gas supply through trucks as it is ultimately the question of how to supply the same energy service in both cases. Consequently, $p^{dem,loc,not}$ consists of two parts as shown in Equation 3.31, whereas $p^{transport}$ represents the costs for transporting gas through trucks and $p^{storage,loc}$ the costs for the local gas storage capacity. Note that $p^{storage,loc}$ significantly depends on the size of the storage and whether for instance monthly or bi-monthly storage is needed.

$$p^{dem,loc,not} = p^{transport} + p^{storage,loc} \tag{3.31}$$

To give an idea, $p^{transport}$ is estimated in the range of 20 EUR/MWh. Of course, this fraction is actually distance dependent, but it is also estimated with this value in the literature for the distribution network as a first approximation (see e.g. in (Economics, 2021)). $p^{storage,loc}$ is in the range of 200 to 300 EUR/MWh, depending mainly on the size of the storage as mentioned above. The higher estimate, for example, is mainly in line with the assumptions made in (Dias et al., 2020). In addition, estimates for other local gas storage capacities, such as hydrogen, can also be used to estimate local storage costs. In this respect, the study in (Abdin et al., 2022) provides relevant information and data for local hydrogen storage capacities. Building upon the assumptions made therein, gaseous storage costs are between 250 and 400 EUR/MWh. However, when comparing the storage costs between gas and hydrogen, it is important to keep in mind the significantly higher pressure levels for hydrogen than for gas. This property is one of the main drivers of storage costs.

3.2.4.2. Decommissioning gas pipelines before the technical lifetime

The decommissioning of gas pipelines, before they reach the end of their technical life, is an important function when there are pipelines of different ages. In particular, pipelines with a "young age", i.e. with a long period of time until the end of their technical life, offer the potential for cost savings in decommissioning. This is mainly achieved through savings in maintenance and fixed costs of pipelines (i.e., opex).[5] In the case study here, the assumed age structure of gas pipelines results in the fact that the time of the refurbishment investment decision and the time of the early decommissioning decision of pipelines coincide. However, in general, this is not the case, which led us to add Equation 3.32 to the model including the decision of early decommissioning of pipelines. Therein, σ is a binary decision variable, and can thus take either the value of zero or one.

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[5] From a regulatory perspective on gas networks, it can also be argued that capex can be saved by saving depreciation costs. However, from an economic point of view, the investment costs and therefore the capex has already been made. It is therefore a question of cost distribution rather than cost saving.

$$\gamma_{p,l,y}^{early} = \sigma \cdot \gamma_{p,l,y}^{pre} \tag{3.32}$$

Consequently, Equation 3.12, which determines the total available transport capacity of a pipeline is extended as shown in Equation 3.33.

$$\gamma_{p,l,y} = \gamma_{p,l,y}^{pre} + \gamma_{p,l,y}^{ref} - \gamma_{p,l,y}^{early} \tag{3.33}$$

In addition to the detailed described new functionalities of the model, the consideration of the capex in the model is extended. Therefore, the depreciation costs of the investments into refurbished pipelines are included. Equation 3.34 shows the formulation of the depreciation costs $\Delta_{p,l,y}$ that are added to the capex as formulated in Equation 3.8. τ represents the economic depreciation period.

$$\Delta_{p,l,y} = \frac{\Pi_{p,l,y_{p,l}^{inv}}^{ref}}{\tau} \qquad : \forall y \mid y > y_{p,l}^{inv} \tag{3.34}$$

3.2.5. Nomenclature *decommissioning model*

Type	Description	Unit
Set and index		
$p \in \mathcal{P} = \{1, \ldots, P\}$	Pipeline for gas transport, index by p	
$n \in \mathcal{N} = \{1, \ldots, N\}$	Node of the gas network, index by n	
$l \in \mathcal{L} = \{1, \ldots, L\}$	Gas network level (e.g., high-pressure), index by l	
$y \in \mathcal{Y} = \{1, \ldots, Y\}$	Years, index by y	
$m \in \mathcal{M} = \{1, \ldots, M\}$	Months, index by m	
Primal Decision Variables (Selection)		
$Capex$	Capital expenditures	EUR
$Opex$	Operational expenditures	EUR
Rev	Revenues generated by gas supply	EUR
$\gamma_{p,l,y}$	Capacity of pipeline p at l in y	MW, GW
$q^{dem}_{n,l,y,m}$	Gas demand supplied at n and l in y and m	MWh, GWh
$q_{p,l,y,m}$	Quantity of gas transported at p and l in y and m	MW, GW
$\Pi_{p,l,y}$	Book value of pipeline p at l in y	EUR
Dual Decision Variables		
$\lambda^{CO}_{n,l,y,m}$	Cost-optimal shadow price of gas supply without ensured supply at n and l in y and m	EUR/MWh
$\lambda^{ES}_{n,l,y,m}$	Cost-optimal shadow price of gas supply with ensured supply at n and l in y and m	EUR/MWh
Parameters (Selection)		
$\gamma^{pre}_{p,l,y}$	Preexisting capacity of pipeline p at l in y	MW, GW
$d^{max}_{n,l,y,m}$	Maximum gas demand at n and l in y and m	MWh, GWh
$q^{fed}_{n,l,y,m}$	Quantity of gas fed in at n and l in y and m	MW, GW
c^{inv}_{l}	Specific refurbishment investment costs at l	EUR/MW/km
$\Pi^{pre}_{p,l,y}$	Book value of preexisting pipeline p at n in y	EUR
$y^{inv}_{p,l}$	Year of refurbishment/decommissioning per p and l	1
ω	Weighted average cost of capital	%
i	Interest rate (for calculating the net present value)	%

3.3. *Demystifying model* for sectoral planning of decarbonized distribution grids

In the following, the methodology of the *demystifying model* is presented. It is divided into two main parts. The coupled open-source models are described in Section 3.3.1. Then, a comprehensive set of benefit indicators is introduced in Section 3.3.2. The nomenclature of the model's variables and parameters is given in Section 3.3.3. The numerical example and scenarios are defined in Appendix C.

3.3.1. Linking the two open-source models "rivus" and "GUSTO"

This work uses the two existing open-source models "rivus" (Dorfner, 2016) and "GUSTO" (Zwickl-Bernhard and Auer, 2021b). Consequently, the approach provides a framework that includes a complete analysis toolbox using the different/unique model strengths. Thereby, rivus facilitates the modeling of the (local) energy system with a high spatial resolution. In contrast, GUSTO's strength is the modeling of local energy systems (i.e., small areas, such as neighborhoods or communities) with a high temporal resolution (e.g., hourly). Exploiting the models' differences and strengths in a single analysis framework that arises from the coupling approach provides a comprehensive toolset to answer this work's research question. The two open-source models used are already applied in different scientific contributions (e.g., in (Fleischhacker et al., 2019)[6], (Zwickl-Bernhard and Auer, 2021b), (Zwickl-Bernhard and Auer, 2021a)). Therefore, the following sections highlight both models' most relevant aspects only (in the context of this work) and, in addition, explain the specific functionality extensions of rivus that are carried out in this work.

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[6] Note that a similar methodological concept has been provided in (Fleischhacker et al., 2019). However, this study is not only a methodological and analytical extension of the latter reference according to the description of the own contribution and novelties in Section 2.5, but also the level of detail and granularity in this work, as well as the complexity and spatial extension of the test-bed in the urban neighborhood exceeds that one in Fleischhacker et al., 2019 substantially.

3.3.1.1. Existing open-source model rivus

The open-source model rivus is developed by Dorfner and published under the terms of the GNU General Public License. The model itself is well-documented, and the Python codebase is available on GitHub[7]. In the following, relevant aspects of the model are described. For a more detailed description, refer to the model's manual, the GitHub repository, and Dorfner, 2016. The model is a mixed-integer linear program for cost-minimizing capacity planning of energy infrastructure networks. In general, different spatial scales of energy systems can be analyzed. In addition, the model allows to consider different energy carriers or commodities (e.g., electricity, natural gas, heating/cooling). The temporal resolution is represented by a few selected characteristic weighted time steps (i.e., base, high, peak).

The main model elements are (i) commodity sources, (ii) commodity transport connections (e.g., distribution lines), and (iii) commodity sinks. Hence, the optimal cost-minimizing solution ensures the satisfaction of the energy demand by using the available energy carrier supply and expansion of the transport connection capacities. Consequently, the essential model constraints address the limitation of the (nodal) commodity sources availability, the maximum transport connection capacity, and the (nodal) energy demand-supply satisfaction. The inputs of the model are technical and economic parameters (e.g., length-specific investment costs, specific capital costs, maximum transport line capacities, etc.) and high-resolved spatial data[8]. The outputs of the model are, among others, the commodity transport connection capacities.

3.3.1.2. Implementation of economies of scale

There are a variety of possibilities to consider economies of scale in energy systems. An example is the reduction of specific investment costs of energy

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[7] `https://github.com/tum-ens/rivus`.

[8] This data is provided in shapefiles, and its handling requires considerable experience. The GitHub repository by Dorfner already provides some small case examples. Furthermore, all relevant files of this work are published in the authors' GitHub profile in a repository. Thus, the authors are committed to removing possible barriers in this context.

technologies and infrastructure as a result of large-scale penetration as a result of technological "learning rates". This is not the approach adopted in this work. Instead, economies of scale of a massive district heating and cooling network expansion are considered from the perspective of opportunity costs and penalty payments due to CO_2 emissions.

In many cases, scientific contributions deal with the optimal expansion path and the corresponding design of district heating networks[9] (see in (Nussbaumer and Thalmann, 2016)). In many instances, the existing district heating distribution grid design aims for supplying special heat consumers with a significant heat demand (see the purple line in Figure 3.2a). Subsequently, further expansion stages can be realized: (Stage 0) connecting technically and economically feasible consumers to the existing infrastructure (e.g., heat consumers in the immediate proximity of the existing infrastructure) and (Stage 1/2/3) expanding the existing infrastructure to further connect those in addition to justify feasibility. Thereby, the different stages (1-3) distinguish by their heat density and consequently by their ratio of additional implemented line length and corresponding heat demand supplied in the case of connection[10] (see Figure 3.2b).

In general, non-linearities along the optimal district heating grid expansion path (i.e., additional line lengths and capacities) and additional heat supply demand are indicated in the connection curve in Figure 3.2b. The implication of this non-linear curve is taken into account in this work's objective function as follows: each point on the non-linear optimal expansion curve factors explicit (e.g., capital costs) and implicit costs. The latter is declared in this work as opportunity costs. These significantly depend (inversely) on the expansion scale of the district heating network (e.g., economies of scale) and consequently directly on the gas-based heat supply. Hence, the objective function is extended as follows:

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[9] Note that this applies to the same extent for the district cooling network. Therefore, it is sufficient to only address the district heating network in the following.

[10] Note that in this work *Case A - Baseline* represents the status quo, and *Case C - Network* represents the exhaustive optimal district heating grid infrastructure expansion within the feasible area. Both cases represent the corners of the analysis in this work. For a detailed scenario definition, it is referred to Section C.2 in the Appendix.

$$\bar{costs} = costs^{cap} + costs^{eos} \tag{3.35}$$

$costs^{cap}$ is the capital and investment costs (i.e., specific costs in EUR/MW and EUR/m), $costs^{eos}$ is the implicit opportunity costs as so-called economies of scale. These latter costs are defined as:

$$costs^{eos} = \sum_{\tau} \alpha_{\tau} \cdot \pi \cdot h \cdot r^{\tau} \cdot \Delta_{\tau}^{CO_2} \cdot p_{\tau}^{CO_2} \tag{3.36}$$

α_{τ} is the annuity present-value factor in 1/year, π is the natural gas connection capacity in MW, h is the full-load hours (or capacity factor) of the natural gas infrastructure in h, r is the renovation rate as a demand reduction factor in %, $\Delta_{\tau}^{CO_2}$ is the difference in specific emissions between natural gas and district heating, and $p_{\tau}^{CO_2}$ is the CO_2 price in EUR/t for each year τ. Hence, $costs^{eos}$ reflects CO_2 emission penalty payments due to gas-based heat supply and limited district heating energy supply (infrastructure expansion). The relation between natural gas connection capacity π and district heating expansion degree is the optimal district heating expansion path f in Equation 3.37

$$\pi = f\left(\sum_{i} \xi_{i}^{dh}\right) \tag{3.37}$$

$\xi_{i,s}^{dh}$ is the implemented line length of the district heating distribution grid at a specific line i. The modus operandi to determine f is as follows. In the first step, the optimization model calculates the optimal district heating expansion path taking into account discrete expansion stages. Hence, a single model calculation run includes the limitation of the total district heating line length as follows

$$\sum_{i} \xi_i^{dh} \leq \xi_s^{dh,max} \tag{3.38}$$

$\xi_s^{dh,max}$ is the maximum district heating grid line length at expansion stage s. Simultaneously, the natural gas connection capacity can be calculated. Finally, this (non-linear) relation (Equation 3.37) is implemented in the optimization framework as an input using the well-known SOS2 variables[11]. This approach highlights a perspective on large-scale energy distribution grid planning decisions (i.e., district heating and cooling network expansion) and its emission cost-saving potentials. In particular, related potentials are even disaggregated on a human scale and building level, respectively, in this work using tailor-made benefit indicators. Further details on these indicators can be found in Section 3.3.2.3.

3.3.1.3. Existing open-source model GUSTO

This section briefly explains the open-source model GUSTO. The model is a mixed-integer linear program and builds upon the existing open-source model "urbs"[12] (Dorfner, 2016). Since the authors already published works using this model, it is referred to the references (Zwickl-Bernhard and Auer, 2021b) and (Zwickl-Bernhard and Auer, 2021a). Therefore, it can be dealt with the most relevant aspects and highlights of the model in the following. GUSTO aims to optimize energy technology planning and technology dispatch on a local level taking into account a high temporal resolution. However, the model's spatial scope is, to some extent, limited. The tailor-made functionality expansion compared with the base model urbs provides a complete toolkit for low-level local energy system analyses (e.g., energy communities or local neighborhoods). In general, different objective functions can be considered. Among others, minimizing total costs of supply (i.e., investments and operation costs) and minimizing total greenhouse gas emissions are those

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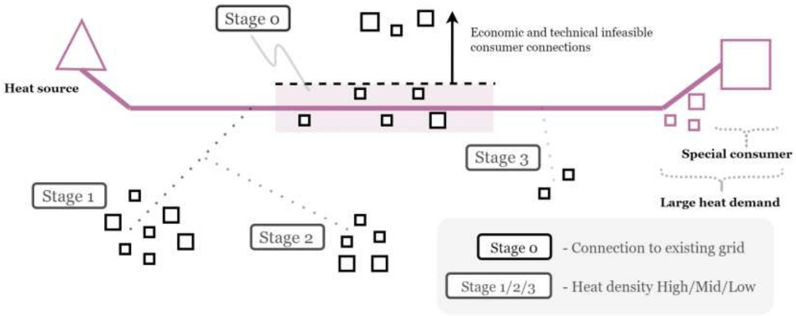
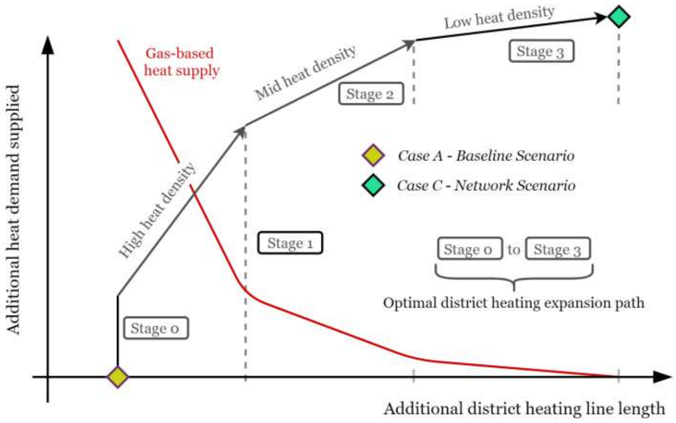
[11] A specific binary decision variable set enables the linearization of non-linear relations between continuous model decision variables.

[12] https://github.com/tum-ens/urbs.



(a) Local area and its different district heating expansion paths (Stage 0-3) taking into account the existing infrastructure (magenta)



(b) Optimal district heating expansion path and corresponding gas-based heat supply considering different stages of expansion for varying heat density areas

Figure 3.2.: Indication of optimal district heating expansion paths on the basis of the existing infrastructure (a) and resulting non-linear relation between the district heating network and gas-based heat supply (b)

with the highest practical applicability. In addition, the model allows taking into account the provision of different energy services (and commodity supply). The main constraints of the model's mathematical framework are the energy demand satisfaction of the (local) energy services (e.g., electricity, heating/cooling). In general, GUSTO includes also natural gas as an energy carrier (not needed here).

In this modeling framework, GUSTO's results are used as an input for the rivus model in the *High Electrification* decarbonization pathway (see Section

C.2). This scenario describes an (almost) complete electrification of the provision of local heating and cooling services within the neighborhood. The model coupling modus operandi is as follows. First, GUSTO calculates the optimal energy technology dispatch on the building level (different building types are carried out - see C.3). Note that the energy technology investment decision is determined by the corresponding decarbonization pathway (i.e., small-scale heat pumps for heat and compression machines for cooling supply). The high-temporal resolved results provide (i) peak demand and (ii) temporal distribution of the required/resulting electricity demand. Both characteristics are included in the rivus model's inputs. With respect to model coupling approaches, this can be denoted as so-called soft coupling.

3.3.2. Definition of benefit indicators

This section provides the definition and description of this work's benefit indicators. They are founded on comprehensive literature research (see among others in (Vera and Langlois, 2007), (Kemmler and Spreng, 2007) and also (Pramangioulis et al., 2019)). Moreover, the expansion of the tailor-made set of benefit indicators allows for a detailed benchmarking of small-scale local energy systems committed to deep decarbonization and sustainable energy supply. Four different benefit indicators dimensions are carried out.

3.3.2.1. Capability and resource benefit indicators

These qualitatively defined indicators address energy system benefits from a capability/resource perspective. This means that the different scenarios (or subsequently decarbonization pathways) enable wide-range resource utilization options. The corresponding benefit indicators (see Table 3.3) serve as a qualitative benchmark of their exploitation potentials. For example, *Waste* qualitatively addresses the integration/utilization potential for the provision of energy services using waste incineration (analogous to the remaining items in Table 3.3).

Indicator	Description	Unit
Waste	Waste incineration	None/Low/Mid/High
Geothermal	Large-scale	
On-site PV	Rooftop, building-integrated	
Heat pump	Small- and large-scale	
Green gas	Biomethane, synthetic gases	
Solarthermal	Rooftop	

Table 3.3.: Description of capability and resource benefit indicators

3.3.2.2. Technological benefit indicators

These quantitative indicators touch on technological benefits from a practical implementation perspective (see Table 3.4). *Peaks* describes the network connection capacity expected to supply the neighborhood's energy services, and *Length* is the total distribution line length in the neighborhood. Note that both indicators take into account sector coupling and, therefore, include all energy carriers/commodities.

Indicator	Description	Unit
Peak	Peak public network connection capacity	MW
Length	Distribution line length	km

Table 3.4.: Description of technological benefit indicators

3.3.2.3. Economic benefit indicators

These quantitively defined economic indicators assess both cost and saving benefits in the different scenarios (see Table 3.5). Thereby, *Costs* describes the annualized technology cycle costs[13]. *Forex* indicates the cost savings per year by replacing natural gas in the energy service supply. In addition, *End-user* considers the average costs per building including (i) the capital and investment costs as well as (ii) the CO_2 price-driven penalty payments as introduced in Section 3.3.1.2.

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[13] I.e., economic depreciation of technologies and infrastructures.

Indicator	Description	Unit
Costs	Annualized technology cycle costs	EUR/MWh
Forex	Annual natural gas forex savings	$/year
End-user	Average end-user energy and emission costs	EUR/building

Table 3.5.: Description of economic benefit indicators

3.3.2.4. Sustainability benefit indicators

Finally, these quantitative indicators address relevant sustainability benefits and benchmark the deep decarbonization process and success in the urban neighborhood. Due to the self-explanatory (and intuitive) description in Table 3.6, a further detailed explanation is renounced.

Indicator	Description	Unit
CO_2	CO_2 tons saved per year	tCO_2/year
Fossil	Reduced fossil fuel consumption per year	MWh

Table 3.6.: Description of sustainability benefit indicators

3.3.3. Nomenclature *demystifying model*

Type	Description	Unit
Set and index		
$c \in \mathcal{C} = \{1, \ldots, C\}$	Commodity/energy carrier, index by c	
$n \in \mathcal{N} = \{1, \ldots, N\}$	Node of the energy network, index by n	
Decision Variables		
c_{inv}	Total investment costs	EUR
c_{fix}	Total annual fix costs	EUR
c_{eos}	Total cost savings from economies-of-scale	EUR
$P^{max}_{c,l,k}$	Line capacity of commodity c between node l and k	MW
$q^{source}_{c,n}$	Connection capacity to the public grid of c at node n	MW
$\sigma_{c,l,k}$	Supplied demand of c by line between l and k	MW
$\xi_{c,l,k}$	Line implemented of c between l and k (Binary)	
l_c	Total line length of commodity c	m
$\psi_{c,l,k}$	Directional use of line of c between l and k (Binary)	

3.4. *Equitable model* for a sustainable heating switch of buildings

This section explains the methodology and the optimization framework of the *equitable model*. After a general introduction to the model in Section 3.4.1, a detailed description of the mathematical formulation is presented in Section 3.4.2. The model's nomenclature of the variables and parameters is given in Section 3.4.3. The case study, input data, and further information can be found in Appendix D.

3.4.1. Overview on the methodology

In general, the three agents governance, property owner, and tenants are considered in the model with the following characteristics:

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

The property owner of the multi-apartment building provides the heating system for the tenants and is profit-oriented. Thus, a heating system change toward a sustainable alternative is only realized in case of the economic viability of an investment. In this context, the property owner 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).

The tenant rents a dwelling/unit within the multi-apartment building from the property owner and has rent-related and energy-related spendings. The tenant cannot change the heating system on its authority but depends on the property owner's willingness to invest into a sustainable alternative. In connection with the existing heating system, the tenant's costs are increasing in consideration of CO_2 emissions and associated CO_2 prices. Nevertheless, the tenant aims to limit total costs in case of a heating system change at the level of the initial condition.

Figure 3.3 shows a sketch illustrating the interrelations between the governance, the property owner, and the tenants. The governance can support the property owner financially through investment grants and by the permission of rent charge adjustments. At the same time, tenants are supported by a heating cost 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 property owner and the tenant.

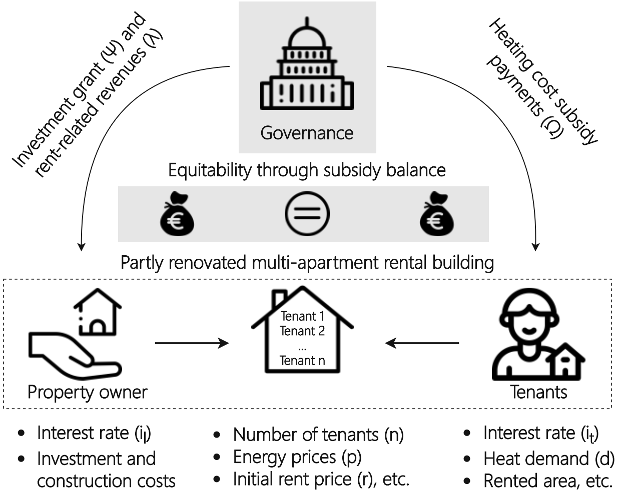

Figure 3.3.: Sketch of the model illustrating the interrelations between the governance, property owner, and tenants. Financial support from the governance is socially balanced at the partly renovated multi-apartment rental building.

3.4.2. Mathematical formulation of the *equitable 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.

3.4.2.1. Model's objective function

The objective function of the model is to minimize governance's total costs, including investment grants and subsidy payments[14]. Therefore, the objective function can be written as follows:

$$\min_{x} \Psi + \sum_{y} \sum_{m} \frac{n}{(1+i_g)^y} \cdot \Omega_{y,m} \tag{3.39}$$

where Ψ is the investment grant paid to the property owner and $\Omega_{y,m}$ is the heating costs subsidy payment paid to a single tenant in year y and month m. In addition, n is the number of tenants[15] and i_g the governance's interest rate. The model's decision variables are included in the decision variable vector x.

3.4.2.2. Model constraints

Equation 3.40 defines the financial support parity between the property owner and all tenants at the multi-apartment building level from the governance's perspective

$$\underbrace{\Psi + n \cdot \sum_{y} \sum_{m} \frac{a \cdot r_{y,m}}{(1+i_g)^y}}_{\text{property owner financial support}} = \underbrace{n \cdot \sum_{y} \sum_{m} \frac{\Omega_{y,m}}{(1+i_g)^y}}_{\text{tenants financial support}} \tag{3.40}$$

---

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

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

where a is the area of a tenant's dwelling and $r_{y,m}$ is the rent charge adjustment associated with the heating system change in y and m. The equation operationalizes equitability as a subsidy balance. Moreover, social equity between the property owner and tenants consists in both bearing no economic burden of the energy transition (i.e., higher energy and/or CO_2 prices). These costs are borne by governance. Note that other definitions of and views on equitability in sustainable energy systems exist in literature[16]. Equation 3.41 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)

$$n \cdot d_{y,m} \leq q_{y,m} \quad : \forall y, m \tag{3.41}$$

where $d_{y,m}$ is the total heat demand of a tenant's dwelling and $q_{y,m}$ is the heat demand covered by the alternative heating system in y and m. Building on this, Equation 3.42 defines the minimum required newly installed capacity of the heating system alternative

$$\alpha_m \cdot q_{y,m} \leq \pi \quad : \forall y, m \tag{3.42}$$

where α_m is the load factor transforming the monthly amount of heat demand to the corresponding peak demand. Equation 3.43 defines the property owner's overnight investment costs (ζ)

$$\zeta = \pi \cdot c_{alt} + n \cdot c_{con} - \Psi \tag{3.43}$$

where c_{alt} is the specific investment costs of the heating system alternative and c_{con} is the construction costs to adapt one dwelling/unit. Equation 3.44 defines the upper bound for the investment grant

$$\Psi \leq \hat{d} \cdot c_{alt} + n \cdot c_{con} \tag{3.44}$$

where $\hat{d}$ is the peak value of the heat demand. Equation 3.45 defines the

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[16] E.g., Green and Gambhir (2020).

rent-related revenues of the property owner ($\lambda_{y,m}$)

$$\lambda_{y,m} = a \cdot n \cdot r_{y,m} \quad : \forall y, m \tag{3.45}$$

As defined here (and as used in Equation 3.46), this is the adjustment of the rent-related revenues (not the total rent-related revenues). The initial rent price does not enter this definition. Equation 3.46 sets the property owner's net present value of the alternative heating system investment equal to 0

$$-\zeta + \sum_{y} \sum_{m} \frac{1}{(1+i_l)^y} \cdot \lambda_{y,m} = 0 \tag{3.46}$$

where i_l is the property owner's interest rate. The equation ensures that the landlord does not gain profits through the subsidy payments from the governance (i.e., avoidance of a snowball effect for the governance). Equation 3.47 defines the initial annual spendings of all tenants (κ_y) using the existing heating system

$$\kappa_y = n \cdot (\bar{r} \cdot a + \sum_{m} q_{load,y,m} \cdot p_{init,y,m}) \quad : y = y_0 \tag{3.47}$$

where $\bar{r}$ is the initial rent price and $p_{init,y,m}$ is the price of the conventional fuel initially supplying the heat demand in y and m. Building on this, Equation 3.48 sets the tenants' total spendings (K_{init})

$$K_{init} = -\sum_{y} \frac{1}{(1+i_t)^y} \cdot \kappa_{y_0} \tag{3.48}$$

where κ_{y_0} represents the initial tenants' spendings from Equation 3.47 above, and i_t the tenant's interest rate. Equation 3.49 defines the total spending of all tenants (K_{alt}) in case of implementing the sustainable heating system alternative.

$$K_{alt} = -\sum_{y} \sum_{m} \frac{n}{(1+i_t)^y} \left(a \cdot (\bar{r} + r_{y,m}) + q_{y,m} \cdot p_{alt,y,m} - \Omega_{y,m}\right) \tag{3.49}$$

The middle term within the brackets on the right-hand side represents the fuel costs of the heat system alternative. Equation 3.50 defines constant remaining spending (i.e., economic viability) for the tenants in case of a heating system change. The equation ensures that the tenant does not gain profits through the subsidy payments from the governance (i.e., avoidance of a snowball effect for the governance).

$$K_{alt} = K_{init} \tag{3.50}$$

Equation 3.51 defines constant heating costs subsidy payments and Equation 3.52 is the constant total rent price for a tenant in y.

$$\Omega_{y,m} = \Omega_{y,m-1} \quad : y \tag{3.51}$$

$$\bar{r} + r_{y,m} = \bar{r} + r_{y,m-1} \quad : y \tag{3.52}$$

Equation 3.53 allows rent charge adjustments by the property owner only every two years and Equations 3.54 and 3.55 set an upper bound to the rent charge adjustment

$$\bar{r} + r_{y,m} = \bar{r} + r_{y-1,m} \quad : \forall y \backslash \{y_0\}, m \text{ if } y \bmod 2 = 0 \tag{3.53}$$

$$\bar{r} + r_{y,m} \leq \rho \cdot \bar{r} \quad : y = y_0 \tag{3.54}$$

$$\bar{r} + r_{y,m} \leq \rho \cdot (\bar{r} + r_{y-1,m}) \quad : \forall y \backslash \{y_0\} \tag{3.55}$$

by introducing ρ as the rent charge adjustment upper bound. Table 3.7 summarizes the mathematical formulation and provides a qualitative overview of the model.

Equation		Qualitative/high-level explanation of the mathematical formulation		
Number	Dimension	Agent/party	Keyword	Brief description
3.39	1	G	Obj. function	Minimize governance's total costs, including investment grants and subsidy payments
3.40	1	PO & T	Parity	Financial support parity between the property owner and all tenants at the multi-apartment building
3.41	$y \times m$	T	Load	Load satisfaction of the total heat demand within the multi-apartment building
3.42	$(y \times m)$	PO	Capacity	Minimum required newly installed capacity of the heating system alternative
3.43	1	PO	Investment	Property owner's overnight investment costs
3.44	1	PO	Upper-bound	Upper bound for the investment grant of the property owner
3.45	1	PO	Revenues	Rent-related revenues of the property owner
3.46	1	PO	NPV_{alt}	Property owner's net present value of the alternative heating system investment is 0
3.47	1	T	$\text{Costs}\mathit{init}$	Initial annual spendings of all tenants using the existing heating system
3.48	1	T	$\text{Total}_{\text{init}}$	Tenants' total spendings using the existing heating system
3.49	1	T	$\text{Total}_{\text{alt}}$	Tenants' total spendings using the alternative heating system
3.50	1	T	Equality	Constant remaining spendings for the tenants in case of a heating system change
3.52	1	T	Rent	Constant total rent price for a tenant per year

Table 3.7.: Overview of the model's mathematical formulation. Abbr.: Governance (G), Property owner (PO), and Tenants (T)

3.4.3. Nomenclature *equitable model*

Type	Description	Unit
Set and index		
$y \in \mathcal{Y} = \{1, \dots, Y\}$	Years, index by y	
$m \in \mathcal{M} = \{1, \dots, M\}$	Months, index by m	
Decision variables		
Ψ	Investment grant to the property owner	EUR
$\Omega_{y,m}$	Subsidy payment to a tenant in y and m	EUR
$\lambda_{y,m}$	Rent-related revenues of the property owner in y and m	EUR
$q_{y,m}$	Heat demand supplied by the new heating system alternative in y and m	kWh
π	Capacity of the new heating system alternative	kW
$r_{y,m}$	Rent charge adjustment in y and m	EUR/m^2
Relevant parameters		
n	Number of tenants within the multi-apartment building	1
i	Interest rate of an agent (governance, property owner, tenant)	%
$d_{y,m}$	Total heat demand per unit in y and m	kWh
α_m	Load factor (ratio total and peak demand) in m	1
c_{alt}	Investment costs of the heat system alternative	EUR/kW
c_{con}	Construction costs (for adaption of one dwelling/unit) of the heat system alternative per unit	EUR
$\bar{r}$	Initial rent price	EUR/m^2
ρ	Upper limit of the biannual rent charge adjustment	%

4. Results

4.1. Deep decarbonization of building heat in Austria 2050

This chapter presents the results of the first research question as presented in (Zwickl-Bernhard et al., 2022b). The focus is put on the mix of heat sources/generation technologies and district heating in the four different scenarios in Austria in 2050. Section 4.1.1 shows the heat supply of a representative Austrian NUTS3 region in detail. Building upon this, Section 4.1.2 compares heat supply in an urban and a rural local administrative unit (LAU). Section 4.1.3 presents the obtained heat densities of district heating networks. Finally, Section 4.1.4 syntheses the results of district heating and provides indications/information that could be returned into more aggregate models, such as GENeSYS-MOD, in the sense of a feedback loop.

4.1.1. Heat supply at NUTS3 level for a representative region

This section presents the results of the NUTS3 region Salzburg and Surroundings (AT323). Figure 4.1 shows the most relevant results in this region on the LAU/district level for the four different scenarios. District heating supplies heat demands in 5 different LAUs/communities. In particular, the LAUs are in the surrounding area of Salzburg City (marked by the star). The remaining LAUs in the NUTS3 region are supplied decentralized/on-site. Details of the heat sources that supply heat demands in LAUs with district heating and with decentralized/on-site heat systems are presented in the following section 4.1.2. The amount of district heating varies between

1.045 and 1.132 TWh per year (Figure 4.5, top right). The highest value is achieved in the Gradual Development scenario since this is the scenario with the lowest heat demand reduction. The heat density of district heating in the 5 LAUs is shown in Figure 4.5, bottom right. The highest heat density is achieved in Salzburg city and reaches approximately 30 GWh/km^2 in each scenario. The comparable low heat densities in two of the five LAUs (marked by a rectangle and plus) are further discussed in section 4.1.4.

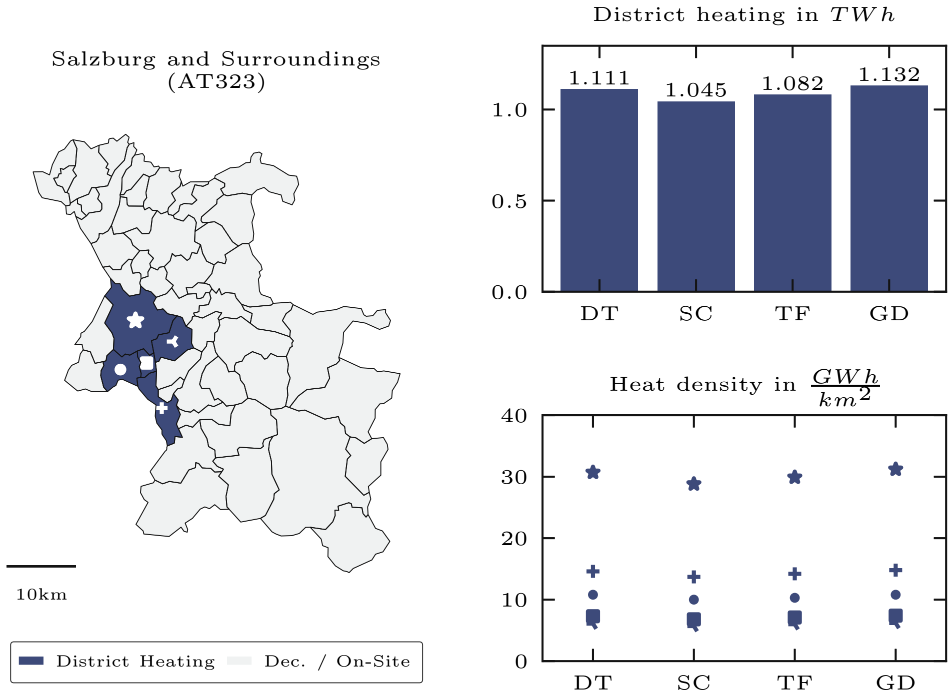


Figure 4.1.: District heating and decentralized/on-site heat supply in the representative NUTS3 region (incl. LAUs/communities) ’Salzburg and Surroundings’ (AT323). Left: LAUs with district heating or on-site heat supply. Top right: Total amount of district heating in the four different scenarios. Bottom right: heat density of district heating in the four different scenarios.

4.1.2. Comparison of the heat supply of urban and rural small region at the community level

Building upon the so-far presented results of the NUTS3 region Salzburg and Surroundings, this section shows the heat sources/generation technologies supplying heat demands in an urban and rural LAU/community. Salzburg City (urban community) and Abtenau (rural community) are used as representative LAUs. Figure 4.6 shows the mix of heat sources supplying heat demands in both LAUs.

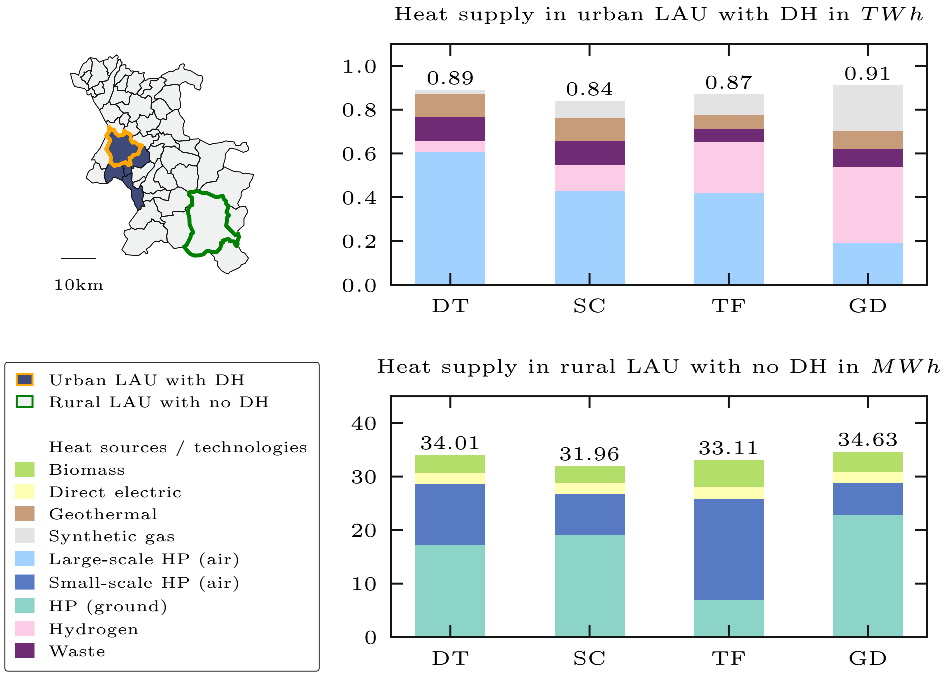


Figure 4.2.: Comparison of heat supply in an urban LAU with district heating ('Salzburg' city) and in a rural LAU with no district heating ('Abtenau'). Top right: Mix of heat sources in the four different scenarios used in district heating. Bottom right: Mix of heat sources used to supply heat demands decentralized/on-site.

The geographical location is shown on the top left in Figure 4.2. In Salzburg city (marked by the orange edge), district heating supplies heat demands, which uses large-scale heat pumps (air-sourced), hydrogen, synthetic gas, and waste as heat sources/generation technologies. High shares of district heating particularly are generated by large-scale heat pumps (air) and using hydrogen. On the contrary, the heat supply in the rural district of Abtenau uses small-scale heat pumps (air), heat pumps (ground-sourced), biomass, and direct electric heating systems. Among all four scenarios, high shares of heat demands are supplied by heat pumps (air- and ground-sourced). However, the share of each technology varies to some extent significantly, which becomes evident when comparing exemplarily the Techno-Friendly and Gradual Development scenarios. In the Techno-Friendly, small-scale heat pumps (air-sourced) are the dominant heat source, whereby heat pumps (ground-sourced) supply high shares of heat demands in the Gradual Development scenario.

4.1.3. Heat density of district heating networks

This section shows the heat density of district heating at the LAU/district level in 2050. Figure 4.3 shows the heat density for the four different scenarios. Particularly, the values of LAU's heat densities are sorted in descending order indicating those LAUs/communities that do not reach the required heat density of economic viability, which is assumed to be 10 GWh/km^2. Exemplarily, in the Directed Transition scenario, 107 LAUs with district heating are found. In this scenario, the highest heat density is 43.17 GWh/km^2. 2 of the 5 LAUs in the NUTS3 region Salzburg and Surroundings are highlighted, namely, Salzburg city (marker by the star in Figure 4.5) and Anif (marked by the rectangle in Figure 4.5). Both LAUs are part of the same district heating network as already illustrated in the left subfigure in Figure 4.5. Accordingly, the appearance of heat densities below the assumed threshold/benchmark for economic viability can be argued as those LAUs are connected to high heat density areas. The distribution of heat density values remains mostly the same between the four different scenarios. For the sake of clarity, explicit annotations are omitted in the three (smaller) scenario subfigures at the bottom.

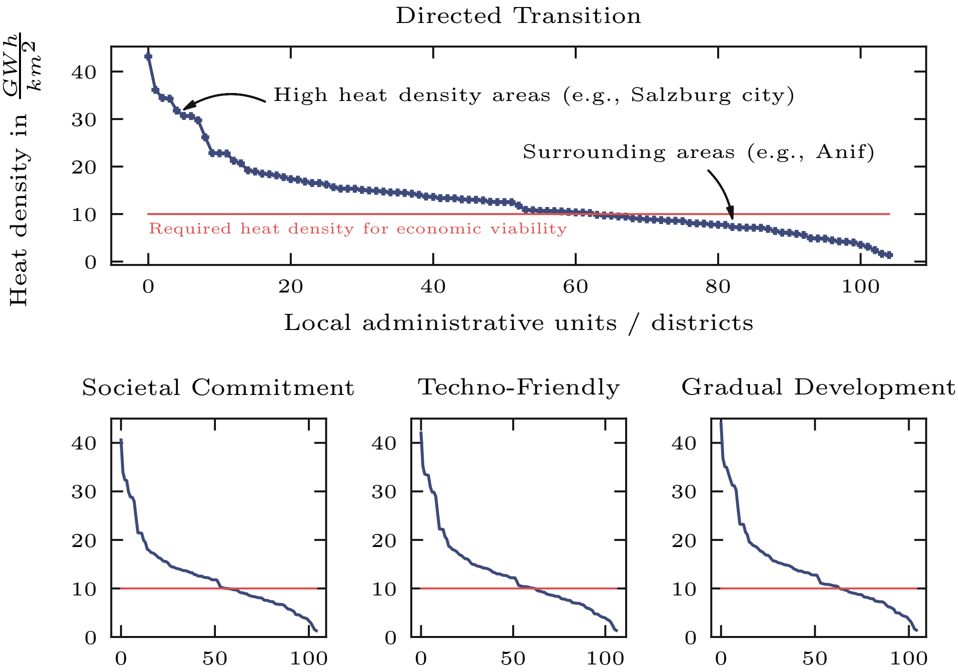


Figure 4.3.: Heat density values at the LAU level in the four different scenarios in descending order indicating those LAUs that do not achieve the required heat density benchmark for economic viability.

4.1.4. Geographical localization of district heating networks

This section focuses on those LAUs with lower heat densities than assumed to be required for economic viability for district heating and their geographical location with respect to other district heating supply areas. As indicated in Figure 4.3, LAUs with low heat densities can be quite justified in case they are located in the surrounding area of high heat density areas (e.g., Salzburg city and Anif). However, other LAUs that do not achieve the required heat density benchmark (of 10 GWh/km^2) and at the same time are not closely located in high heat density areas are unlikely to be implemented. Accordingly, Figure 4.4 shows the heat map of district heating in Austria at the LAU level under the requirement that district heating achieves the required heat density benchmark within NUTS3 regions in the Directed Transition scenario. As previously mentioned, the model basically decides to supply heat demands in 105 LAUs by district heating. 63 of them already achieved heat densities higher than the benchmark value. The heat map in Figure 4.4 still shows 68 LAUs since 5 are closely located in high heat density areas and thus achieve in total the benchmark (at the NUTS3 level).

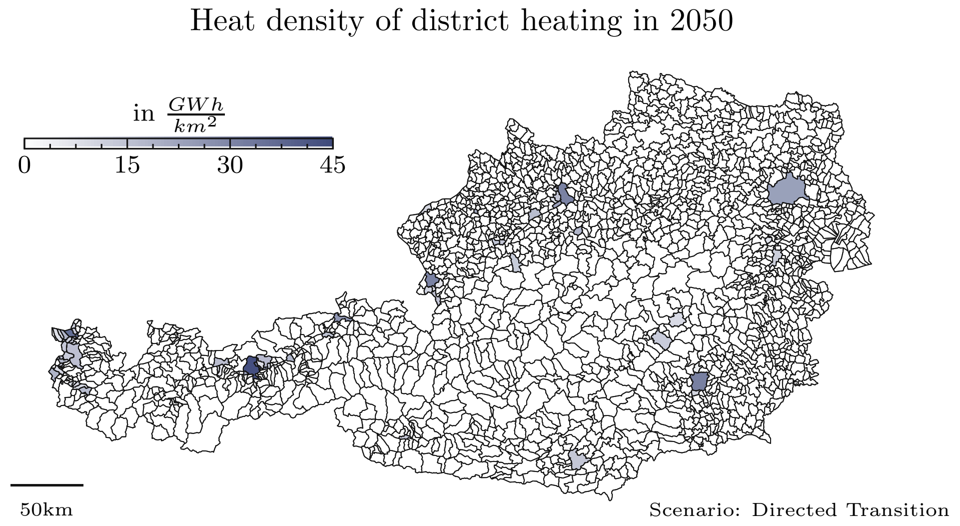


Figure 4.4.: Heat density of district heating in the Directed Transition scenario in 2050 achieving the required heat density benchmark value of 10 GWh/km^2 at the NUTS3 level.

Accordingly, district heating is unlikely to be implemented in 37 LAUs. Table 4.1 summarizes the results for district heating in the four different scenarios. It shows that as a result of the heat density benchmark at the NUTS3 level, the share of implemented district heating varies between 74 and 90%. In particular, this means exemplarily that in the Techno-Friendly scenario, 74% of the assumed heat supply using district heating leads to heat density values higher than 10 GWh/km^2. In view of the previous assumptions that 50% of heat pumps (air-sourced) are used in district heating, this results in implemented shares between 23% and 40%, whereby the highest share is achieved in the Directed Transition scenario.

Results in the four scenarios (from Section 3.1.1)	DT	SC	TF	GD
District Heating (from GENeSYS-MOD) in TWh	16.75	15.38	27.20	22.84
LAUs with district heating (from downscaling)	105	105	107	105
- of which with more than 10 GWh/km^2	63	57	62	64
- of which with less than 10 GWh/km^2	42	60	45	41
LAUs with district heating (10 GWh/km^2 at NUTS3)	68	66	68	68
District heating (10 GWh/km^2 at NUTS3) in TWh	14.57	13.08	20.09	20.62
- share in district heating from GENeSYS-MOD in %	87	85	74	90
- share of large-scale heat pumps (air) in %	40	35	23	26

Table 4.1.: Overview of district heating supplying heat demands in 2050 in the four different scenarios Directed Transition (DT), Societal Commitment (SC), Techno-Friendly (TF), and Gradual Development (GD). The resulting district heating that reaches the heat density benchmark of 10 GWh/km^2 at the NUTS3 level is marked in gray.

In view of the underlying narratives of particularly the three ambitious decarbonization scenarios from Section 3.1.1 (therefore excluding the Gradual Development scenario), two interesting implications can be derived from the results here:

- In absolute terms, the Techno-Friendly scenario demonstrates the highest share of district heating with 20.09 TWh under the condition that district heating networks within the NUTS3 levels achieve the heat density benchmark of 10 GWh/km^2. The main driver for this is the significant penetration of (large-scale) heat pumps (air-sourced) that characterizes this scenario.

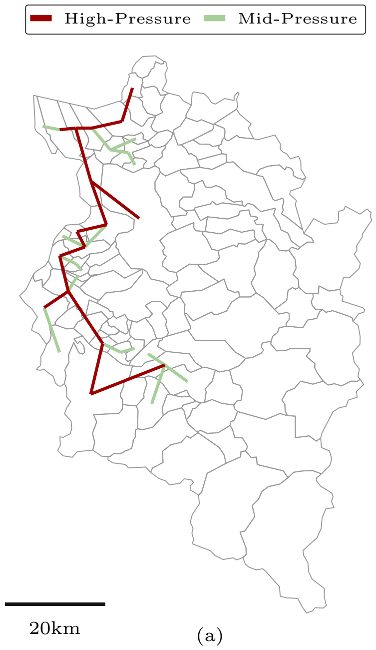
- Nevertheless, the implemented share of district heating in GENeSYS-MOD's district heating assumptions is the highest in the Directed Transition scenario and reaches 87 %. Also, this result is reflected in the fact that the share of large-scale heat pumps (air-sourced) achieves here its maximum with 40 %.

4.2. Decommissioning and refurbishment investment decisions for a cost-effective gas network trajectory to 2050

This chapter presents the results of the first research question as presented in (Zwickl-Bernhard et al., forthcoming). It presents the most relevant results of the analyzed test bed in Vorarlberg, Austria. A detailed description of the test bed can be found in Appendix B. Section 4.2.1 presents the cost-optimal gas network without an ensured supply of available gas demands (model run 1). Section 4.2.2 puts focus on the (nodal) shadow prices of the cost-optimal gas network without ensured supply (model run 2). Especially, the latter highlights the impact of supplying additional gas demands at the community (or local administrative unit (LAU)) level on network planning. Section 4.2.3 shows the cost-optimal gas network with ensured supply (model run 3). Section 4.2.4 compares total costs and shadow prices w/ ensured supply. This includes the socialization of network costs until 2050. Finally, Section 4.2.5 shows the cost-optimal gas network without ensured supply under the lumpiness of gas pipelines.

4.2.1. Cost-optimal gas network without an ensured supply of gas demand (CO)

In this case, the planning decision is made as follows: if the network operator can treat all energy services equally and thus can decide without restrictions if gas demands are supplied or not, then the gas networks will look like those presented here. Accordingly, it is assumed that competitive alternatives without dependence on gas networks exist for each energy service need. Figure 4.5 shows an overview of the most relevant results in this case. Figure 4.5 (a) shows the high- and mid-pressure gas networks. Given the existing gas networks (see Figure B.1), it is evident that all high-pressure pipelines (in red) are refurbished. At the same time, 59 % of the length of mid-pressure pipelines are refurbished and 41 % are decommissioned. The maximum capacity of the high-pressure network level is 161.92 and 40.58 MW of the mid-pressure (see Figure 4.5 (b)). Figure 4.5 (c) and (d) shows the development of gas demands supplied and not supplied for both pressure/network levels. Particularly, high shares of the mid-pressure demands are covered as a result of comparable high revenues at this pressure level. At the same time, no high-pressure gas demands are covered after 2030. Note that 2030 is the assumed year of the decommissioning and refurbishment investment decision for all pipelines within the networks.



(b)

	High-Pres.	Mid-Pres.
Max. [MW]	161.92	40.58
Length [km]	84.5	57.2
Decom. [%]	0	41
Refurb. [%]	100	59

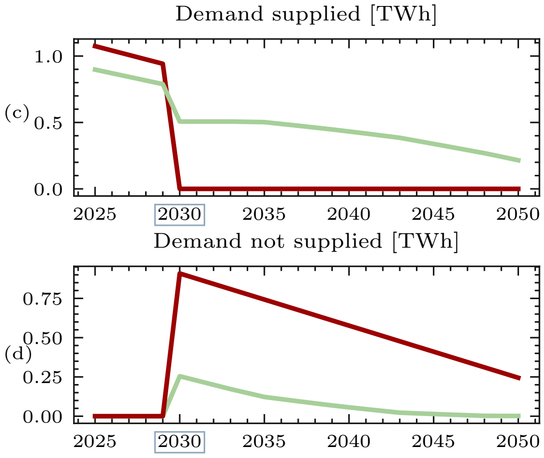
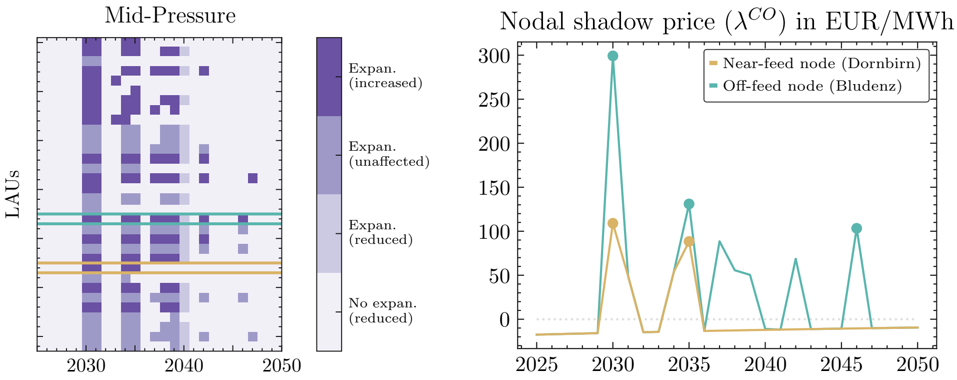


Figure 4.5.: Cost-optimal gas networks without ensured supply (model run 1): (a) high- and mid-pressure pipelines, (b) overview of max pipeline capacity, length, and share of decommissioned and refurbished pipeline lengths, (c) demand supplied, and (d) demand not supplied at the high- and mid-pressure network level.

4.2.2. Shadow prices for supplying additional gas demands of the cost-optimal gas network without an ensured supply of gas demands

This section takes the cost-optimal gas network without an ensured supply of gas demands as a starting point and investigates the dual variables and shadow prices of the (nodal) gas balance constraints. In this case, emphasis is put on the question: What costs arise, and what network adaption is required if the network operator is required to supply an additional gas demand at the nodal level? Since the results of the previous section indicate that mid-pressure gas demands are supplied only (see particularly Figure 4.5 (c)), this section highlights (nodal) shadow prices of supplying additional gas demands at the mid-pressure network level. Figure 4.6 shows shadow prices for LAUs between 2025 and 2050.



(a) Heat map/capability of the network

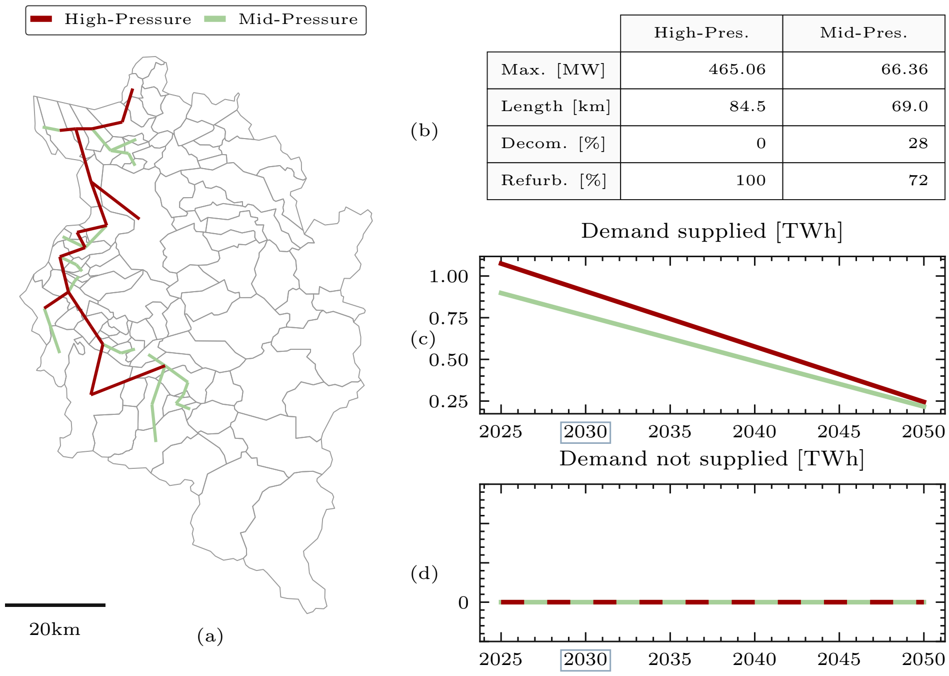
(b) Near-feed and off-feed node

Figure 4.6.: Shadow prices for supplying additional gas demands at the mid-pressure network level: (a) heat map identifying the capability of the gas network to supply additional mid-pressure gas demands, and (b) temporal development of the shadow price for a near-feed node (Dornbirn) and an off-feed node (Bludenz).

Figure 4.6 (a) shows the heatmap of the shadow prices, where the x-axis covers each year between 2025 and 2050 and the y-axis each node potentially connected to the mid-pressure network level. Thereby, each combination (i.e., node and year) is divided on the basis of four categories (i) No expansion (reduced), which means that the network is able to supply the additional gas demand without expansion and thus the objective function value is reduced by the revenues for selling the additional gas demand at the mid-pressure network level; (ii) expansion (reduced), which means that the network needs to be extended to supply the additional gas demand but the objective function value remains reduced but less than by the total revenues for selling gas demand at the mid-pressure network level; (iii) expansion (unaffected), which means that the network must be extended and the objective value is unaffected and remains constant (i.e., shadow price equal to 0), and (iv) expansion (increased), which means that the network needs to be extended and the objective value would be increased (i.e., shadow price greater than 0). Figure 4.6 (b) presents the exact numbers of the shadow prices for two representative nodes, namely, a near-feed node (Dornbirn) and an off-feed node (Bludenz). Dornbirn is therefore near the gas supply/source node, and Bludenz is further away from it. The shadow price at the off-feed node has several peaks (three are marked in 2030, 2035, and 2046) and its maximum is 299.2 EUR/MWh in 2030. The near-feed node has two peaks (in 2030 and 2035) and its maximum is 109 EUR/MWh in 2030. Particularly, the development of the near-feed node after 2036 shows the capability of supplying additional gas demands since pipeline capacities are available without expansion.

4.2.3. Cost-optimal gas network with an ensured supply of gas demands (ES)

This section shows the results in the case that the network operator should cover all gas demands within the supply area. Contrary to the previous two sections, no gas demands are not supplied. Figure 4.7 shows an overview of the most relevant results in this case. Again, all high-pressure pipelines are refurbished; however, 28 % of mid-pressure pipeline lengths are decommissioned. The maximum capacity of the high-pressure network level is 465.06 and 66.36 MW of the mid-pressure. Unsurprisingly, the objective function value increases significantly compared with the case without ensured supply. The objective function value increases by 96.29 MEUR. This value has great importance and implications for the practical planning of future gas networks. It can serve as a benchmark and is further investigated in the following section, which is dedicated to the comparison of the different cases.



	High-Pres.	Mid-Pres.
Max. [MW]	465.06	66.36
Length [km]	84.5	69.0
Decom. [%]	0	28
Refurb. [%]	100	72

Figure 4.7.: Cost-optimal gas networks with ensured supply (model run 3): (a) high- and mid-pressure pipelines, (b) overview of max pipeline capacity, length, and share of decommissioned and refurbished pipeline lengths, (c) demand supplied, and (d) demand not supplied at the high- and mid-pressure network level.

4.2.4. Comparison of the cost-optimal gas network w/ ensured supply of gas demands

This section compares the cost-optimal gas network with and without an ensured supply of gas demands. The following abbreviations, as already used in Table 3.2, are used: CO for the cost-optimal network without ensured supply and ES with ensured supply. Focus is put on the difference in total costs for the network operator and the shadow prices. Figure 4.8 shows the most relevant results to compare the two cases, namely, the extra costs in the case of ensured supply (see Figure 4.8 (a) and (b)), the distribution of 2030's shadow prices (see Figure 4.8 (c)), and shadow price development between 2030 and 2050 for the near-feed and off-feed nodes.

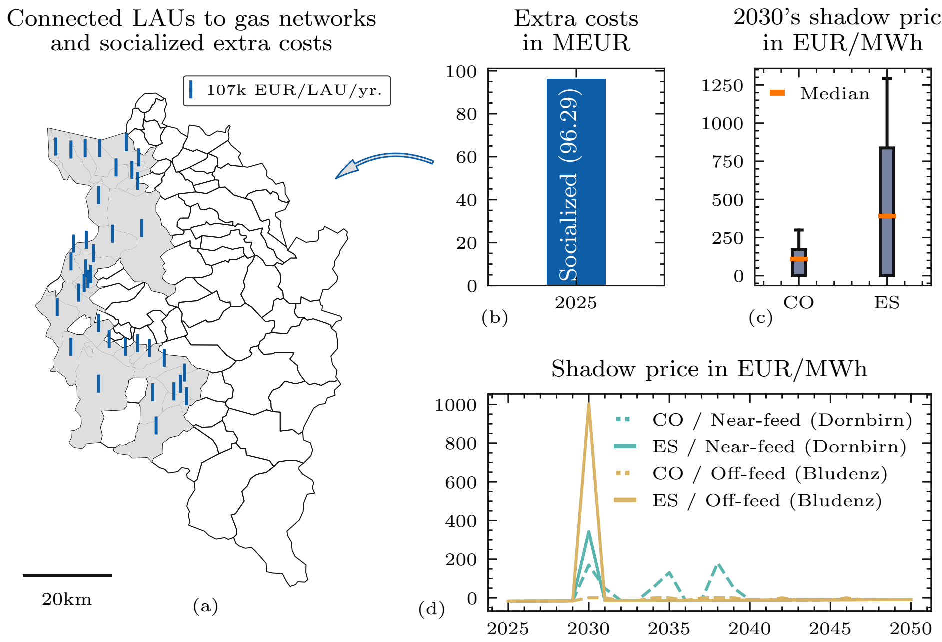


Figure 4.8.: Comparison of the cost-optimal gas network w/ ensured supply of gas demands: (a) and (b) socialized extra costs, (c) 2030's shadow prices, and (d) shadow prices between 2025 and 2050 for the near-feed and off-feed node. CO: Cost-optimal without ensured supply; ES: Cost-optimal with ensured supply.

As mentioned, the ensured supply of all gas demands within the network results in extra costs of 96.29 MEUR. Given an equal allocation to the LAUs and years, this results in extra costs of 107 kEUR per LAU and year. This value must be considered as an additional offset to the shadow prices of the cost-optimal network with ensured supply to obtain the effective shadow price and respect the already increasing total costs of the network operator. Nevertheless, even the comparison of 2030's values without this offset shows that the shadow prices in the case with ensured supply increase significantly compared with the case without ensured supply. Particularly, the median raises from approximately 100 EUR/MWh to 400 EUR/MWh. Additionally, the max value raises from approximately 300 to 1300 EUR/MWh. This increase in shadow prices is also presented in Figure 4.8 (d), where again the near-feed and off-feed nodes are shown.

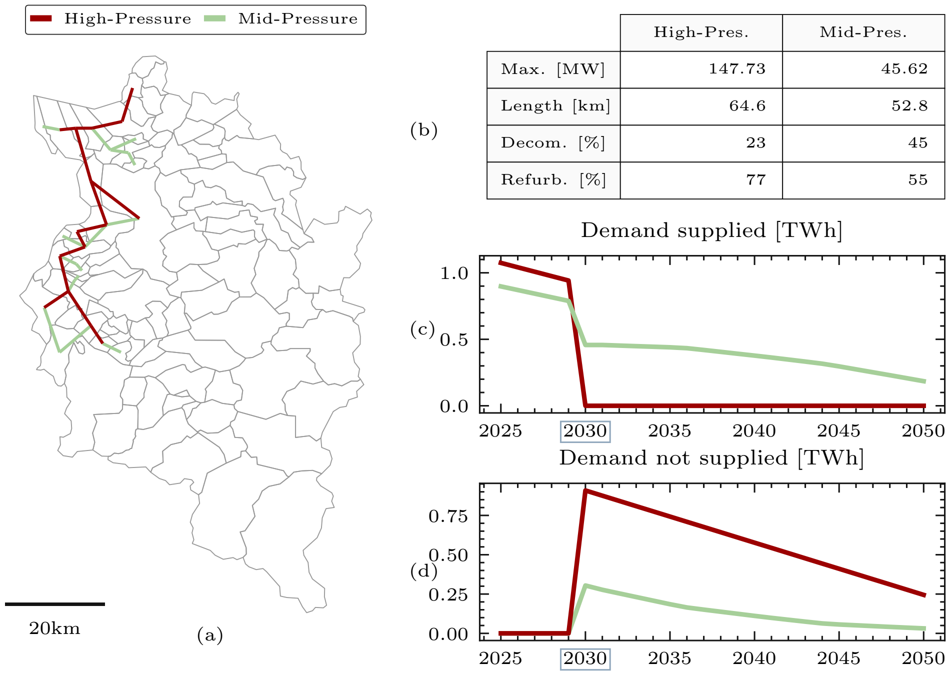
4.2.5. Cost-optimal gas networks without ensured supply under lumpiness of gas pipelines

This section shows the results of the cost-optimal gas network without ensured supply. Contrary to the results presented above, the lumpiness of gas pipelines in the network operator's planning decision is considered here. This analysis completes the results section against the background of two important aspects. First, considering the lumpiness of gas network pipelines increases the significance of the generated results for practical proposals since the network operator's decision is related to choosing specific diameters of gas pipelines. Second, however, the introduction of the lumpiness of gas pipelines extends the previous linear program to a mixed-integer linear program. This is why no dual variables and shadow prices can be obtained. Table B.4 in B.2 shows the assumptions for the lumpiness of gas pipelines. 14 different capacities (diameters between 0.1 and 1.3 m) for both the high- and mid-pressure pressure/network levels are considered.

Figure 4.9 summarizes the results of the generated gas networks in case of lumpiness. Interestingly, the consideration of lumpiness of gas pipelines leads even in the cost-optimal case network without ensured supply to the decommissioning of 23 % high-pressure and 45 % mid-pressure pipeline length. Furthermore, only gas demands at the mid-pressure network level are supplied (as in Section 4.2.1 and model run 1). Again, all the high-pressure gas demands are not supplied.

Figure 4.10 shows a comparison of the results under lumpiness with the previous results of the cost-optimal gas network w/ ensured supply (i.e., CO and ES). Particularly, it shows the impact of lumpiness on an optimal network design decision. In summary, the following interesting findings can be observed:

- The cost-optimal network design without ensured supply under lumpiness of gas pipelines increases the total costs (i.e., objective function value) by only 1% (Figure 4.10, top left) but at the same time the amount of mid-pressure gas demand increases (Figure 4.10, bottom



	High-Pres.	Mid-Pres.
Max. [MW]	147.73	45.62
Length [km]	64.6	52.8
Decom. [%]	23	45
Refurb. [%]	77	55

Figure 4.9.: Cost-optimal gas networks with ensured supply under lumpiness of gas pipelines: (a) high- and mid-pressure pipelines, (b) overview of max pipeline capacity, length, and share of decommissioned and refurbished pipeline lengths, (c) demand supplied, and (d) demand not supplied at the high- and mid-pressure network level.

right).

- Moreover, the lumpiness of gas pipelines results in both the decommissioning of high shares of the high-pressure network/pressure level (Figure 4.10, top right) and the further decreasing of the maximum pipeline capacity within the network (Figure 4.10, bottom left).

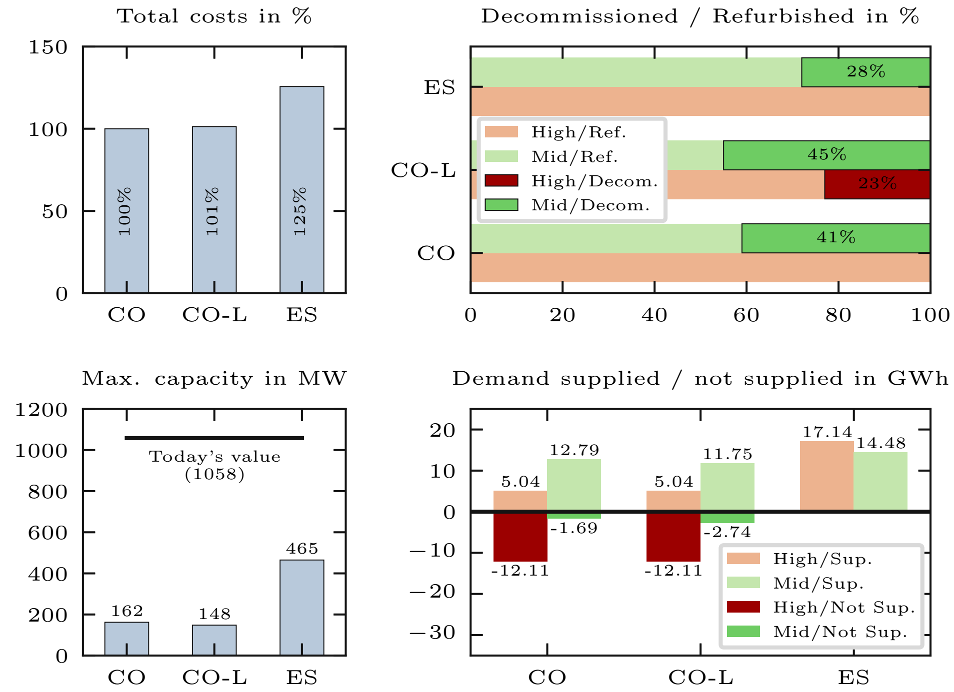


Figure 4.10.: Results of the cost-optimal gas networks without ensured supply under lumpiness of gas pipelines (CO-L). Top left: Comparison of the total costs. Top right: Decommissioning and refurbishment decision at the mid- and high-pressure network level. Bottom left: Maximum pipeline capacity. Bottom right: Mid- and high-pressure gas demand that is supplied or not.

4.3. Distribution grids and sector coupling technologies for the provision of sustainable heat services in a neighborhood

This chapter presents the results of the third research question as presented in (Zwickl-Bernhard and Auer, 2022). The presents the results of the analyzed neighborhood in Vienna, Austria. A detailed description of the test bed can be found in Appendix C. Section 4.3.1 presents the current state of supply (*Case A - Baseline*). Sections 4.3.2 and 4.3.3 elaborate on *Case B - Electrification* and *Case C - Network*, respectively. Section 4.3.4 shows the end-user benefits in *Case C* as a result of the economies of scale achieved. Finally, Section 4.3.5 compares the three scenario results through the application of the benefit indicators.

4.3.1. Case A - Baseline

At present, high shares of the local energy demand are supplied by the electricity (Figure 4.11) and natural gas distribution grid (Figure 4.12). The mean electricity line capacity in the test bed is 1.34 MW, and the maximum is 28.48 MW. The largest electricity line capacities serve as a grid connection capacity to the public grid and supply the three special consumers (*Stadium*, *University*, and *Fair*).

The natural gas distribution network supplies almost the entire heat demand in the neighborhood. In addition, the district heating network supplies heat demand of the three special consumer in the district (Figure 4.13). The maximum district heating line capacity is 7.6 MW. Note that *Case A* neglects cooling services because currently no district cooling network is implemented. Figure 4.14 shows the line capacity frequency for electricity, natural gas, and district heating using the so-called *violin plot*. In this illustration, the x-axis (frequency) in the subplots is normalized to the width of 0.5 as common in this plotting type. The horizontal bars indicate the mean line capacity value for each energy carrier distribution network. Figure 4.15 shows the total line length for the three energy carriers. Almost the same line lengths are required for electricity and natural gas, accounting for 96 % of total local line lengths. Finally, Figure 4.16 shows a binary heatmap for the networks of the three energy carriers electricity (top), natural gas (middle), and district heating (bottom). Each available distribution line is represented by a single element in the map. Note that the location of the elements is derived from the spatial setup in Figures 4.11-4.13.

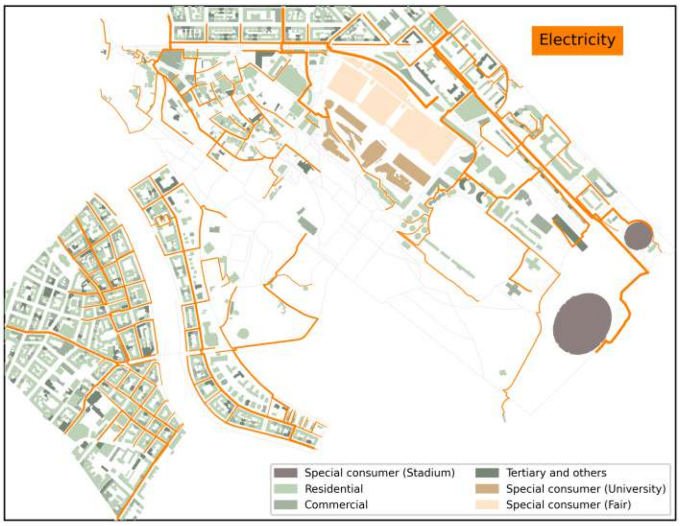


Figure 4.11.: Local electricity distribution network in *Case A - Baseline*

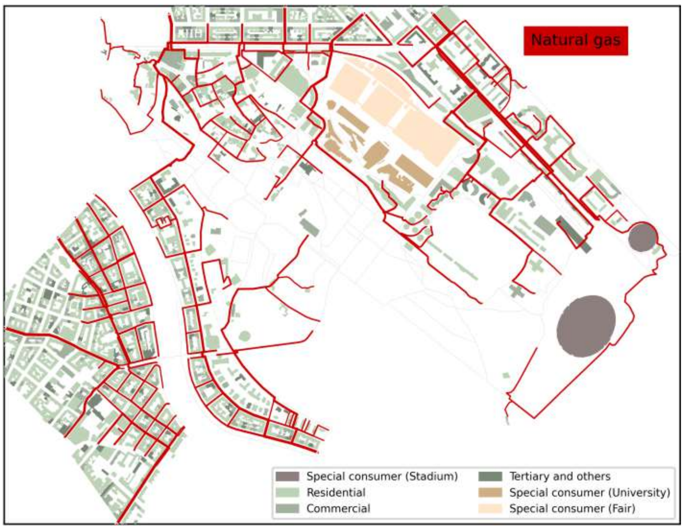


Figure 4.12.: Local natural gas distribution network in *Case A - Baseline*

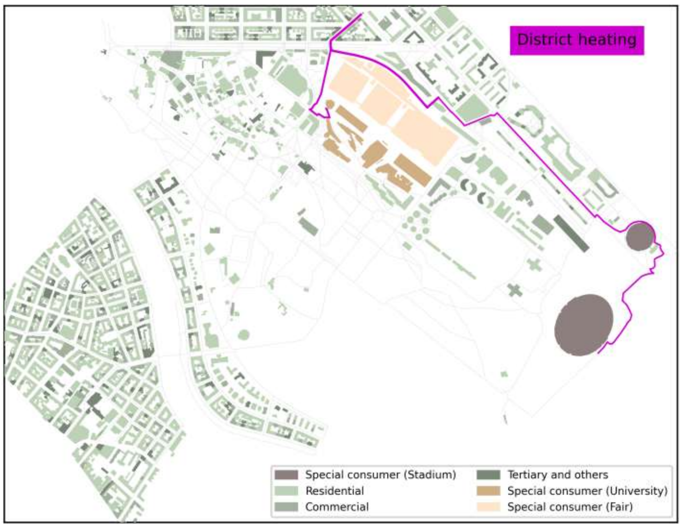


Figure 4.13.: Local district heating network in *Case A - Baseline*

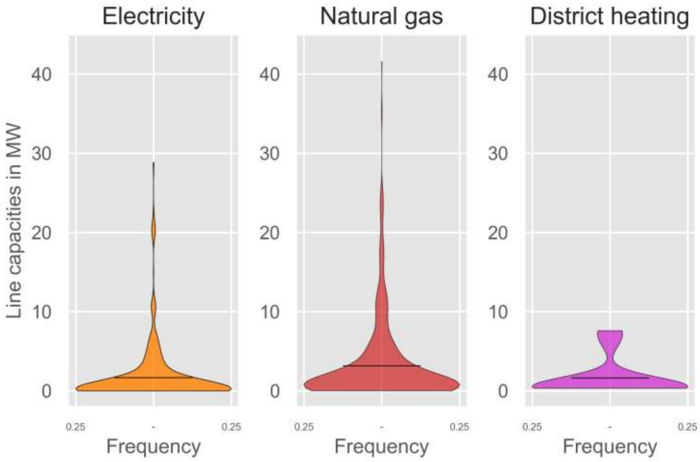


Figure 4.14.: Local distribution line capacity frequency of electricity (left), natural gas (middle), and district heating (right) in *Case A - Baseline*

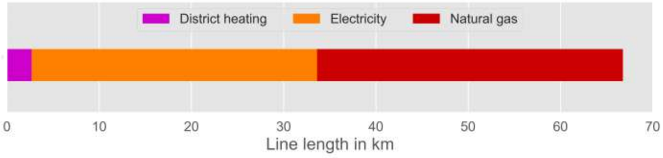


Figure 4.15.: Local distribution line length and its components in *Case A - Baseline*

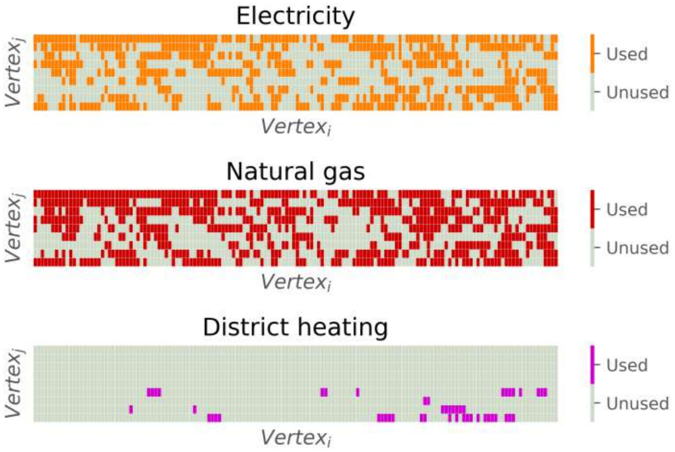
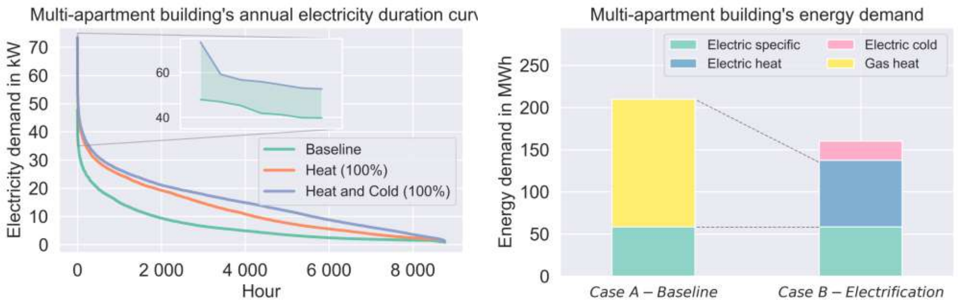


Figure 4.16.: Binary heatmap of the local distribution network for electricity (top), natural gas (middle), and district heating (bottom) in *Case A - Baseline*

4.3.2. Case B - Electrification

In this scenario, the urban neighborhood pursues deep decarbonization by electrification of its energy supply. In addition, the natural gas phase-out in the heat supply, this scenario takes into account the cooling demand. The latter is mainly supplied by compression cooling machines. As a consequence, this further increases the local electricity demand. For example, the changes in the local energy system patterns are shown in Figure 4.17a. It shows the annual electricity duration curve for a characteristic multi-apartment building in the neighborhood. Thereby, three different electrification levels are compared: (i) Baseline (*Case A - Baseline*), (ii) Heat (100 %) considering the electrification of the heat demand only but neglecting the cooling demand, and (iii) a complete electrification (Heat and Cold (100 %)). Figure 4.17b compares the total energy demand in *Case A - Baseline* and in *Case B - Electrification* for the same multi-apartment building. Note that this section's further results take into account the electrification of both heating and cooling demand (indicated by the blue duration line in Figure 4.17a).



(a) Annual electricity duration curve

(b) Energy demand comparison

Figure 4.17.: Annual electricity duration curve (left) and comparison of total energy demand (including its components) for a characteristic multi-apartment building

For the sake of clarity, a fully analogous result presentation similar to *Case A - Baseline* is omitted. Instead, Figure 4.18 presents the distribution line capacities (again by the *violin plot*) for the local electricity (left) and district heating (right) distribution grid. Again, the mean line capacity values are marked by the horizontal bars. In addition, the three figures in the middle of Figure 4.18 highlight the differences in electricity line capacities between *Case A - Baseline* and *Case B - Electrification* (cutout of the line capacity frequency (top), max line capacity (middle), and mean line capacity (bottom)).

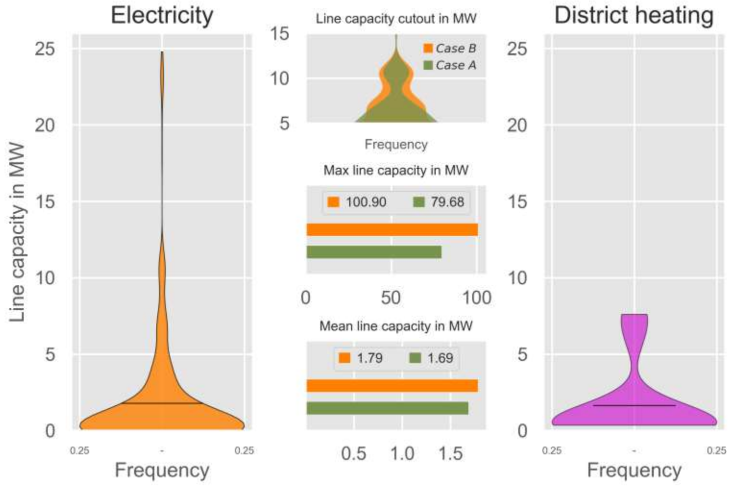


Figure 4.18.: Local electricity (left) and district heating (right) distribution line capacity frequency including selected highlights comparing electricity line capacities in *Case A - Baseline* and *Case B - Electrification* (cutout (top), max (middle), and mean (bottom))

Figure 4.19 shows the resulting local distribution line lengths for electricity and district heating. The latter are unchanged compared to *Case A*. The electricity distribution line lengths are split into two parts, namely, the existing share of *Case A* (light orange) and the extra share of *Case B* (rich orange).

Figure 4.19.: Total line length and its components in *Case B - Electrification*

The extended (binary) heatmap in Figure 4.20 shows the use of locally available distribution lines for electricity (top) and district heating (bottom). For district heating the same results occur as in *Case A - Baseline* (Figure 4.16) as the existing network still supplies the special consumers' heat demand. For electricity, it mainly highlights the extra distribution lines demanded in *Case B - Electification* (rich orange) compared with those in *Case A - Baseline* (light orange).

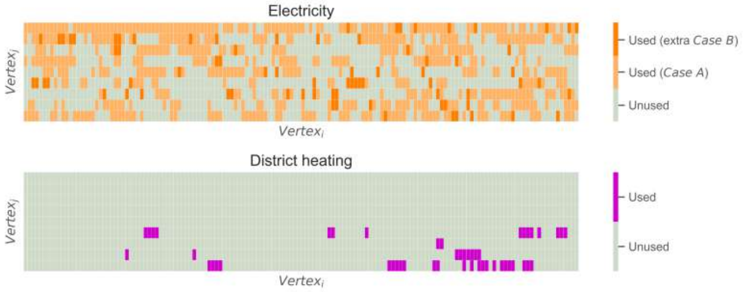


Figure 4.20.: Extended (binary) heatmap of the local distribution network for electricity (top) and district heating (bottom) in *Case B - Electrification*

4.3.3. Case C - Network

Figure 4.21 shows the local distribution line capacities for district heating (left) and cooling (right). The district heating mean line capacity (top) and max line capacity compared with the *Case A - Baseline* is shown in the middle. It is evident that a significant increase for both is necessary to cover the heat demand. In addition, a massive expansion of the district cooling distribution grid is implemented, which is not existent in *Case A - Baseline*.

The massive district heating and cooling network expansion is also reflected by the extended heatmap in Figure 4.22. The latter indicates a high level of available distribution line capacity utilization. Furthermore, it highlights available distribution line elements that are used for both district heating and cooling. The total distribution line length of the district heating network is 34.7 and 34.9 km of the district cooling network. Naturally, in this scenario, the corresponding indicator (*Costs*) in Table 3.5 is very high as a result of the scenario definition and the resulting massive network expansion. Nevertheless, it could be assumed that related results are too pessimistic (i.e., too costly) as possible synergies and related cost-savings from a simultaneous im-

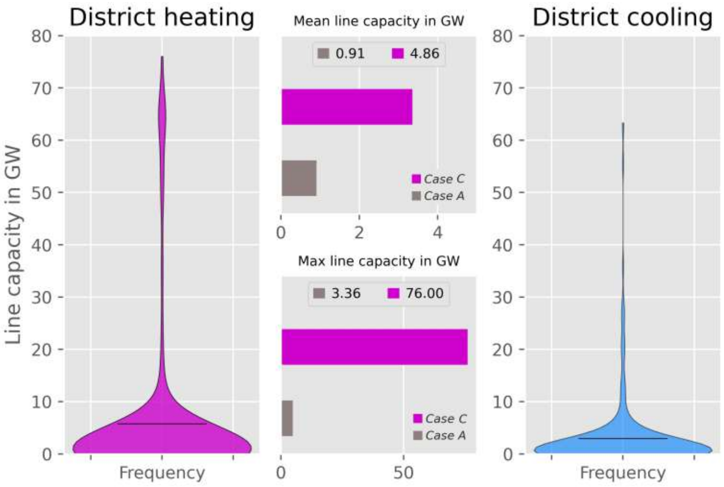


Figure 4.21.: Local district heating (left) and district cooling (right) distribution line capacity frequency including a comparison of the district heating mean (top) and max (bottom) distribution line capacity in *Case C*

plementation of the district heating and district cooling network expansion are only considered to a limited extent. Thus, the following Section 4.3.4 considers the economies of scale of a district heating network expansion and related cost components exclusively. The latter are mapped on the building level to disclose end-user benefits in this sustainable local deep decarbonization pathway.

Figure 4.22.: Local district heating and cooling network heatmap in *Case C - Network*

4.3.4. Economies of scale related to cost savings on an end-user level

The following analysis emphasizes the expansion of the district heating network on a large scale in the entire supply area of the neighborhood according to the outlined scenario definition. This includes the associated "non-discriminatory right" of the end-users to be connected to the grid (*Case C - Network*). In particular, the analyses emphasize the cost comparison between the current state of supply (*Case A - Baseline*) including its increasingly negative implications due to increasing CO_2 emission costs and the deep decarbonization pathway in *Case C - Network*. Figure 4.23 compares the average building costs within the neighborhood in *Case A - Baseline* and *Case C - Network* for the heat demand supply taking into account a CO_2 price development[1] aiming for the European climate target for the period under review until 2050.

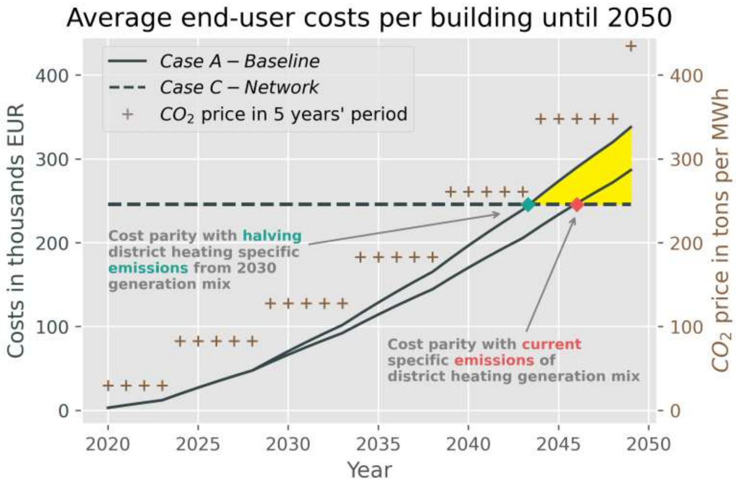


Figure 4.23.: End-user cost parity (on building level) comparing *Case A - Baseline* and *Case C - Network* with current district heating specific emissions (red diamond) and halving specific emissions from 2030 (green diamond)

In addition, two different scenarios of the district heating energy generation mix are illustrated. The first scenario includes no further decarbonization in the district heating fueling energy mix and assumes that today's specific emis-

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[1] This CO_2 price development is taken from the European Horizon 2020 project *openENTRANCE* (`https://openentrance.eu/`). As a main contribution of the project, both four different narrative storylines and corresponding quantitative scenarios have been developed. Thereby, three ambitious storylines/scenarios aim for the 1.5 °C climate target, the more conservative one (*Gradual Development*) for 2.0 °C. The corresponding endogenous CO_2 prices from the *Gradual Development* scenario are taken in this analysis. For more details, it is referred to (Auer et al., 2020b).

sions remain constant until 2050. This assumption leads to average building cost parity between *Case A - Baseline* and *Case C - Network* in 2046 as indicated by the red diamond. Increasing decarbonization achievements of the district heating generation mix (i.e., the stronger convex curvature of the solid black line *Case A - Baseline* as a result of halving district heating specific emissions from 2030) achieve earlier cost parity (green diamond in 2043). Moreover, the yellow marked area indicates the resulting total end-user cost-savings after the trade-off years. These cost-savings also increase with stronger convex curvature.

4.3.5. Result comparison with benefit indicators

Finally, this section conducts a results comparison using selected highlights of the introduced benefit indicators. Figure 4.24 shows the capability and resource benefit indicator results.

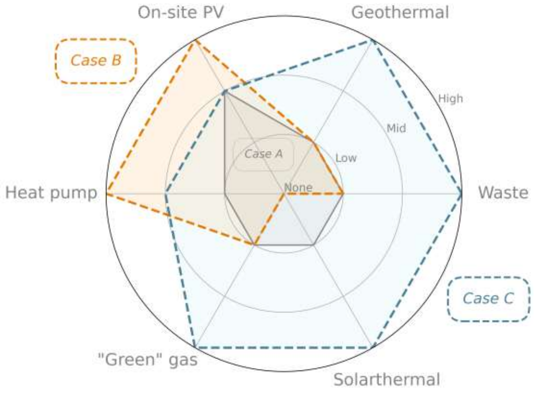

Figure 4.24.: Qualitative evaluation of capability benefit indicators including energy supply-side options in the three *Cases A, B, and C*

They qualitatively assess the energy supply-side options in the different *Cases A, B, and C*. Note, that the analysis of the quantitative energy supply-side mix has not been the focus of this work. Thus, the discussion is qualitative in nature. Nevertheless, *Case A* (marked by the solid gray line) enables the integration of various distributed energy generation technologies, notably on-site PV systems for local electricity self-generation. In addition, limited integration potentials for geothermal, waste, solar thermal, green gas, and heat pumps exist. The main reason for this is the already existing heat supply of the special consumers within the neighborhood by the district heating network. *Case B - Electrification* may boost both technologies, on-site PV systems and small-scale heat pumps. As before, integration potentials for further technology/resource options are limited. In addition, the share of local PV self-consumption may significantly increase as a result of the electrification of the cooling supply. In *Case C - Network*, sustainable heat generation resources, such as geothermal, waste, solar thermal, green gas, and heat pumps, can be used to enable deep decarbonization in the heat supply. In particular, in the context of fueling cogeneration plants for feeding into the district heating grid, green gas may deliver a significant contribution in this deep decarbonization pathway.

Figure 4.25 shows further selected (and partly quantitative) benefit indicators related to the definition in Tables 3.3-3.6.

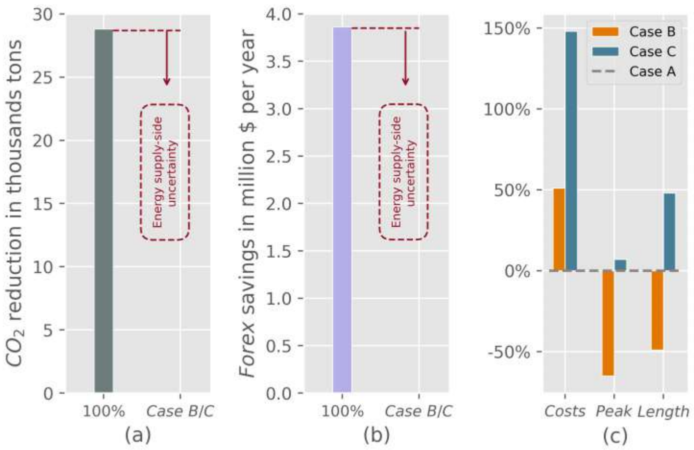

Figure 4.25.: Quantitative benefit indicators comparison between the three *Cases A,B and C*

Thereby, in the two alternative decarbonization pathways, both a significant reduction in CO_2 emissions and natural gas forex savings can be achieved. However, as indicated in both illustrations in Figure 4.25a&b, the real-world application achievements of deep decarbonization in *Case B* and *Case C* may substantially depend on the energy supply-side mix. Furthermore, Figure 4.25c compares the two decarbonization pathways with results from the status quo in *Case A*. The massive district heating and cooling network expansion in *Case C* results in significant increasing *costs* related to the distribution grid (see also the increasing total distribution line *length*). At the time, the increase in costs is significantly lower in *Case B*. Furthermore, the high-efficient electricity-based energy service supply in *Case B* leads to a significant reduction of the *Peak* (max) connection capacity in the neighborhood. In *Case C*, this capacity is almost constant compared with *Case A*.

4.4. Socially balanced subsidy strategy for investment in sustainable heat supply to buildings

This chapter presents the results of the third research question as presented in (Zwickl-Bernhard et al., 2022a). It presents the most relevant quantitative results of the proposed case study. A detailed description of the case study can be found in Appendix D. Section 4.4.1 elaborates on the district heating option in the *Directed Transition* scenario. Section 4.4.2 focuses on the implementation of a heat pump system in the *Societal Commitment* scenario where the model indicates feasible solutions for a retrofitted building with a lower heat demand only (compared with the default settings). A comparison of the results of the district heating and heat pump-based heat supply in the different scenarios quantified in this work is conducted in Section 4.4.3. Finally, Section 4.4.4 presents the results in case of varying CO_2 pricing cost allocation between the property owner and the tenants.

4.4.1. District heating in the Directed Transition scenario

This section presents the results of the district heating implementation in the *Directed Transition* scenario in detail. Figure 4.26 shows the net present value of cash flows in general, and revenues in particular, of the property owner and a single tenant within the time horizon of 2025-2040. Figure 4.26 (top left) presents the different items of the property owner consisting of the overnight investment costs, investment grant, and rent-related revenues. Note that the latter represents the additional rent-related revenues due to the newly installed sustainable heating system. Figure 4.26 (bottom left) shows the development of the property owner's net present value of their cash flow over time. Thereby, it is shown that the investment pays off for the property owner by zero in 2040. The two Figures 4.26 (top right, bottom right) illustrate the corresponding tenant's cash flow items (top) and total net present value (bottom) until 2040. The tenant receives subsidy payments from the governance between 2025 and 2030. Thus, the tenant's net present value in 2040 matches the value in the reference case. The reference case considers constant remaining rent and heat-related costs for the tenant based on the initial rent, gas-based heat system parameters, and CO_2 prices as of 2025. In the years 2025-2029, the subsidy payments exceed the heating costs of the tenant. Note that the tenant already pays a higher rent charge to the property owner within the same period (see the yellow bars in Figure 4.26 top left). Most importantly, the tenant's reference net present value ("Ref. (Gas/2025)"; gray dashed line in the Figure 4.26 bottom right) shows a crucial aspect of the results and assumptions of the analysis which requires an explanation. Since "Ref. (Gas/2025)" is used as the initial tenant's spending, the results also take into account the total opportunity costs (i.e., those costs that would be incurred by sticking to the initial gas-based heating system for the tenant due to a rising CO_2 price). Note that the openENTRANCE decarbonization scenarios used in this work do consider both a significant increase of the CO_2 price and a decrease of the specific emissions of the district heating and electricity fueling mix. The quantitative results indicate that the heating system change in this scenario is achieved with manageable total governance subsidies.

4.4.2. Heat pump and building stock quality in the Societal Commitment scenario

Interestingly, the model indicates for the heat pump implementation in the *Societal Commitment* scenario is an infeasible solution. The reason for that is, among others (investment costs of the air-sourced heat pump and the electricity price), the high heating demand used in the default input settings[2]. Therefore, in the following the focus is put on the impact of different building renovation levels, the associated heating demand decrease, and finally the impact on the feasibility of the model.

Figure 4.27 shows the results of the heat pump implementation in the *Societal Commitment* scenario for four different building qualities (and thus heat demand levels) in detail. Since the initial setting of the default building in terms

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[2] The high electricity demand resulting from the low COP and related increasing electricity costs need high subsidy payments for the tenants in this case. Against the background of comparable low investment costs of the property owner, Equation 3.40 cannot be satisfied.

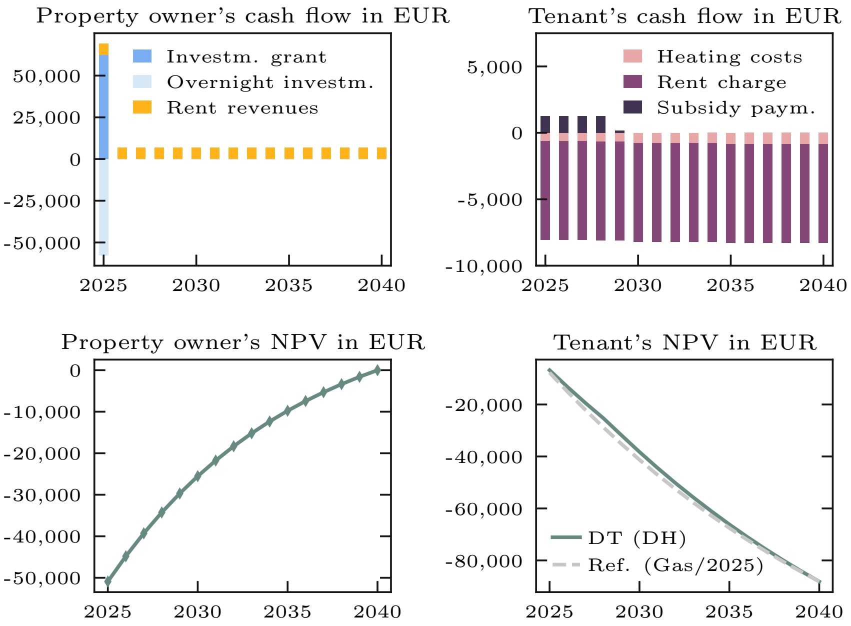

Figure 4.26.: Development of the property owner's and tenant's economic viability of the district heating option in the *Directed Transition* scenario. Top left: property owner's cash flows, bottom left: property owner's net present value, top right: tenant's cash flows, bottom right: tenant's net present value

of total and peak heat demand leads to the infeasibility of the model, the following three additional renovation levels are studied: 10 %, 20 %, and 30 % reduction of both the total and peak heat demands. In Figure 4.27 (top left), the corresponding settings of the specific heat load (describing building quality) are indicated. In case of a 10 % reduction of the heat demand, the property owner receives a significant investment grant equivalent to 29 % of the property owner's total overnight investment costs of the building retrofitting measures (Fig. 4.27 top right). The associated tenant's subsidy payment takes place between 2025 and 2030 with a maximum of 2040 EUR/year (Fig. 4.27 bottom left). The rent charge adjustment and related revenues remain almost constant during the period (Fig. 4.27 bottom right). In the case of a 20 % reduction of the heat demand, the property owner receives only a small investment grant related to the total overnight investment costs (2 %). The tenant's subsidy payment takes place between 2025 and 2032 with a maximum of 2556 EUR/year. The property owner's rent-related revenues increase until 2031 and then remain constant. In the case of a 30 % reduction of the heat demand, the property owner receives as before a small investment grant (3 %). Instead, the property owner makes significant rent-related revenues (the highest among the three renovation levels). The tenant gets subsidy payments in most years, excluding 2026 and 2028 to 2030 (mainly as a result of the matching of the CO_2 price and the specific CO_2 emissions of the fueling energy mix). The maximum is 2796 EUR/year in 2040. The lower heat energy-related costs as a result of the building renovation lead to higher rent charge payments. Hence, smaller investment grants supporting the property owner are sufficient.

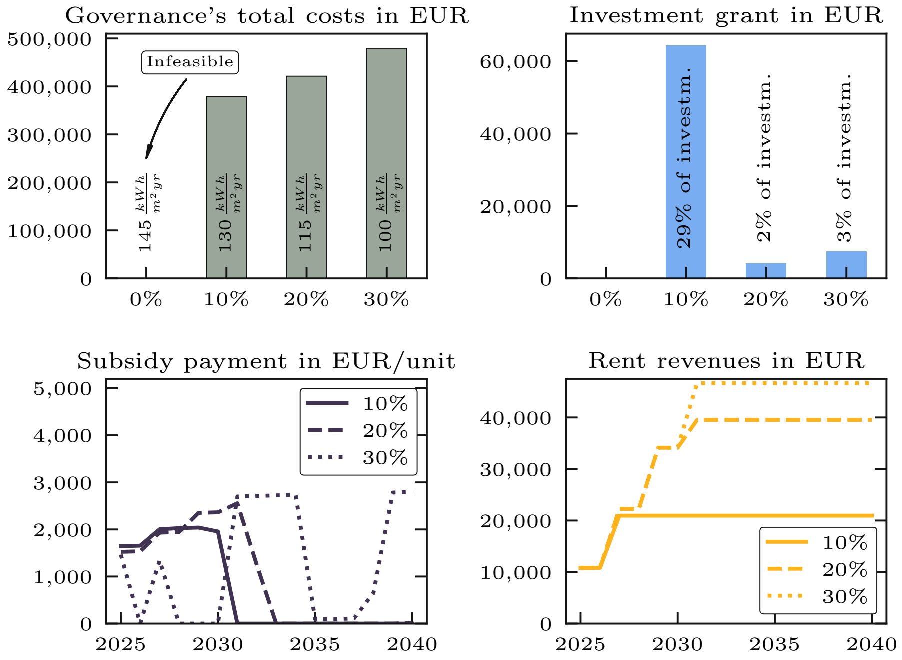

Figure 4.27.: Comparison of the heat pump option in the *Societal Commitment* (SC) scenario for different renovation levels. Top left: governance's objective value, top right: property owner's investment grant, bottom left: tenant's subsidy payment per unit, bottom right: property owner's rent-related revenues in total

4.4.3. Governance's total subsidies in the different scenarios

In this section, a comparison of the governance's total subsidies for district heating (DH) or heat pump (HP) implementation in the different scenarios is conducted. Table 4.2 and Figure 4.28 present the result of this comparison.

Governance's total financial support	District heating (DH)			Heat pump (HP)		
	DT	GD	LD	SC	GD	LD
	(1.5 °C)	(2.0 °C)	(-)	(1.5 °C)	(2.0 °C)	(-)
Absolute in thous. EUR	211.4	195.5	190.1	*infeasible*	*infeasible*	351.5
Rel. change in % of LD (DH)	11.2	2.8	-			82.6
CO$_2$ tax revenues in thous. EUR	66.6	38.9	25.7			10.3
Public financial deficit in thous. EUR	144.8	156.6	164.4			341.2

Table 4.2.: Comparison of governance's total financial support for the different heating system alternatives and scenarios (incl. CO$_2$ tax revenues and public financial deficit)

In summary, the following interesting observations are made:

- The total subsidies across the three district heating cases are relatively stable and are within 11.2 %.

- The heat pump implementation in the two decarbonization scenarios *Societal Commitment* and *Gradual Development* is infeasible for the default setting of the building quality (see discussion already in Section 4.4.2).

- Only the low CO$_2$ price development scenario provides a solution for the heat pump but with a significantly higher subsidy +82.6 % compared with the lowest subsidy scenario.

- The public financial deficit (governance's total financial support minus CO$_2$ tax revenues) is the lowest (144.8 thous. EUR) in the *Directed Transition* scenario.

When comparing Table 4.2 and Figure 4.28, it is important to note that the

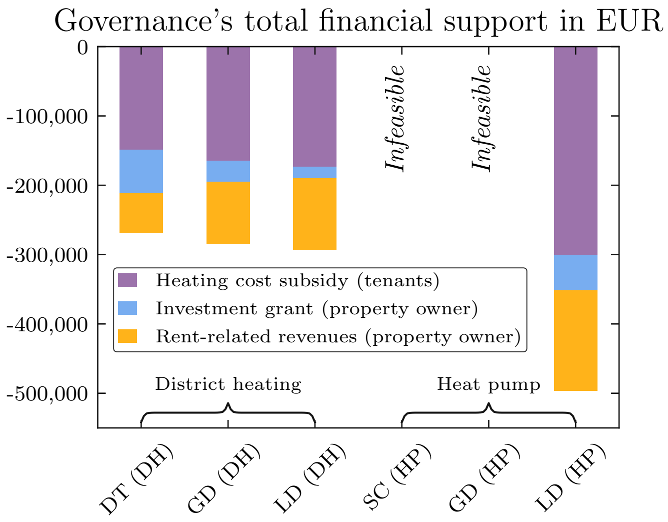

Figure 4.28.: Comparison of governance's total financial support for the property owner and the tenants for the district heating (DH) and heat pump (HP) implementations in the different scenarios

property owner's rent-related revenues (orange bar) are an "implicit" subsidy. Hence, the governance's total financial support is equal to the sum of the tenants' heating costs subsidy (purple bar) and the property owner's investment grant (blue bar).

4.4.4. Allocation of carbon pricing related costs between the governance, property owner, and tenant

This section examines the impact of the costs of inaction (i.e., sticking to the initial gas-based heating system) on the governance's total financial support. In detail, this means that the CO_2 costs (i.e., opportunity costs) to be expected due to increasing CO_2 prices have to be allocated to the different parties/agents (or a single one): governance, property owner, and tenant. Table 4.3 shows the objective value (absolute value and relative change in % from GD (DH)) for different allocations of opportunity costs. Exemplarily, "Equally" (first row in Table 4.3) takes into account that the CO_2 costs are shared equally among the governance, property owner, and tenants. Each of them bears one-third of the costs. Note that the scenario setups from Section D.4 (i.e., GD (DH)) considered so far that the total costs of inaction are covered by the governance (see Equations 3.48 and 3.50). The mathematical formulation of the modifications here in this section can be found in D.1. Most importantly, the highest total subsidy reduction is obtained when the property owner has to cover the costs of inaction (-49 % compared with the reference value). The second highest reduction is achieved when the opportunity costs are shared equally within the building among the property owner and tenants (-34 %). Equally allocated opportunity costs reduce the total subsidy by 25 %. It is evident that an even allocation between the governance and the tenants (fourth row in Table 4.3) hardly leads to a reduction of the objective value. The main reason for this is the financial support of the property owner, which is necessary to create an investment incentive and the fact that the financial support between the property owner and tenants necessarily has the same net present value.

Building upon, Figure 4.29 shows the objective value for the varying property owner's interest rates. The varying property owner's interest rates have two important impacts. First, a decreasing interest rate reduces the objective value as revenues are discounted less (see Fig. 4.29 for a fixed property owner's share in costs of inaction, e.g., 0.2). Second, as the interest rate decreases, a feasibility limit becomes apparent. This means that the feasible maximum of the property owner's share in costs of inaction depends on the property owner's interest rate i_l (e.g., 100 % for $i_l = 10\,\%$, 70 % for $i_l = 5\,\%$ and 60 % for $i_l = 3\,\%$). Two interesting energy policy implications can be derived from the results here:

- In case the property owner is very much profit-oriented (e.g., an interest rate of 10 %) and the governance's total subsidy payments are to be kept as low as possible, complete allocation of the CO_2-related opportunity costs to the property owner results in a cost-optimal strategy.

- In contrast, in case the property owner rather serves a public-benefit purpose (e.g., an interest rate of 3 %), the CO_2-related opportunity costs allocation among governance, property owner, and tenants is an adequate strategy.

	Rel. allocation of opportunity costs			Objective value	
Brief summary	Governance	Property owner	Tenant	Absolute in EUR	Rel. change in % from GD (DH)
Equally	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	146.6	-25%
Property owner & tenant	0	$\frac{1}{2}$	$\frac{1}{2}$	129.0	-34%
Property owner	0	1	0	99.7	-49%
Governance & tenant	$\frac{1}{2}$	0	$\frac{1}{2}$	183.8	-6%
GD (DH) from Sec. D.4 (Governance)	1	0	0	195.5	-

Table 4.3.: Comparison of objective value (absolute and in %) for varying allocations of CO_2-related opportunity costs. As reference serves the *Gradual Development* scenario with district heating (GD (DH)) from Section D.4 where the total opportunity costs are allocated to the governance.

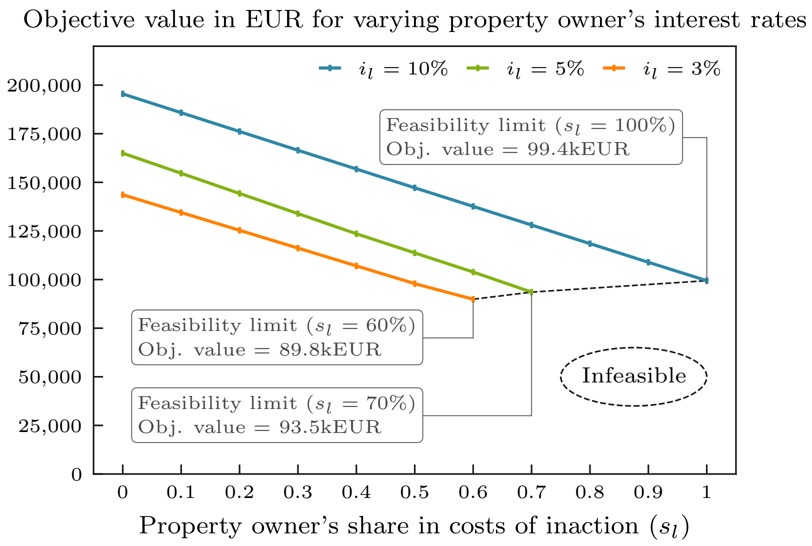

Figure 4.29.: Comparison of the objective value for varying property owner's interest rates and share in costs of inaction

5. Synthesis, discussion, and interpretation of the results

This chapter provides a synthesis of the results. In particular, the main findings for each research question are broadly discussed. This includes the aspects such as the transferability of the results and the proposed underlying methodology. In addition, the strengths and limitations of our work and point out the lessons learned are critically discussed. The chapter is divided into four Sections 5.1 to 5.4, one for each research question.

5.1. District heating 2050 (RQ1)

What would a deep decarbonization of building heat demands in Austria by 2050 look like, and what are the implications of this sustainable energy mix for district heating?

The research question at hand is addressed by using a simplified optimization model that scales down the cost-optimal solution of the European energy system to the level of Austrian communities. By analyzing the heat supply portfolio, it becomes possible to estimate the potential heat density and economic efficiency of district heating networks. The findings indicate that, by 2050, there will be a significant increase in the use of electricity-based heat supply, as a result of the complete substitution of natural gas in energy systems and building heating. However, other renewable heat sources, such as waste heat, biomass, and geothermal heat, will also play a considerable role in meeting the heat demand of buildings. The cost-optimal supply of building heat will be affected by the regional availability of renewable heat sources.

The three renewable heat sources mentioned above, together with the limited use of hydrogen and synthetic natural gas, will require district heating networks for their efficient use and integration on a scale. Consequently, the supply of building heat will become a regional issue, which highlights the importance of optimal regional heat supply solutions in the future. This will require the extension and density of existing district heating networks and the development of new supply areas. The latter is likely to lead to some district heating networks in areas where today's heat densities, which indicate economic viability, are not achieved. This leads directly to the question of under what conditions these district heating networks with comparable low heat density can nevertheless be operated economically in decarbonized energy systems. Ultimately this will be a question answered by the competitiveness of district heating with other heat supply options. On the supply side, two main stages can be outlined. In the near future, district heating networks will compete primarily with gas heating systems and, in the medium to long term, with electric-based heating systems such as small heat pumps. However, the development of building renovation (i.e., the demand side) is also highly relevant and is able to drive the share of district heating in both directions. On the one hand, it is to be expected that the heating demand and thus the heat density of district heating areas will decrease in the course of renovations; on the other hand, it is also conceivable that more efficient buildings will make areas eligible for district heating supply. This refers to the reduction of the flow temperature of district heating networks when supplying buildings with a high standard, which makes the integration of renewable heat sources possible in the first place.

The basic trend towards more district heating that is emerging in the results for Austria by 2050 is probably also transferable to other European countries. The European decarbonization targets in the building heat sector make a change in the energy generation mix necessary, which is likely to lead to more district heating in other countries as well, for the aforementioned reasons of the highly efficient integration of renewable heat sources. Whether this will inevitably also lead to the supply of areas with lower heat density by district heating is difficult to assess in general terms. What is certain, however, is that building renovation will be necessary in other regions of Europe, for example. This certainly indicates that the heat densities of district heating networks in other regions are also likely to be lower than those operated economically today. In any case, a detailed further analysis of other regions regarding their shares of district heating might be necessary.

A primary strength of the proposed method is certainly its simplicity, with which aggregated values of the cost-optimal heat supply of the European energy system can be projected to the level of district heating networks. In principle, the choice of heat sources in the energy generation mix in connection with district heating networks can be very flexible and tailor-made selected. Thus, the method offers the possibility to estimate quickly and with few assumptions where district heating networks could be located. In addition, the supply-side determination of district heating networks of the method also allows rough statements on the electrification rate. The previous point leads frankly to the limits of the method. The downscaling results heavily depend on all assumptions that are implicitly assumed in the aggregated values or in the large-scale energy system model. If there is no differentiation between small and large heat pumps or if, for example, geothermal energy is not considered a heat source, difficulties arise in the proposed methodology. Besides, the proposed spatial resolution is another limitation of the methodology. While the community level already represents a very high spatial resolution of aggregated values (i.e. at the national level), it is still very highly aggregated for detailed planning of district heating networks. The planning of district heating networks is usually done at the level of districts or even streets, i.e. at a level where statements about the length of the required pipelines, the exact location of the feeders and consumers can be taken into account and not only an average value of the heat density is known. Furthermore, and this is the supposed last point of limitation worth mentioning, the heat density is only the first rough indicator of the economic efficiency of district heating networks. The extent to which the heat density of economic district heating networks will change in the course of the decarbonization of the entire energy system is unclear. Generally, development in both directions is conceivable, i.e., toward higher or lower heat densities for economic operation.

5.2. Cost-effective gas network decommissioning (RQ2)

Which decommissioning and refurbishment investment decisions result in a cost-effective gas network infrastructure by 2050?

The research question is addressed by developing a tailored graph-based optimization model which is then applied to an Austrian case study at the federal-state level. Although the model was developed specifically for the present case study, general observations can be made with an eye on the findings. The results clearly show that both elemental decisions, i.e. decommissioning and the refurbishment investment of the existing gas network infrastructure, will be taken by 2050. This also applies, considering a significantly reduced gas demand in the course of the decarbonization of the energy system in the coming years and decades. The split between decommissioning and investment decisions will ultimately depend on how the cost-optimality of gas-based energy services in decarbonized energy systems is determined. If there is a demand for gas in the future, it is likely that piped gas will be the most cost-effective way to deliver it. Other alternatives, such as stand-alone solutions, are much more expensive and therefore not a realistic option.

However, with the overall demand for gas falling, the question for gas network operators will be how to concentrate demand and consumers and still meet significant volumes of demand with fewer pipelines and a smaller network. On the one hand, this probably can be achieved by identifying and using duplicate structures in the existing network or by rerouting (i.e. supplying consumption via another pipeline). At the same time, the question of regional biomethane production and integration into the existing gas grid arises. In particular, the decentralized nature of biomethane production could be another driver for re-investment and still large networks. In this case, the decision to decommission high-pressure pipelines would also be strongly influenced, as these are likely to be needed for the inter-regional transport of biomethane. At present, biomethane is mainly connected to the mid-pressure network level. It is likely that recompression from the mid-pressure to the high-pressure network level will be required for the inter-regional transport of biomethane. From today's point of view, this is not promising, as recompression requires high energy consumption. However, as the demand for gas decreases, the operating pressure levels of the gas networks can be expected to decrease. This will open the door to more uniform and lower pressure levels, leading to significantly lower energy requirements for compression. The reasons for re-investment are thus not only the point of aging of the existing network, which is dealt with in detail in this work but also the changed transport and supply task due to a strong integration of biomethane production. Against the backdrop of refurbishment investments and considerably reduced demands, an increase in network charges is also able to be expected. In our work, an optimistic assessment in this regard has been made, namely, that network charges will remain constant until 2050 compared to today. An increase in network charges to ultimately compensate for the declining demand and number of customers may also further reduce the economic viability of gas compared to other energy supply options (e.g., electrification of energy services). The higher network charges exemplarily can be implemented, as suggested in our work, through the socialization of the additional costs to the remaining consumers. Eventually, this discussion will also include not only the socialization of costs within a network but also whether the socialization of costs between networks (i.e., electricity, gas, hydrogen) can be justified.

With regard to the transferability of the results, some very clear trends can be identified. On the one hand, independent of the present case study, it can be deduced that even a low-utilized network and thus pipeline transport is significantly cheaper than the alternative (i.e. trucks and local storage). However, it also emerges that the cost-optimal gas network will be a regional issue, which may be unsatisfactory in terms of transferability. The trajectory of gas networks in the future will depend not only on the regional demand and production of gas and biomethane but also on the availability of alternatives (e.g. possible access to electricity and hydrogen networks). In some countries, such as Germany, Italy, or Austria, regional biomethane production will play a major role in the future role of gas networks.

A major strength of the approach is that differences in the future gas network infrastructure can be made quantitatively visible. In this way, the aspect of cost-optimal handling of the available gas demand in the future is taken into account and raised. The parameter of gas demand, which often dominates gas network modeling and is usually defined exogenously, is critically examined here and its influence is investigated. The long-term planning horizon allows for the investigation of long-term decarbonization and its impact on the gas network infrastructure. However, for computational reasons, this long-term perspective requires a limited temporal resolution within one year (a monthly resolution was chosen as a compromise), which means that hourly demand peaks can only be modeled to a limited extent. This could lead to an underestimation of gas network rehabilitation investments, as it only partially captures daily peak demand and the associated need for network flexibility.

5.3. Distribution infrastructure of local neighborhoods (RQ3)

Which alternative distribution grid capacities and sector coupling technologies are required to ensure adequate, but sustainable development in the provision of local heat energy services (e.g., space heating and hot water)?

The research question has been addressed by using two existing open-source energy system models. In particular, the different scope of the models (one focuses on temporal resolution, the other on spatial resolution) enables us to determine not only the required capacities of the heat generation technologies but also the transport capacities of the electricity, gas, and district heating distribution grids. To demonstrate how an adequate, but sustainable development in the provision of local heat service needs would look like, a small neighborhood in a densely populated area in Vienna has been selected. So far, this area's heat demand is mainly covered by gas, whereas there is a possibility of being connected to the existing district heating network. Based on the existing distribution grid, the required capacities, investments, and costs are calculated for a scenario where the heat demand is mainly electrified and a scenario where the heat demand is covered by the district heating network. In the electrification scenario, the results indicate that the existing distribution grid capacities can essentially handle the additional load of electric heat supply within the neighborhood. However, large investments are needed in heat generation technologies, such as small heat pumps in buildings to replace existing gas-based heating systems. In the district heating scenario, the results indicate that large investments into the district heating grid and its transport capacities are required. Nevertheless, the comparison with the "no action" scenario, which maintains the current gas-based supply, shows the economic advantage of the district heating scenario when an increasing carbon price is assumed.

The present results are essentially transferable to other neighborhoods and areas with comparable characteristics in terms of heat demand and heat demand density. This is especially true for densely populated urban areas with a high share of gas-based heat supply. However, even if the characteristics of the areas are similar, some factors are relevant and need to be taken into account when it comes to transferring the present findings to other areas. Essential for the findings is namely the fact there is an existing and well-developed electricity distribution grid and a possible connection to an existing district heating network. The possibility of connection is an argument that the district heating network on its supply side can meet the additional heat demand of the neighborhood. In most cases, the latter can be assumed small compared to the total heat demand covered by the network. Besides, (local) energy prices play a key role when it comes to the question of whether or not results are transferable and should be taken into consideration. In particular, the district heating prices are important for the finding of the previously mentioned economic advantages compared to the existing gas-based heat supply. The specific carbon emissions of the district heating network are also relevant, as rising carbon prices have a significant impact not only on the cost of gas but ultimately also on the price of district heating depending on the share of carbon-emitting energy carriers in the heat generation mix. As with the price of district heating, the same applies to the electricity price and its dependence on the carbon price.

Strengths of the methodology used lie in the comparison of the two most-realistic decarbonization options for the heat supply in urban neighborhoods. In particular, the method allows considering the existing distribution grid infrastructure, which is essential when assessing quantitatively the costs of decarbonizing heat supply with the cost of sticking to a gas-based heat supply. Moreover, as all the available heat demand is covered when switching to the district heating network, the approach reveals the future trade-off between the additional supply of as much heat demand as possible in an already developed supply area (i.e., going in the direction of connection commitment) and the possible supply of sub-areas with low heat density. This aspect ties in with research question 1 and underlines its importance.

Limitations of the methodology include the cost components considered. So far, only the costs of distribution network expansion and small heat pumps have been included. For the district heating network, for example, no costs are included for the additional heat generation capacity. It is simply assumed that the district heating network can cover the additional heat demand without additional costs on the generation side. This assumption reduces the comparability of the two sustainable heat supply scenarios. Moreover, the impact of electric vehicles is not considered. Electric vehicles are likely to put a greater strain on the electricity distribution grid, which may require more investment in the grid. In fact, this can already be seen in Norway, a country with a significantly high share of electric vehicles and electric heat supply. The distribution grid operator there sees district heating as a major opportunity to reduce the load on the electricity distribution grid. This is remarkable because district heating has not played a significant role in Norway so far. The reasons for this are the lack of economic efficiency (the price of cheap electricity essentially determines the price of district heating for customers) and the comparatively low heat densities. Furthermore, costs incurred by implementing either district heating or a small heat pump in the buildings are only partially reflected. In principle, it is difficult to estimate these costs within the building from the perspective of the distribution network operator without knowing the relevant characteristics of the building. Not only the size of the building in terms of individual apartments but also to what extent components of the existing heating system are used play a key role. For example, if a water-based heating system is already in place, the switch to either district heating or a small heat pump can build on existing water pipes within the apartments. In particular, this question of what is necessary to trigger a sustainable heat supply in buildings is below addressed in research question 4.

5.4. Cost-optimal and socially balanced subsidization (RQ4)

What is a cost-optimal and socially balanced subsidization strategy for a multi-apartment building to trigger investments in a sustainable heat supply?

The research question is investigated based on a representative multi-apartment building in an urban area that is currently heated with gas. Decarbonization of the building achieves either a connection to the district heating network or the installation of small heat pumps. A developed and tailor-made optimization model enables the determination of a cost-optimal and socially balanced heating switch from the governance's perspective, taking into account the individual strategies of the property owner and tenant. Essentially, the focus is on the split between investment grants, which reduce the property owner's overnight investment costs, and subsidy payments, which reduce the tenant's heating and rent costs. Against this background, the cost-optimal and socially balanced subsidy strategy is defined as an equal split between an investment grant, a rent increase, and a heating subsidy. The main findings show that the district heating option is advantageous compared to the small heat pump option.

Transferability of the results is given in particular for buildings in urban areas and densely populated areas where currently heating systems are also based on gas. Even for larger or smaller buildings (in terms of number of apartments), the main findings are likely to be transferable. As described in the text of the previous research question 3, energy prices of district heating and electricity are important and could lead to the results in one or the other direction, and thus total subsidies are required. However, even if other energy prices are assumed, the results point in a similar direction as described above. This can be drawn from the conducted sensitivity analysis regarding the allocation of a rising carbon price between the property owner and tenant. It is made on the assumption that waterborne heating systems are in place and their components can continue to be used after the heating system has been replaced. This assumption should be true for most countries, as gas-based heating systems are actually always waterborne. However, an example should also be given where this is not the case. Norway, a country that was already used as an example in the discussion of research question 3, is to be assessed differently in this respect. If one were to examine a comparable multi-apartment building there and consider a switch of the heating system (e.g. from inefficient direct electricity heating to more efficient small heat pumps or district heating), costs would have to be expected, some of which would be considerably higher, as additional water pipes would have to be laid in the apartments. However, as mentioned above, distribution system operators in Norway do consider such cases, as electricity distribution systems in particular are already sometimes operating at their limits and all possible measures to relieve the pressure on the systems are being evaluated.

The strength of the methodology used is that the cost-optimal governance solution respects the individual strategies of both the owner and the tenant. This ensures not only a theoretically optimal cost-optimal solution but also practicality. As the methodology incorporates the costs associated with a rising carbon price (and therefore rising heating costs for the tenant), events such as the energy price rally in 2022, when energy prices rise dramatically, can be easily incorporated into the solution-finding process. In addition, the method enables an investigation of the relation between the switch of the heating system and the building renovation. This corresponds to the consensus that both aspects of urban areas have to be considered together. Indeed, it is very important to consider the efficiency of small heat pumps in the modeling, especially when looking at social balance. Inefficient small heat pumps, which are to be expected in most cases in urban area buildings without building refurbishment, lead to comparatively high energy costs that can hardly be compensated in the model by subsidies to the property owner. In contrast, the district heating solution in refurbished proves to be somewhat more robust and flexible in this regard.

Although the focus of the model/method is on the replacement of the existing gas-based heating system, some relevant aspects are only considered to a limited extent perhaps. In particular, the findings on the strong influence of building renovation on the results show that special attention should be paid to the modeling of building renovation. However, the modeling of building renovation is limited. Particularly in urban areas with a high proportion of old buildings, the extent to which refurbishment can be carried out must be carefully examined. The associated cost aspects and the effects on the heating load or heating systems could be improved. From a very practical point of view, the aspect of changing tenants should certainly be mentioned. This point becomes particularly explosive when temporarily higher costs arise for the tenant. The extent to which this cost increase can be borne by the tenants from a social point of view is not currently being considered.

6. Conclusions

A broad consensus exists on phasing out fossil natural gas as part of decarbonizing the energy system. However, its far-reaching implications in various dimensions (e.g., economic, technological, social) are still unclear. Against this background, the present work seeks to contribute to a clearer picture of an energy system without fossil natural gas focusing on sustainable building heat supply and gas networks. The research questions addressed in this thesis highlight the economic benefits and challenges of the energy system's natural fossil gas independence at different levels and perspectives. Moreover, the thesis underlines how maintaining dependence on fossil natural gas can lead to an even more socially unbalanced energy system in the future.

While the downscaling of European decarbonization scenarios to the level of communities brings light on the economic efficiency of future district heating networks, the coupling of different open-source models with a focus on the spatial and temporal resolution reveals which electricity and heat distribution grids are required in gas-free urban neighborhoods. While typical energy system models tend to overlook social equity aspects, developing a tailor-made model demonstrates how to achieve a socially balanced "last mile" of heat decarbonization for multi-apartment buildings, considering the different interests of property owners and tenants. Given declining natural gas demands, a simplified techno-economic model for the trajectory of future gas networks proves to be appropriate in discussing up-to-now taboos such as supplying or not supplying future gas demands.

Decarbonizing the energy system will change the framework of (existing) business models. For example, district heating networks are likely to be driven by the ability to efficiently integrate local renewable heat sources, even in areas where they would not be built today for current economic reasons. Gas network operators are confronted with the issue of deciding regionally to no longer meet the available but strongly declining demand for gas, as reinvestment because of the aging of the pipelines or simply operating the network is no longer economically justified. Both aspects underline the regional dimension in deciding how to deliver energy services in future energy systems. In terms of how they are delivered, a "MWh" demand thus needs to be likely treated differently depending on the region and location in future energy systems. Against this background of intentional regional differences in the provision of energy services, and because the costs of inaction will exacerbate injustice, social equity needs to increasingly come to the forefront. Exactly what that can look like is certainly a big challenge, but the work has shown an example of the equitable and sustainable heating system switch in rented multi-apartment buildings.

The study's findings rigorously analyze and showcase the capability of a large-scale energy system model for district heating and demonstrate the economic viability and equitable social impact of gas-free neighborhoods and buildings. The latter is particularly evident when considering the effect of monetary and regulatory incentives triggering the switch to sustainable heating systems. Furthermore, the cost-effective trajectory of gas networks provides applicable insights for policymakers, as related results reveal the trade-off decision between investment costs, expected revenues/purchase streams of gas pipelines, and supplying or not supplying available gas demands.

The work has methodological limitations that necessitate downstream analyses. For instance, if the economic efficiency of district heating networks at the community level cannot be adequately evaluated based on the heat density, it may be necessary to further downscale the results to the neighborhood or even the building level. Additionally, concerns about the impact of other energy services, such as mobility or cooling, on distribution networks may require an extension of the energy demand under consideration. Therefore, electricity, heat, mobility/transport, and cooling must be considered. At the building level, the individuality of agents (e.g., tenants) could be more robustly incorporated. Implementing different willingness to pay for the sustainable provision of energy services or, more fundamentally, agent-based modeling can consider these aspects. Analogous to the willingness to pay of agents, a finer differentiation between gas demand and the associated energy service it covers could strengthen the statement of whether gas demand is economically supplied. Ultimately, this question can only be answered by looking at which alternative is possible and what is required for a stand-alone solution regarding hubs, local storage, and transport options.

7. Future work

This final chapter provides an outlook for future work that builds on this thesis. Four different ideas/questions are described, each closely related to one of the previous research questions. Each idea is discussed by first formulating an open question that could be the starting point for future research. A broader discussion then follows in a second step.

Refining assumptions in large-scale energy system models based on downscaling results

Open question: *How can the obtained district heating networks and their heat densities be returned into more aggregate and large-scale energy system models, such as GENeSYS-MOD, in the sense of a feedback loop? More generally, how can results from local energy systems be used to refine the assumptions and modeling of aggregate energy system models?*

The following remarks are based on the ongoing work of the author published in (Zwickl-Bernhard and Otti, forthcoming). Ultimately, the question heads in the direction of how to increase the plausibility and realism of pathways at the European level. In fact, best practices for elucidating the cornerstones of sustainable energy systems are mainly built on model-based integrated analyses. These models are, in particular, large-scale energy system models that focus on the long-term decarbonization of energy systems. Their broad vision of energy systems typically determines the optimal investment decision and deployment of energy generation technologies and infrastructure at the national or subnational level. However, the increasing complexity and size of the models (e.g., due to the integration of further sectoral demands such as heat and transport or the consideration of a finer spatial granularity) require simplifications with respect to various domains in the modeling, mainly to keep computation time within reasonable limits. The scope here is to address one of these simplifications often made in the representation of the heat sector in large-scale energy system models. The focus is on district heating and its role in large-scale energy system models because this centralized heat supply option is often neglected and not explicitly considered in these models. Even when district heating is considered in large-scale energy system models, it is usually quantified aggregated values at the country level. This has proven to be an insufficient spatial resolution for the analysis of district heating, as at this resolution, for example, a realistic representation of infrastructure-related investments is significantly limited or even impossible. There is no doubt that most decarbonization pathways show a strong trend toward the electrification of the heat sector. However, this trend does not necessarily say anything about district heating, which is essentially a heat transport infrastructure but can also be "fueled" electric (e.g. large-scale heat pumps). The focus here is therefore on the trade-off between district heating (centralized) and building heating (decentralized). The problem with large-scale energy system models is that they cannot separate these two types of heating infrastructure.

The author's first preliminary results on the topic have already been published (see in Zwickl-Bernhard and Otti (forthcoming)). They are based on a newly developed methodological approach, which is based on the method described in Section 3.1. A detailed description of the methodology is therefore not given here and reference is made to the literature cited above. Instead, selected key findings are briefly exemplified.

- First, large-scale energy system models should separate heat pump generation into large-scale and small-scale. This could significantly improve the relevance of their solution for further in-depth analyses (e.g., then not all heat generation of heat pumps can be used for district heating). The electrification of heat demand is identified together with high shares of unused other heat sources (e.g. waste heat and geothermal) that could be used at the same time to relieve the electricity sector.

- Second, the representation of geothermal sources can be improved. However, this may also lead to the need for improved representation of large-scale heat storage and how to enable a seasonal shifting of heat generation. In addition, the use of waste (incineration) should be examined in detail as this heat source is sometimes not represented in the cost-optimal decarbonized energy system.

Development of gas network tariffs in decarbonized energy systems

Open question: *How will the expected increase in gas network tariffs due to lower gas demand affect the economics of gas and sustainable energy alternatives?*

Until now, natural gas has mainly been transported through pipelines. This has been done at a very low cost, so the impact of transport on the economics of gas and its competitiveness with other fuels has been limited. However, with declining demand for natural gas and lower utilization of gas networks, it is expected that gas network tariffs, and therefore the cost of transporting natural gas, will increase significantly. This raises the question of the trade-off between maintaining the supply of energy services through piped gas and other supply options. There are two straightforward supply option alternatives. First, the trade-off between natural gas and sustainable energy alternatives could be studied in detail. This refers to the shift in the economic efficiency of the two energy options for providing an energy service as a result of the increase in gas network tariffs. However, even if the intention is to maintain a natural gas-based energy supply for some reason (e.g., for the so-called "hard-to-abate" energy sectors/services), alternative gas supply options to piped supply, such as stand-alone solutions combined with on-site gas storage, could be possible.

Two selected aspects that are relevant when examining gas network tariffs in decarbonized energy systems are briefly discussed below.:

- The use of hydrogen has a direct impact on the share of natural gas, as they are usually used as alternatives to provide the same energy service. However, a number of questions remain unanswered in the context of hydrogen supply. In addition to the question of where and how hydrogen will be economically produced in sustainable energy systems, it is also unclear what the cost of transporting hydrogen will be. This raises the question of how to set tariffs for hydrogen networks. This is particularly important in the early stages of hydrogen deployment. One possibility is to link hydrogen network tariffs to gas network tariffs, but other options are also possible. Linking to electricity network tariffs is also seen as a practical and pragmatic option. These broadly outlined options point very strongly in the direction of socialization of network costs, as already indicated in this paper. However, more detailed work is needed.

- Utilizing the available biomethane potential in future energy systems offers the opportunity to meet gas-based energy services in a sustainable way. Depending on local conditions, there is a significant aggregated potential for biomethane production. However, it is likely that these production facilities will be widely dispersed, as they achieve rather small production capacities per unit. This leads to the need for an extensive gas transport network to make biomethane usable on a large scale. In view of this, the design of the gas network in the future may be driven more by the production side than by the demand side. However, it is not clear how the network tariffs of such generation-driven gas networks will be distributed between consumers and producers.

Comparing individual and system approaches for phasing out natural gas in building heating

Open question: *Compared to an individual-oriented approach, is there an economic advantage to a system-oriented optimal phase-out of natural gas in the heat supply of urban neighborhoods?*

In European countries, national governments have decided to phase out the use of natural gas for heating buildings. In Austria, for example, the aim is to be gas-free by 2040. When it comes to practical implementation, there are two implications. On the one hand, from the point of view of individual end users (e.g., households), the question arises as to when is the optimal time to switch heating systems (i.e., from gas boilers to sustainable alternatives such as small heat pumps or district heating) from an economic point of view. In addition to the expected evolution of energy prices, such as electricity, gas, and district heating, this also depends to a large extent on the existing end-use equipment (i.e., already fully depreciated, recently replaced, or refurbished). On the other hand, gas distribution network operators are confronted with issues of decommissioning and continued operation of existing parts of the gas distribution network. The latter applies in particular to the low-pressure gas network level. Investigating various representative supply areas could shed more light on this and provide essential insights for decision-makers. The following pathways of phasing out natural gas could be considered.

- Individual or end-customer-oriented decision planning and subsequent decommissioning or operational decision of the gas distribution network operator (i.e., the gas demand of the end customer determines the decision regarding the natural gas distribution network)
- System-oriented optimization, which considers both viewpoints, i.e., the end customer and the distribution grid operator together

As an example, the results can provide insights into the possible financial room for operating compensation payments for end-user equipment and the development of gas network tariffs, especially at the low-pressure level.

Interaction between government subsidy payments and carbon tax revenues in decarbonizing building heating

Open question: *What is the interaction between government subsidy payments and carbon tax revenues when considering the public finance deficit of* *triggering a switch to sustainable heating systems in buildings?*

This thesis has already presented a socially balanced subsidy strategy for rented apartment buildings. The results show that in such a case massive cash flows from the government to the owner and the tenant are necessary. However, it can be argued that, from a governance perspective, the focus is more on the public finance deficit and how to keep it as low as possible:

- The government faces high risks if rising carbon prices lead to an increase in energy and heating costs for end consumers. A similar situation has been already observed in 2022 when high energy prices for consumers, due to peak fossil natural gas prices, had to be mitigated by massive compensation payments from governments. In such a sense, the costs of inaction for maintaining natural gas dependency have been carried by the governance. Of course, one can argue that the situation of energy prices in 2022 was an outliner. However, the carbon price can have an identical effect on energy and heating prices in the future. This raises the question of how possible revenues from carbon taxes and subsidies for sustainable building heating compare. How can a scattergun approach be avoided and how can targeted incentives and measures be designed to support property owners and tenants? Moreover this questions also the optimal timing for the governance of monetary support.

- When it comes to modeling end-user decisions, the literature suggests that agent-based modeling approaches are valuable. For example, agent-based modeling could be useful to incorporate that the socially balanced subsidy strategy requires building renovation measures. However, this reasonable aspect may affect the property owner's position on the sustainable heating system change and how a socially balanced subsidy strategy can be determined. The high investment costs of renovating a building can quickly exceed a property owner's financial means, even if the renovation and replacement of the heating system may generate higher rental income in the future. A new socially balanced and cost-efficient subsidization strategy between the three agents may be needed in such a case.

8. List of papers

i **Zwickl-Bernhard, Sebastian**, Daniel Huppmann, Antonia Golab, and Hans Auer (2022). "Disclosing the heat density of district heating in Austria in 2050 under the remaining European CO2 budget of the 1.5 °C climate target". In *Sustainable Energy, Grids and Networks* 31, p. 100775. doi: 10.1016/j.segan.2022.100775.

ii **Zwickl-Bernhard, Sebastian**, Antonia Golab, Theresia Perger, and Hans Auer (forthcoming). "Designing a model for the cost-optimal decommissioning and refurbishment investment decision for gas networks: application on a real test bed in Austria until 2050". In *Energy Strategy Reviews*

iii **Zwickl-Bernhard, Sebastian** and Hans Auer (2022). "Demystifying natural gas distribution grid decommissioning: An open-source approach to local deep decarbonization of urban neighborhoods". In *Energy* 238, p. 121805. doi: 10.1016/j.energy.2021.121805.

iv **Zwickl-Bernhard, Sebastian**, Hans Auer and Antonia Golab (2022). "Equitable decarbonization of heat supply in residential multi-apartment rental buildings: Optimal subsidy allocation between the property owner and tenants". In *Energy and Buildings* 262, p. 112013. doi: 10.1016/j.enbuild.2022.112013.

Complementary publications during PhD project:

- Backe, Stian, **Sebastian Zwickl-Bernhard**, Daniel Schwabeneder, Hans Auer, Magnus Korpås, and Asgeir Tomasgard (2022). "Impact of energy communities on the European electricity and heating system decarbonization pathway: Comparing local and global flexibility responses". In *Applied Energy* 323, p. 119470. doi: 10.1016/j.apenergy.2022.119470.

- **Zwickl-Bernhard Sebastian**, Marcus Otti (forthcoming). "Is the decarbonization of the European energy system driving district heating in Norway?". In *19th International Conference on the European Energy Market (EEM)*, pp. 1-6

Other relevant publications during PhD project:

- **Zwickl-Bernhard Sebastian** and Hans Auer (2022). "Green hydrogen from hydropower: A non-cooperative modeling approach assessing the profitability gap and future business cases". In *Energy Strategy Reviews* 43, p. 100912. doi: 10.1016/j.esr.2022.100912.

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Appendices

Appendix A.

Appendix to the *downscaling model*

A.1. Spatial nomenclature and examples

Table A.1 explains the spatial nomenclature and gives examples of each of the spatial levels included.

A.2. Proportional downscaling using population as a proxy

In order to determine total heat demand at the local administrative unit (LAU) level (q_l^{total}), we apply proportional downscaling using population as a downscaling proxy. The fields of application of proportional downscaling are not limited to the modeling of energy systems but to different fields of scientific and practical studies. The reason for this is the intuitive application and that it offers possibilities for tailor-made adaptions, in particular, related to the downscaling driver and proxy. In this context, the study in (Van Vuuren et al., 2006) provides a comprehensive analysis of different proxies for the downscaling of global environmental change, including gross domestic product, emissions, and other indicators. However, downscaling aggregated values of energy systems often uses proportional downscaling and population as a proxy (Alam et al., 2018). Table A.2 shows the data used to obtain heat demand at the LAU level in 2050 including population estimates for

NUTS level	Description	Number	Example (2020's population)
NUTS0	Country level	1	AT Austria (8.86 million)
NUTS1	Major socio-economic regions	3	AT3 Western Austria (2.78 million)
NUTS2	Basic regions for the application of regional policies (federal states)	9	AT31 Upper Austria (1.48 million)
NUTS3	(Small) sub-regions for specific diagnoses (political/court districts)	35	AT312 Linz-Wels (529 thousand)
LAU (former NUTS4/5)	Subdivision of the NUTS 3 regions (communities)	2095	Enns AT312 Linz-Wels (11 thousand)

Table A.1.: Spatial nomenclature of different spatial levels using the NUTS nomenclature. Besides the number of regions per NUTS level, examples for the Austrian case study (incl. population) are given. The gray-colored rows mark the spatial levels used for downscaling in this work.

Austria until 2050. Moreover, we use STATatlas (`https://www.statistik.at/atlas/`) in order to set ϕ_l for each LAU l. The four different categories encompass the following items: urban (I), suburban (II), and rural (III and IV). We set ϕ_l to 0.5 for urban and suburban LAUs and equal to 1 for rural LAUs.

	Description	Data availability/source
GENeSYS-MOD v2.0	Heat generation by source	(Löffler et al., 2017) (Huppmann et al., 2019)
Austrian population density	in 2019	*Statistik Austria*
Austrian population	in 2050	*Eurostat*

Table A.2.: Empirical data settings

The developed optimization model is implemented in Python 3.8.12 using the modeling framework Pyomo version 5.7.3 (Hart et al., 2017). It is solved with the solver Gurobi version 9.0.3. For data analysis, we use the IAMC (Integrated Assessment Modeling Consortium) common data format template with the open-source Python package pyam (Huppmann et al., 2021). All materials used in this work are available on the author's GitHub webpage. We refer to the corresponding repository in (Zwickl-Bernhard, 2022a).

Appendix B.

Appendix to the *decommissioning model*

B.1. Test bed description

B.1.1. Gas network in Vorarlberg, Austria

We illustrate the proposed model using the existing gas networks in Vorarlberg, Austria. Reasons for this test field include the fact that the gas networks there (i) are not connected to the rest of the Austrian gas network and can therefore be studied independently of it, (ii) include both high- and medium-pressure network levels that supply different energy services (e.g., heat for residential buildings, small and medium businesses (SMBs), and industry), and (iii) have cross-border pipelines to Germany and Liechtenstein. Therefore, the investigation of the Vorarlberg gas networks in this work can be seen as a reasonable balance between complexity and simplification against the background of a newly developed and to-be-tested model. As mentioned above, the existing gas network in Vorarlberg, Austria, encompasses both a high- and a mid-pressure network. Particularly, the high-pressure network level includes a cross-border pipeline to Germany and Liechtenstein. Table B.1 provides a summary of Vorarlberg's gas network. The list of general indicators encompasses information related to the gas network, demand, and supply. Figure B.1 shows the existing gas networks (left) and their representation in the model (right) in Vorarlberg, Austria. The high-pressure network

List of general indicators	
Number of communities supplied	39
Number of end-user systems	32 615
Gas supply within Vorarlberg, Austrian	2098 GWh/year
Transmision to Liechtenstein	644 GWh/year
Number of green gas production facilities	2
Total green gas production	6.4 MWh/year
Length of high-pressure network	83 km
Length of mid- and low-pressure network	2128 km

Table B.1.: Summary of Vorarlberg's gas network, demand, and supply in 2020. Source: (Vorarlberg Netz, 2021).

level is comparatively well represented (difference of only 3 km or less than 4%). Nevertheless, the mid-pressure network level is underrepresented in the model. In summary, Vorarlberg's gas networks are represented in the model by 36 nodes and 43 individual pipelines.

B.1.2. Assumptions of the gas demand to 2050

This section is dedicated to describing the assumptions regarding the development of gas demands at the community level in Vorarlberg, Austria, until 2050. In a first step, we assess total gas demands at the community level in 2018 using information from the open data platform (Abart-Heriszt et al., 2019) and our own database. In the second step, we use the classification of communities regarding the energy demand provided by "energiemosaik" to estimate the composition of local gas demands. Accordingly, the local gas demand in the community is allocated to one or more of the following sectors of end-use or items: residential, agriculture, industry, SMB, service, and mobility. Building upon this characterization of gas demands by items, the following claim is made:

> The composition of the local gas demand at the community level in 2018 determines its development until 2050. Each sector of end-use/item is

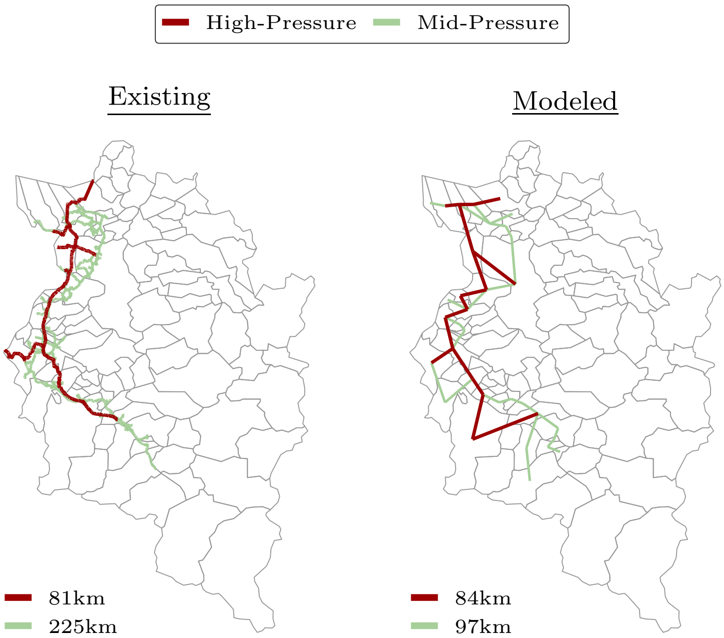

Figure B.1.: Existing gas networks (high-pressure in red and mid-pressure in green) in Vorarlberg, Austria (left), and its representation in the model (right). Source: (Vorarlberg Netz, 2021).

associated with a decline pathway until 2050. Thus, the total gas demand at the community level until 2050 is described by a linear combination of the individual decline pathways per sector of end-use.

Table B.2 shows the assumed annual decline rate (and thus decline pathway until 2050) per sector of end-use. We use the naming convention from energiemosaik and use the names Type A, B, C, and D for a combination of different sectors of end-use. We restrict ourselves to four different types (A-D) only. Note that 2050's share in gas demands are rough estimates including higher values if industry and SMBs are located there. For the residential/building heat demand, a linear decrease until 2040 is assumed.

Name	Residential	Industry	SMB	Service	Decline rate (2050's share)
Type A	✓				Linear until 2040
Type B	✓	✓	✓		Linear (15%)
Type C				✓	Linear (20%)
Type D		✓	✓		Linear (35%)

Table B.2.: Annual decline rates for different compositions of gas demands at the local community level under the naming convention and sectors of end-use from (Abart-Heriszt et al., 2019).

B.2. Data

This section shows a selection of the most relevant input data. At the same time, we refer to the authors' GitHub repository (details in Section B.4) for the complete input data. Table B.3 shows the cost assumptions for gas networks including the specific investment costs (c_l^{inv}) and fixed costs per year (c_l^{fix}) for the different gas network levels. Note that 2030 is the assumed year of the decommissioning and refurbishment investment decision for all pipelines within the networks. Additionally, the development of natural gas prices in Europe is taken from the World Energy Outlook 2021 (International Energy Agency, 2022). The values from the so-called Stated Policies Scenario are taken: 26.28 EUR/MWh in 2030 and 28.33 EUR/MWh in 2050.[1] Revenues are generated in this work on the basis of gas network usage fees. Accordingly, we assume the following values for $p_{l,y}^{loc}$ for each year: 1 EUR/MWh (high-pressure) and 20 EUR/MWh (mid-pressure).[2]

Similar to Von Hirschhausen, 2006, we assume a simplified relationship between the diameter of gas pipelines and their capacities. Accordingly, we assume that the capacity of high- and mid-pressure gas pipelines increases by 2.5 times the power of the diameter. Table B.4 summarizes the set of potential diameters and the corresponding calculated capacity.

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[1] Assuming a linear development between 2030 and 2050.

[2] Note that the currently high natural gas prices are not explicitly considered. However, it can be argued that they are implicitly included as an additional driver for the assumed declining gas demand rates.

Type of costs	Symbol	Network level (l)	Value	Source
Specific investment costs (used in Equation 3.16)	c_l^{inv}	Transmission	4600 EUR/MW/km	(ACER, 2022)
		High-pressure	4000 EUR/MW/km	(EEG-EC, 2022)
		Mid-pressure	3000 EUR/MW/km	
Fixed costs per year (used in Equation 3.10)	c_l^{fix}	Transmission High-pressure Mid-pressure	2000 EUR/MW	(EEG-EC, 2022)

Table B.3.: Cost assumptions of gas networks. The value of specific investment costs of the mid-pressure network level is scaled by the ratio between the existing and the modeled pipeline length (as shown in Figure B.1).

B.3. Limiting model features

Below, we discuss two different limitations of the model, whereas both can be associated with the trade-off decision between (spatial and temporal) granularity and computation time of the model. Besides, nonlinear hydraulic constraints and the book values of compressor stations are not considered.

B.3.1. Representation of mid-pressure pipelines

With an eye on the representation of the mid-pressure gas network presented in Figure B.1, it is evident that the corresponding pipelines of the mid-pressure network level are underrepresented in the model. The main reason for this is the (limited) spatial granularity at the community level since large parts of the mid-pressure network are within communities. Within the simplification of the geometry of gas pipelines to the spatial granularity on a community level, mid-pressure gas pipelines within a single community are not considered. This is why the introduction of a tailor-made scaling factor is needed to adjust the specific refurbishment investment costs ($c_{mid-pressure}^{inv}$) accordingly (see Table B.3 in Section B.2). Exemplarily, this scaling factor is $\frac{225}{97}$ (on average) in the case of the mid-pressure network level in Figure B.1.

Diameter in meters	Pipeline capacity in MW
0.1	0.82
0.2	4.62
0.3	12.72
0.4	26.11
0.5	45.62
0.6	71.96
0.7	105.8
0.8	147.73
0.9	198.31
1.0	258.07
1.1	327.51
1.15	366.0
1.2	407.09
1.3	497.27

Table B.4.: Set of diameters of gas pipelines and assumed pipeline capacity.

B.3.2. Monthly resolution of gas balances

The temporal granularity of the model is limited since it generates results monthly within an individual year. Consequently, again, a scaling factor is needed to link the nodal gas balance constraints (monthly values) with the calculation of needed peak pipeline capacities (Equation 3.21). An hourly resolution could eliminate this calculation process, but, at the same time, one could run into serious computation time matters as the number of equations (i.e., gas balance constraints for node and network level) increases significantly.

B.4. Open-source environment and computing time

The developed optimization model is implemented in Python 3.8.12 using the modeling framework Pyomo version 5.7.3 (Hart et al., 2017). It is solved with the solver Gurobi version 9.0.3. For planning the development of gas networks in Vorarlberg, Austria, the model consists of 124155 equations and 98610 continuous variables. It takes on average 3 s to be solved using a computer with an Intel Core i7-8565U with 16 GB of RAM running Microsoft Windows 10 Pro with 64-bit. We use for data analysis the common data format template developed by the Integrated Assessment Modeling Consortium using the open-source Python package pyam (Huppmann et al., 2021). Note that all materials used in this study are disclosed as part of the publication on GitHub (`https://github.com/sebastianzwickl`). We refer to the repository for the codebase, data collection, and further information.

Appendix C.

Appendix to the *demystifying model*

C.1. Numerical example

In this work, a local natural gas distribution grid decommissioning and, consequently, natural gas phase-out in an urban neighborhood in Vienna, Austria, is proposed. This area is located in parts of two Viennese districts (2nd and 3rd districts) and describes a considerable spatial extension of the investigated energy community in the author's published work in (Zwickl-Bernhard and Auer, 2021b). The latter work focuses on a small fraction of this work's urban neighborhood with an emphasis on demonstrating the local renewable energy sharing potentials inside the community[1]. In contrast, this work primarily deals with a high spatial analysis of distribution network capacities and implications resulting from an entire natural gas grid decommissioning in a much larger and more complex neighborhood. Hence, emphasis is placed on the spatial dispersion of the distribution grid capacity needs of a multiple-energy carrier energy system considering high shares of local renewable energy technology utilization.

In particular, this neighborhood is selected because it not only provides high diversity in (i) load profiles (electricity, heating, and cooling), (ii) building

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[1] The energy community in (Zwickl-Bernhard and Auer, 2021b) is built by four different sites, namely two special consumers (i.e., football stadium and university), a residential area, and a new building area.

structures, and (iii) occupancy intensity but also describes a diverse representative urban area not only restricted to Austrian settlement patterns. Moreover, the characteristics of the testbed include a residential area, public administration buildings, special consumers, a recreation area with selective energy service needs, a spatial separation by a river canal, cross-district administrative planning responsibilities, and more.

Two more aspects related to the distribution grid analysis are important in this work. First, the local natural gas phase-out concerns the low-pressure grid in the range of 3-6 bar[2]. Second, the electricity distribution grid capacities (in MW) considered neglect the detailed analysis of the different voltage levels ranging in Austria from 0.23 to 30 kV.

C.2. Scenarios

In the following, three scenarios (including the current state of supply and two different local deep decarbonization pathways) are described narratively. The scenario analysis shall bring further insights, among others, into the (i) sustainability degree of the current state of supply (Case A) and (ii) efforts as well as benefits from different perspectives in case of ambitious decarbonization of the energy service supply (Cases B and C). The narratives of the three different scenarios are based on dedicated "what if/how" questions. The two local deep decarbonization pathways (Cases B and C) focus on distinct structural changes in the energy distribution grid portfolio and, subsequently, technology supply options feeding into these grids.

Case A - Baseline (current state of supply) This scenario builds upon the existing distribution grid in the urban neighborhood. It contributes to answering the question: what distribution grid capacities are available/required to supply the current local energy demand? Note, at present, there is no

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[2] As mentioned in the introduction section of this paper, co-firing of green gas in cogeneration plants as a fueling technology feeding into the district heating network is possible. However, this is not the focal point of this analysis.

comprehensive cooling demand service available in the area. The distribution grid includes mainly electricity and gas infrastructure. Furthermore, the special consumers within the area are connected to and supplied by the district heating network only (see also Figures 4.11-4.13 in Section 4).

Case B - High electrification This scenario considers high electrification of the energy service supply in the entire neighborhood subject to investigation. Consequently, the heat demand (previously mainly supplied by natural gas) is completely covered by electricity "fueled" technologies (i.e., small-/large-scale heat pumps). Note that the special consumers within the area are still supplied by the district heating network. Furthermore, this scenario takes into account an expected increasing local cooling demand, which is delivered by electricity-based technologies (i.e., compression cooling machines). Thereby, the integration of high shares of local renewable energy generation plays a crucial role (see related benefit indicators in Table 3.3). Synoptically, this scenario investigates a local decarbonization pathway of the urban neighborhood by almost the entire electrification of the energy service supply.

Case C - District heating/cooling network expansion This scenario considers a large-scale district heating and cooling network expansion within the urban neighborhood. The local natural gas distribution grid/demand is replaced by the district heating network supply. In addition, the increased cooling demand is covered by the district cooling network. Furthermore, the electricity demand remains constant in comparison with the current state of supply. Note that this distribution grid-focused scenario places no emphasis on the energy generation technologies feeding into the heating/cooling grid. The technology portfolio in the district heating/cooling generation mix does not directly influence the distribution grid capacities determined in this analysis. However, related generation technology-specific aspects are discussed qualitatively in the results in the context of the different benefit indicator evaluations. Furthermore, this scenario considers a case study of the "non-discriminatory right" to be connected to the heating/cooling grid, regardless of the distance to the existing grid and heat/cold densities. The corresponding economies of scale of the socialized costs of this non-discriminatory grid connection are benchmarked according to the tailor-made benefit indicator definition in Table 3.5 (End-user) and presented in the related result in Section 4.3.4.

C.3. Building stock assumption and further empirical settings

The existing building stock within the urban neighborhood is split into different types and described in the following. Note that these building types can be easily adjusted or expanded according to the needs of further investigations.

Residential comprises different scales of multi-apartment buildings (e.g., small and large multi-apartment buildings). In this work, it is assumed that a characteristic residential building has four floors. The authors are aware that this assumption is to some extent a simplification. However, a more detailed consideration of the existing building stock composition (including its building quality/codes) can be part of further work (see this work's outlook). *Commercial* includes the whole building stock used for commercial purposes (e.g., small industrial, retail, office, lodging, restaurant). *Tertiary and others* take into account buildings that are occupied by public authorities. Furthermore, it covers buildings such as shopping centers, hotels, and theaters. In addition, three different *Special consumers* complete the neighborhood's building stock (Stadium - *Ernst-Happel Stadium* and *Ferry-Dusika Stadium*, University - *Vienna University of Economics and Business*, and Fair - *Fair-Vienna*).

The empirical settings related to technical and economic assumptions are from (EEG-EC, 2022). These include the demand for energy services within the area. Note, that this work takes into account a continuous distribution line capacity available. Further empirical settings, in particular, related to district heating and cooling economic parameters are used from (Ahlgren et al., 2013).

Appendix D.

Appendix to the *equitable model*

D.1. Varying allocation of the costs of inaction

This work considers the CO_2 price-related costs as the costs of inaction and opportunity costs (OC) respectively. Hence, Equation D.1 describes the costs of inaction per year y and month m

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

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

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

where s_l is the share of the costs of inaction borne by the property owner. Consequently, Equation 3.46 is modified as follows by considering the property owner's costs of inaction.

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

A similar logic is developed in the modification of the tenant's net present value. The tenant's share of the costs of inaction (OC_t) are considered in Equation 3.50. The tenant's OCs influence the initial spendings that are assumed to be the limit in the sustainable heating system alternative (see Equation D.4).

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

D.2. Multi-apartment building

The model proposed in this work is applied to a typical multi-apartment building in an urban area. In particular, a partially renovated and natural gas-fired heating system in an old building in Vienna, Austria, is investigated. In 2020, more than 440 000 natural gas-based heated dwellings existed in Vienna, Austria (48.5 % of the total building stock) (Statistik Austria, 2020b). Nevertheless, this case study is representative of the European multi-apartment building stock in densely populated areas, as similar proportions of natural gas-fired heating systems, exist in the residential heating sector there as well[1]. It is assumed that the multi-apartment building (including all dwellings) is privately owned by the property owner. The number of dwellings is 30, whereby the area and rent price for each unit is equal. Each dwelling is rented by a tenant and heated by an individual natural gas-based heating system. The decarbonization of the existing heating systems can be

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[1] For example, there are more than 600 000 natural gas-based systems covering residential heat demand in dwellings in Berlin, Germany, in 2019 (BDEW Bundesverband der Energie- und Wasserwirtschaft e.V., 2019).

realized by two different options, namely, a connection to the district heating network or the installation of an air-sourced heat pump[2]. It is assumed, that only one of the two technology alternatives is realized for all the dwellings.

We consider passive retrofitting measures in this study in a very simplified way and focus here on the insulation of the building skin and the wall to neighboring buildings only. The economic and technical assumptions are oriented to the study in (Fina et al., 2019). Accordingly, we assume passive retrofitting investment costs of 1.75 EUR/kWh. Besides, the following relationships between the specific heat demand and the heat pump's (average) coefficient of performance (COP) are assumed: 130 kWh/m^2 (COP= 2.5), 115 kWh/m^2 (3.0), 100 kWh/m^2 (3.5).

D.3. Data

Table D.1 contains the empirical settings of the multi-apartment building including the agent's specific interest rates and further economic parameters. Note that the property owner's interest rate i_l implicitly considers the natural change of tenants and the associated temporary empty dwelling state. We use a measured normalized heat demand profile of a multi-apartment building from (EEG-EC, 2022) to convert the annual values to monthly. The heat demand includes space heating and hot water demands. The construction costs include the necessary construction measures within the building only.

In addition, Table D.2 shows specific emissions, energy prices, and further technical assumptions. The values correspond to the initial input parameters in 2025 in our analysis. Maintenance costs are considered implicitly as part of the fuel costs. Furthermore, it is assumed that the specific emissions of electricity and district heating decrease linearly between 2025 and the corresponding decarbonization target year of the scenario (2040 in the *Directed Transition* and *Societal Commitment* scenario as well as 2050 in the *Gradual*

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[2] 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 work and is not further examined.

Symbol	Variable	Unit	Value
n	Number of tenants	-	30
i_g	Governance's interest rate	%	3
i_l	Property owner's interest rate	%	10
i_t	Tenant's interest rate	%	5
q	Heat demand (per dwelling)	kWh	8620
$\hat{d}$	Peak heat demand (per dwelling)	kW	5
c_{alt}	Heat pump|Investment costs	EUR/kW	1000
c_{con}	Heat pump|Construction costs (per dwelling)	EUR	1000
c_{alt}	District heating|Investment costs	EUR/kW	320
c_{con}	District heating|Construction costs (per dwelling)	EUR	2000
$\bar{r}$	Initial rent price	EUR/m^2	10
ρ	Maximum rent charge adjustment (ρ)	%	10
a	Rented area (per dwelling)	m^2	60

Table D.1.: Data assumptions of the partly renovated multi-apartment rental building and the agents (property owner, tenants, and governance). Source: (EEG-EC, 2022).

Development scenario). The energy price development of electricity, natural gas, and district heating is in line with the assumptions in (Fina et al., 2019). According to this, the (retail) electricity price increases by 2.37 % and the district heating price by 5 % per year. Additionally, the CO_2 price increases the energy price according to the specific emissions per year. Table D.3 shows the CO_2 price development in the different scenarios.

D.4. Scenarios

Four different quantitative scenarios are studied with the tailor-made model presented above. Input settings of three of them have been developed in the Horizon 2020 research project openENTRANCE (`https://openentrance.eu/`) and describe a future European energy system development assuming to achieve the 1.5 °C or 2.0 °C climate target. These three scenarios are called *Directed Transition* (DT), *Societal Commitment* (SC), and *Gradual Devel-*

Variable	Unit	Value	Ref.
Specific emissions|Electricity	$kgCO_2/kWh$	0.130	(Umweltbundesamt, 2019)
Specific emissions|District heating	$kgCO_2/kWh$	0.132	(Umweltbundesamt, 2007)
Specific emissions|Natural gas	$kgCO_2/kWh$	0.220	(Umweltbundesamt, 2019)
Price|District heating	EUR/kWh	0.047	(Arbeiterkammer Wien, 2020)
Price|Natural gas	EUR/kWh	0.050	(Eurostat, 2019b)
Price|Electricity	EUR/kWh	0.200	(Eurostat, 2019a)
Coefficient of performance (average)	1	2.35	(Fraunhofer ISE, 2020)

Table D.2.: Relevant economic parameters and further empirical settings for Austria in 2020

Scenario (EUR/tCO_2)	2020	2025 – 30	2030 – 35	2035 – 40
Directed Transition	30	196	357	510
Societal Commitment	30	62	137	273
Gradual Development	30	83	128	183
Low Development	30	60	70	80

Table D.3.: CO_2 price development (Auer et al., 2020b)

opment (GD) scenario[3]. The first two scenarios consider the remaining CO_2 budget of the 1.5 °C climate target. Below, we briefly summarize the three openENTRANCE scenarios used in this work and refer to a detailed description of the studies in (Auer et al., 2020b) and (Auer et al., 2020a). For the reader with a particular interest in the openENTRANCE scenarios, we refer to the work in (Auer et al., 2019) in which the underlying storylines outlining the narrative frames of the quantitative scenarios can be found. Note that the scenarios are used to set an empirical framework at the aggregate level for this work's analysis, which is carried out ultimately at the local level. Against this background, European decarbonization scenarios are projected to the building level, making them accessible in practical applications.

- The DT scenario leads to limiting the global temperature increase to 1.5 °C. This is achieved by a breakthrough of new sustainable technologies triggered through strong policy incentives. The markets themselves

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[3] The openENTRANCE scenario *Techno-Friendly* is not part of this work.

do not push this development sufficiently and deliver weak financial impulses for the clean energy transition only. Besides, society is also too passive in supporting achieving the ambitious 1.5 °C target. Thus, in this work, it is assumed that the multi-apartment building is connected to the district heating network to reflect the strong policy-driven character of implementing an alternative sustainable heating system. In the DT scenario, the CO2 price rises from 196 EUR/tCO_2 (in 2025) to 680 EUR/tCO_2 (in 2040) results in deep decarbonization of the European electricity and the heating sector, which is achieved in 2040.

- The SC scenario also leads to limiting the global temperature increase to 1.5 °C. In contrast to the previous scenario, decentralization of the energy system and active participation as well as societal acceptance of energy transition pushes sustainable development. In addition, currently, existing clean technologies are significantly supported by policy incentives to foster its accelerated rollout. Thus, the SC scenario assumes deep decarbonization of the energy system without fundamental breakthroughs of novel technologies. Therefore, the multi-apartment building implements an air-sourced heat pump as a sustainable heating system alternative. A CO2 price increase from 62 EUR/tCO_2 (in 2025) to 497 EUR/tCO_2 (in 2040) achieves deep decarbonization of the European electricity and heating sector in the SC scenario by 2040.

- The GD scenario aims at limiting the global temperature increase of 2.0 °C. In general, this describes a more conservative expression of a European energy system transition. This scenario includes a little of each of the ingredients of the remaining openENTRANCE scenarios: reduced policy incentives, limited social acceptance, and less promising technological advances. Both heating system alternatives (district heating connection and air-sourced heat pump installation) are examined in this work. The CO2 price in the GD scenario is between 83 EUR/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" (LD) 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 changed with today's values. Again, both heating system alternatives are studied. The CO_2 price in this scenario is between 60 EUR/tCO_2 (in 2025) and 90 EUR/tCO_2 (in 2040). No target year for achieving deep decarbonization of the European electricity and heating sector is set.

D.5. Open-source programming environment and data format

The developed optimization model is implemented in Python 3.8.12 using the modeling framework Pyomo version 5.7.3 (Hart et al., 2017). It is solved with the solver Gurobi version 9.0.3. We use for data analysis the common data format template developed by the Integrated Assessment Modeling Consortium using the open-source Python package pyam (Huppmann et al., 2021). Note that all materials used in this study are disclosed as part of the publication on GitHub. We refer to the repository (Zwickl-Bernhard, 2022b) for the codebase, data collection, and further information (incl. underlying cost assumption data for the district heating and heat pump alternative).