Economic assessment of the long-term development of buildings' heat demand and grid-bound supply

A case study for Vienna

DISSERTATION

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Abstract

The long-term reduction of the building stock's space heating and domestic hot water demand and its efficient and ecological supply can contribute significantly to climate change mitigation targets. In order to contribute to these targets, the economic aspects as well as the resulting CO_2-emissions of potential future developments of the heat demand and its supply options have to be considered simultaneously. Especially in the case of existing grid-bound heating infrastructure, a wide range of decision-makers, including building owners, network operators and policy makers, are involved.

Within the scope of this thesis, a model environment was developed which optimizes the investment paths for district heating and gas grids from the network operator's point of view. This optimization is based on the simulation of the long-term investment decisions of the building owners' with regard to thermal refurbishments and the installation of heating technologies. A spatially highly resolved implementation on registration district level allows the identification of district heating and gas target areas within considered regions. The integrated modelling approach is applied on the case study of Vienna. The model was calibrated with building stock data and technical and economical properties of the gas and district heating network infrastructure. Then, three scenarios were defined and analysed which take into account possible future developments of the economic development. Furthermore, additional analyses compare these scenarios regarding adapted legislative framework conditions and the complete substitution of the remaining gas demand by either district heating or decentral renewable energy sources.

The results show a decrease of the buildings' heat demand from 2015 up to 2050 by 20 % to 40 %, depending on the considered scenario and assuming the current legislation. With regard to fulfil the Paris Agreement, a drastic decrease of the share of gas on the heating demand up to 2050 is required. But even in the most ambitious scenario, the share of gas in 2050 still accounts for 25 %. One possibility to achieve a further decrease of the gas demand is to adopt the current legislation and allow a flexible change from district heating to gas from a network operators' point of view. Then, the CO_2-emissions can be reduced by further 8 % in 2050 and the total costs for heat distribution decreases by 2 %. In this case, the share of gas accounts for 14 % in 2050, while the share of district heating increases from 47 % to 64 %. Under the assumptions of the ambitious climate protection scenario, this share also corresponds to the economically viable share of the buildings' heat demand to be supplied by district heating, under the precondition that in 2050 the whole remaining gas demand has to be substituted either by renewable energy sources or by district heating.

Kurzfassung

Die langfristige Reduktion des Raumwärme- und Brauchwasserbedarfs des Gebäudebestands sowie dessen effiziente und CO_2-neutrale Versorgung kann einen wesentlichen Beitrag zu den Klimaschutzzielen leisten. Im Sinne der Nachhaltigkeit und Leistbarkeit der Wärmeversorgung müssen die ökonomischen Aspekte sowie die damit verbundenen CO_2-Emissionen verschiedener zukünftiger Bedarfs- und Versorgungsvarianten simultan betrachtet werden. Speziell bei vorhandener leitungsgebundener Wärmeinfrastruktur, sind mehrere Entscheidungsträger involviert, deren Interessen zu berücksichtigen sind.

Im Rahmen dieser Arbeit wurde eine Modellumgebung entwickelt, die langfristig die ökonomisch optimalen Investitionspfade aus Sicht der Fernwärme und Gas Netzbetreiber aufzeigt. Diese Optimierung basiert auf der Simulation der Entscheidungen der Gebäudeeigentümer hinsichtlich der Investitionen in thermische Sanierungen und den Tausch der Heiztechnik und der daraus resultierenden Entwicklung des Wärmebedarfs. Eine räumlich hoch aufgelöste Analyse auf Zählbezirksebene erlaubt es, Vorranggebiete für Fernwärme und Gas zu identifizieren. Der integrierte Modellansatz wurde im Rahmen einer Fallstudie auf Wien angewandt: Dazu wurde das Modell mit Daten zum Gebäudebestand und der Gas- und Fernwärmenetzinfrastruktur kalibriert und drei Szenarien hinsichtlich der energiewirtschaftlichen und -politischen Rahmenbedingungen definiert und analysiert. Des Weiteren wurden diese Szenarien hinsichtlich einer Adaption der rechtlichen Rahmenbedingungen und den vollständigen Ersatz der verbleibenden Gasheizungen mit dezentral erneuerbaren Energietechnologien verglichen.

Die Ergebnisse zeigen auf, dass, unter Berücksichtigung der Gebäudeeigentümerentscheidungen und der jetzigen rechtlichen Rahmenbedingungen, der Wärmebedarf des Gebäudebestands je nach Szenario um 20 % bis 40 % von 2015 bis zum Jahr 2050 abnimmt. Der Anteil von Gas entspricht aber auch im ambitionierten Klimaschutz-Szenario noch 25 % des gesamten Wärmebedarfs, was nicht zur Zielerreichung der in Paris verabschiedeten Klimaschutzziele beiträgt. Ein Rückbau der bestehenden Doppelinfrastruktur und die Fokussierung auf eine leitungsgebundene Versorgungsvariante aus Netzbetreibersicht bringt sowohl ökologische als auch ökonomische Vorteile: So reduzieren sich die CO_2-Emissionen im Jahr 2050 um weitere 8 % im Vergleich zum ambitionierten Klimaschutz-Szenario, während sich die Kosten für die Wärmeverteilung um 2 % verringern. Der Anteil von Gas am gesamten Wärmebedarf liegt in diesem Szenario dann bei 14 %, der Fernwärmeanteil steigt von 47 auf 64 %. Unter den Annahmen des ambitionierten Klimaschutzszenarios entspricht dieser Anteil auch dem ökonomisch optimalen Anteil, der durch Fernwärme gedeckt werden kann, wenn vorausgesetzt wird, dass im Jahr 2050 der gesamte Gasbedarf entweder durch Fernwärme oder dezentrale Erneuerbare versorgt werden muss.

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One of the key elements to get this work done was the inspiring and diversified URBEM^{DK}-setting, which was enabled as a cooperation of TU Wien and Wiener Stadtwerke. A special thanks to my colleagues Nikolaus, Nadine, Manuel, Thomas, Dominik, Peter, Julia, Christina, Paul and Johannes as well as Gudrun Weinwurm and Valentina Fünder for the coordination of this doctorate course.

I would also like to thank Andreas, that I could build on his findings, use his tool and develop a further module in this context. Another valuable colleague I want to thank is Michael, who motivated me within all the discussions and always gave me the right inputs on my thoughts. Eric, Raphael, Marcus and Richard - I want to thank you for the great and enriching time we spent together in our office. It was also great to discuss and plan further steps with the other colleagues from our working group - thank you Agne, Fabian and Sebastian.

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And last but not least, I would like to appreciate the support of the ones I love - especially my family! You inspire me every day to get the right things done with passion!

Contents

CHAPTER 1

Introduction

1.1 Motivation

Vienna is a fast growing city in Europe and it is expected that more than 2 million people will live in the capital of Austria in the year 2030 Stadt Wien, MA 23 [2014]. This expected population growth requires new living space as well as new infrastructure. The construction of new living space raises many questions. One of these questions is the optimal heat supply from an economic point of view considering the resulting CO_2-emissions as well.

Besides newly constructed living areas, the existing building stock, its heating demand and the efficiency of it's supply is a substantial part of discussion in the context of an ecological and economic energy planning. In the case of Vienna, 38 % of the final energy consumption arises from space heating and air conditioning (Statistik Austria [2014c]). In residential and public buildings its share is about 64 % (Statistik Austria [2014c]). Therefore, the European Union adopted two directives concerning these end use categories: The directive 2010/31/EU on the energy performance of buildings (European Parliament and the Council of the European Union [2010]) and the EU-directive 2012/27/EU on energy efficiency, article 14. In these directives it is determined that all member states have to conduct a potential as well as a cost-benefit analysis for the economic feasibility and the technical potential for efficient district heating- and cooling supply (European Parliament and the Council of the European Union [2012]). Thus, the efficient supply of the buildings' heat demand with sustainable energy carriers is essential. Austria implemented the directive 2010/31/EU in 2014 and formulated minimum requirements for the energy performance in newly constructed buildings and for renovations of the existing building stock. 47.4 % of Vienna's building stock is older than 50 years (Statistik Austria [2013a]). These buildings come along with high demand for space heating due to low thermal quality of the buildings. Hence it is necessary to focus on thermal refurbishments in Vienna to decrease the heat demand. A part of this, the EU member states need to ensure that decentralised energy supply systems in new buildings based on energy from renewable sources, co-generation, heat pumps or district heating and -cooling is considered. These ambitions are also in line with the Paris Agreement, which was negotiated within the 2015 United Nations Climate Change Conference (COP21).

In consulted literature, district heating is seen as one of the best heat supply options, which can reduce the CO_2-emissions, depending on the used fuels for the supply Finney et al. [2012]. Bartelt et al. [2013] also pointed out that the expansion of the existing district heating network not only leads to a reduction of CO_2-emissions, but also increases the economic efficiency of existing infrastructure and thus lowers the cost for heat supply by district heating, as the higher utilisation of the existing infrastructure reduces the fixed costs. Furthermore, district heating can support the transition of the current energy system to a 100% renewable energy system. Lund and Mathiesen [2009] analysed possible paths to achieve this sustainable energy system until 2050 for the case of Denmark and proposed to reduce the heat demand in buildings and expand district heating by 10 %. This is also one of the main conclusions in Lund et al. [2010], where a gradual expansion of district heating is proposed and the supply with individual heat pumps for the remaining buildings is suggested. Connolly et al. [2014] stated that an expansion of district heating leads to the 80 % reduction of the annual greenhouse gas emissions in 2050, which is proposed in the European Commission's report. The authors stated that in comparison to the proposed EU Energy Efficiency (EU-EE) scenario in the Energy Roadmap 2050, the total costs for heating and cooling in buildings will be approximately 15 % lower. Also the authors in Connolly and Vad Mathiesen [2014] stated that district heating can contribute to the transition of a 100 % renewable energy system. According to Möller and Lund [2010], the highest potential regarding the reduction of emissions, fuel consumption and socio-economic costs is located around cities, as the heat densities are rather high in these areas. These authors, as well as Harrestrup and Svendsen [2014] suggest to invest in energy savings in building and to increase the district heating network efficiency at the same time. Paiho and Reda [2016] dealed with the contradicting problems of increasing the energy efficiency in buildings and the technological challenges of existing district heating networks. Åberg and Henning [2011] analysed the combined effects of more energy-efficient buildings and the expansion of district heating systems and the consequences of the heat and electricity production. In this study, combined heat and power (CHP)-technologies are used and the author identified the optimal heat reduction potential in the sense of minimizing CO_2-emissions. Münster et al. [2012] showed for the case of Denmark, that an increased share of district heating can also be cost-effective, although substantial heat savings are installed.

In Vienna, almost 40 % of the buildings' space heating and domestic hot water demand was supplied by district heating in 2013 Statistik Austria [2014c] and more than 40 % of the district heat generation capacities to supply the district heating demand are fossil fired CHP plants Höller [2014]. Facing this situation and the well-known problems and analyses mentioned above, Vienna also implemented a lot of strategies in the Smart city context, especially concerning buildings and the supply of it's demand with renewables and district heating. A climate change programme „Klimaschutzprogramm II " (KliP II)[1] is introduced, where goals for 2020 are defined. The share of district heating shall be increased due to expansion and efficiency improvements through the usage of renewables shall be implemented. The requirements for new buildings and renovations shall be tightened and the subsidies for renovations and new buildings have to be adapted. Another programme, called „Städtisches Energieeffizienz- Programm " (SEP)[2] contains instruments to increase the renovation rates and -quality of buildings, the energetic improvements of new buildings and the increase in the efficiency of heating and cooling technologies.

[1] https://www.wien.gv.at/umwelt/klimaschutz/programm/klip2/
[2] https://www.wien.gv.at/stadtentwicklung/energieplanung/sep/

For the sake of completeness two other programmes regarding energy have to be mentioned, first the Stadtentwicklungsplan 2025 (STEP)[3], which defines Viennas urban development and the Renewable Action Plan Vienna (RAP)[4].

The current situation as well as the international, national and regional legislatives lead to new challenges for stakeholders in the sector of energy policies and for energy providers. Besides the already discussed problem regarding the contradicting aims of reducing heat demand and increasing the share of district heating at the same time, the interdependencies on the economy of multiple grid-bound heating infrastructures (in the special case of this thesis namely gas and district heating) can also influence the economic assessment and decision-making process of politicians and energy providers.

In any case, to reach the European targets, policy frameworks are necessary, as the investments in the reduction of heat demand or the significant increase of the share of renewables are costly. Additionally, all decisions regarding subsidies, new regulatory frameworks or initiatives influence the energy system of a smart city as a whole. Thus, an interdisciplinary analysis of the topics concerning smart cities is needed.

1.2 URBEM^{DK}

This work was conducted within the doctorate course URBEM^{DK}. URBEM - entitled as Urban Energy and Mobility System Forschungszentrum "Energie und Umwelt", TU Wien [2013] - is an interdisciplinary cooperation instituted by TU Wien and the Wiener Stadtwerke Holding AG (Vienna's biggest utility company), established in 2013. The aim is to develop and establish an interactive environment for analysing scenarios towards a sustainable,secure supply, affordable and liveable city by the example of Vienna in a holistic and interdisciplinary approach. Thus, 10 PhD candidates, multiple scientific supervisors from TU Wien as well as many experts of the Wiener Stadtwerke Holding AG are involved. The 10 PhD-theses,

[3] https://www.wien.gv.at/stadtentwicklung/strategien/step/step2025/

[4] https://smartcity.wien.at/site/wp-content/blogs.dir/3/files/2014/08/Langversion_SmartCityWienRahmenstrategie_deutsch_einseitig.pdf

where a strong focus is on the comprehensive and interdisciplinary approach. They consist of the following topics:

- economics I: Analysis regarding the heat demand and grid-bound supply (scope of this thesis).
- economics 2: Determination of the optimized district heating generation portfolio using stochastic optimization Rab [2017]
- sociology: Analysis regarding the energy consumption and mobility behaviour for the population of Vienna Haufe [2017]
- buildings: Establishing scalable load profiles for residential and office buildings Ziegler [2016]
- thermal heat and gas: Technical analysis of the grid infrastructure Bothe [2016]
- electrical grid: Technical analysis of the electrical energy grid Kaufmann [2016]
- ICT: Planning of ICT structures for controlling the urban energy supply Eder-Neuhauser [2017]
- mobility: transport in a growing city Pfaffenbichler [2016]
- visualization: Implementation of a visualization tool to support the stakeholder decision process Forster [2016]
- distributed computing: Management of complex distributed process and development of the URBEM smart city application (USCA) Schleicher [2017]

Figure 1.1 displays the interfaces and dependencies within the URBEM^{DK} with a special focus on the interdependencies considered in this thesis.

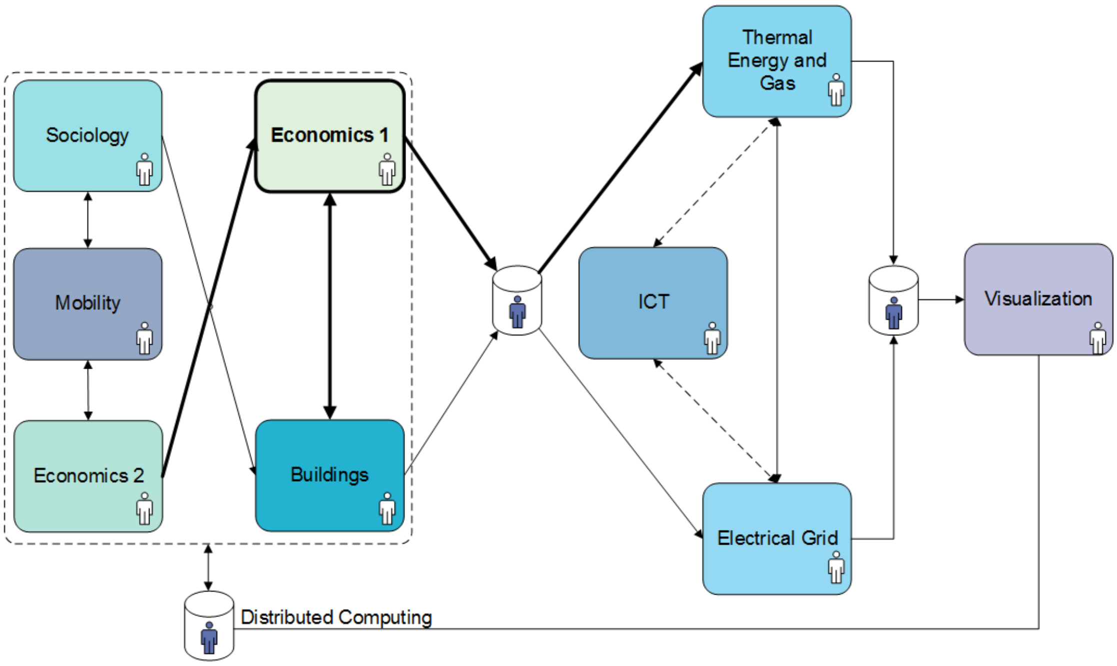

Figure 1.1: Interactions between the single topics in the URBEM^{DK}, Source: own illustration

1.3 Core Objective

The core objective of this thesis is to point out possible pathways for the future development of buildings' heat demand (space heating and domestic hot water in residential and office buildings) and the interaction with the economic feasibility of grid-bound heat supply (namely district heating and gas) up to 2020/2030/2050. The analysis needs to combine two perspectives: On the one hand, the building owners' perspective concerning the investment decisions in thermal refurbishments and the change of technologies for space heating and domestic hot water in the existing building stock. On the other hand, the network operators' perspective concerning the investments in the expansion and extension[5] of the existing grid-bound heat supply infrastructure.
These paths are obtained by developing model-based scenarios, which results in information regarding space heating and domestic hot water demand and the

[5]Expansion is the connection of areas which are not connected to the existing infrastructure in the moment, whereas extension describes the process to invest in the connection of areas where a certain share of the heating demand is already supplied by grid-bound heating supply

share of used energy carriers to supply this demand. The paths are evaluated under economic criteria, considering the effects on the CO_2-emissions as well. Respectively, the costs for building owners, the costs for network operators as well as the corresponding CO_2-emissions are indicated.
The scenarios, which are based on the URBEM^{DK}-scenarios URBEM Scenario Taskforce [2016], differ regarding the assumptions for future development of energy prices and subsidies. Furthermore, the analysis comprises aspects where the current legislatives are changed.

Referring to the core objective of this thesis, three research questions are derived:

1. What are possible developments of the buildings' heat demand and supply (demand for domestic hot water and space heating) in different scenarios up to 2020/2030/2050 considering the building owners' investment decisions in thermal refurbishments and change of heating system?
2. What are the most preferable investment strategies in the extension and expansion of the existing district heating and gas infrastructure from an economic point of view of grid operators?
3. Which grid-bound energy carrier is most economic to supply specific areas within the city?

The core objective of this PhD-thesis is extended due to the interdisciplinary URBEM^{DK} approach. In this context, it is essential to analyse the urban energy and mobility sector in a holistic and comprehensive way. This means that not just the stated research questions above are considered and analysed, rather the interfaces with the other PhD-researchers in URBEM^{DK} have to be included in the work.

In the sense of the interdisciplinary approach, the following objectives are formulated:

1. Definition of interdependencies between the different fields within the URBEM^{DK}.
2. Implementation of the interfaces of all expert models, where the results of this analysis influence the other research questions and models.
3. Consideration of findings of the other URBEM^{DK} fields in the own analysis, which are required to answer the research questions stated above.
4. Provide the integrated modelling for the URBEM smart city application (USCA) and preparation of results for the visualization to support stakeholders in their decision process.

1.4 Major Literature

Many scientific works deal with the research questions regarding the future potential of district heating, the involved costs and optimized investment paths for the expansion of an existing district heating network. The level of details of the different approaches varies, depending on the exact research questions the works deal with.

The models developed in Hackner [2004] and Hensel [2013] use the highest level of detail, as the expansion of the district heating network is conducted for each single building and the costs for the required pipes are determined. Additionally, Hensel [2013] also examines the interdependencies of the expansion of the district heating networks in consideration of an existing gas infrastructure. The advantages due to an applied graph theory formulation of the model allows the almost exact determination of the investment costs, as the algorithm ensures a feasible solution from an technical point of view. However, this modelling approach requires detailed information about the building stock and exact assumptions regarding buildings, which can be connected to the existing district heating infrastructure.

As this information is often not available, Roth and Häubi [1980] developed an approach to analyse potential heat supply variants depending on settlement characteristics. This allows an identification of potential district heating areas, as the settlement characteristics describe the heat densities. Based on these interdependencies of the settlement characteristics and the heat supply, heat atlases can be generated, as it is done e.g. in Blesl [2002] and Esch et al. [2011]. Blesl Blesl [2002] analyses the expansion and extension in grid-bound energy supply for low-temperature heat demand. The author formulates a time-discrete, mixed-integer optimization model to determine the optimal investment strategy in heat generation technologies, distribution and buildings' heating technology. The spatial information is displayed similar to a network flow model. The model uses different types of settlement to determine the costs of a change of the energy carrier and the required connection length to the existing grids. The types of settlement are determined by the urbanistic appearance of regions. This method is also used in various other works Neuffer and Witterhold [2001],Hausladen and Hamacher [2011]. Additionally, a heat atlas then can serve as input data for the future determination of the district heating potential Blesl et al. [2008], Petrovic and Karlsson [2014] or Eikmeier et al. [2011].

The recent years, a lot of GIS-based model frameworks have been developed to determine the potential for district heating. Pusat and Erdem [2014] selected a simplified approach to determine the effective parameters on costs based on basic parameters regarding the region like area, number of buildings and dwellings, the total heat energy need and the peak load demand. Finney et al. [2012] use heat maps to identify the expansion potential for district heating. Another approach is described by Nielsen and Möller Nielsen and Möller [2013], where the future potential for district heating in Denmark is considered. The methodology is based on the Danish heat atlas with all the buildings and their heat demand. The economic feasibility of a connection to the existing district heating network considers costs for heat generation, transmission and distribution costs. It shows that due to the high spatial resolution of the input data and the developed modelling approach, a better determination of the heat distribution costs is possible. A similar approach is conducted to determine the district heating potential in the United States in Gils et al. [2013]. Persson and Werner [2011] use the plot ratio to determine the costs for the expansion of the district heating network.

Grundahl et al. [2016] determined the socio-economic and consumer-economic costs for the expansion of district heating based on the Danish heat atlas. The geographical GIS-based approaches are also used to identify regions where a substitution of gas with district heating is possible. Möller and Lund [2010] determined the CO_2-emissions, the fuel consumption and socio-economic costs for Denmark if gas is substituted by district heating, while at the same time the buildings' heat demand decreases due to heat savings.

In contrast to the used methodological framework in this paper, the focus of the works mentioned above is the economic expansion planning of gas and district heating grids considering heat densities in general or explicit expansion plans and defining the optimized paths for it. In addition, most of the works assume that the full determined heat load can be connected. Although Sperling and Möller Sperling and Möller [2012] generate marginal costs curves for energy savings and district heating expansion, the explicit effects of different policy frameworks on the development of the buildings' heat demand and the endogenously modelled consequences on the expansion and extension are not considered. The model Invert/EE-Lab, developed in Müller [2015], which is also integrated in this approach, focuses on the development of the buildings' heat demand explicitly under consideration of the building owners decision behaviour in heating-related investments.

However, up to now there was little work done on the calculation of the economic potential under explicit consideration of development of the buildings' heat demand and the effects of subsidies for different heating systems.

1.5 Personal Contribution

The problem statement regarding the interaction of the buildings' heat demand and the district heating network operators' investment decisions is also a controversial topic in Vienna. Thus, a specific focus of this thesis is to conduct a case study regarding the research questions and core objective stated in 1.3 for Vienna. Summarized, the personal contribution mainly consists of three parts:

- First, the calibration of a existing bottom-up simulation model to point out possible paths of the future development of the buildings' heat demand.
- Second, the development of a optimization model to determine economic optimized investment paths from a network operator's point of view. This model uses the processed output data of the simulation model as input.
- Third, the implementation of the integrated modelling approach. This includes the data processing and generation of a heat atlas. The heat atlas serves as input for the optimization model and points out district heating potentials based on results of the existing simulation model, where the building owners' investment decisions are considered in detail.

Furthermore, this approach is applied on a case study for Vienna and the results were analysed regarding the stated research questions with focus on the interdisciplinary URBEM^{DK} approach.

The new aspects this thesis deals with are the analysis of the interdependencies of the heat energy system, focusing on the demand- and distribution-related aspects. This means that this analysis considers two perspectives of decision-makers, influenced by the policy frameworks: On the one hand, the building owners, which decide to invest in the building-related technologies and on the other hand, the network operator, who has to make investment decisions for the existing infrastructure from an economic point of view. Most scientific works in this field mainly consider one of these aspects, either a detailed analysis of the building owners' investment decision (as analysed e.g. in Müller [2015]) or the future potential of district heating, considering the development of the buildings' heat demand as an exogenous parameter (analysed e.g. in Blesl [2002] or Nielsen [2014]). The building owners investment perspective is taken into account by using the existing simulation model Invert/EE-Lab (see Müller [2015]). The network operators perspective is modelled within this thesis and linked to the existing simulation model. Furthermore, this analysis is based on high-resoluted spatial data taking into account structural differences within the city of Vienna. This contains the different structures of the building stock in terms of construction period and usage, as well as spatial differences regarding the expected population growth in the city.

As the emphasis of the URBEM^{DK} is to develop the scenarios for a „sustainable supply secure, affordable and livable city“ Forschungszentrum "Energie und Umwelt", TU Wien [2013] in a holistic and interdisciplinary approach, an additional focus is to implement the interfaces within the URBEM^{DK}.

The following paragraphs describe the links to the other disciplines and research questions.

Thesis „Economics 2“: The topic Economics 2 Rab [2017] deals with the determination of the optimal district heating generation portfolio. The stochastic modelling approach results in different generation mixes up to 2050 depending on the URBEM^{DK}-scenario assumptions. The investments in the different technologies and the yearly dispatch of the technologies interact strongly with the network operators investment decision in the expansion of the existing district heating network. On the one hand, the expected district heating demand influences the investment decision for the generation portfolio. This could result in changes of the heat distribution costs, which on the other hand, can influence the network operators' investment decision, as higher heat generation costs reduce the expected profit, if household prices are assumed to be fixed.

Thesis „Buildings“: The main output of the topic buildings Ziegler [2016] is the generation of scalable load profiles for residential and office buildings, which considers construction and mechanical engineering technologies as well as the impact of social differentiation . As the technical analysis of the district heating and gas network requires the hourly load profiles, the method is applied on the building stock data, also processed and analysed in this thesis, and thus the combination of the topic buildings and this thesis can provide hourly profiles.

Thesis „Thermal energy and Gas“: The economic analysis conducted in this thesis can not consider all technical constraints regarding the extension and expansion of the existing district heating network in detail. Thus, a technical analysis of the remaining capacities of the existing district heating infrastructure is done, based on the model-based scenario results of this thesis. Hence, the yearly expected district heating demand for different scenarios in 2020/2030/2050 is transferred to hourly load profiles (buildings) and serves as input for the technical analysis Bothe [2016]. If technical constraints are violated or additional investments are required, the consequences are considered in this thesis.

CHAPTER 2

Method

2.1 Model Overview

In order to answer the research questions, two models are linked and used: (1) The results of an existing bottom-up simulation tool for the building stock point out the long-term development of the heat demand based on the building owners' investment decision for thermal refurbishments and heating technologies. Here, the detailed distribution costs for a district heating and gas supply aren't considered and thus this demand is the upper bound of the heat demand, which can be connected to the existing district heating grid by the network operator. Based on this development, the newly developed optimization model for district heating and gas network expansion and extension (2) determines the share of the demand which should be connected to the existing district heating or gas grid due to economic decisions from the district heating company's resp. gas grid operator's point of view.

The integrated analysis of the demand and distribution of a heat energy system is conducted by using two different spatial resolutions of the particular input data. First, the existing simulation model uses a lower spatial resolution to determine the development of the buildings' heat demand as the building owners' investment decision is mainly influenced by the costs for thermal refurbishments, by the costs for the change of heating system and the annual costs for heat supply and there is hardly any variation within one city. Secondly, the grid expansion model needs higher resolution of the input data, as the total investment costs are mainly affected by the costs for the required pipes. Thus, the distance of units (e.g. building, building block, area), where the model has to decide if it is connected to the existing grid, is important. As the distance varies within different city areas, the cities' building stock has to be disaggregated. Thus, a regionalisation is conducted, which results in a heat atlas for Vienna, pointing out the potential for district heating and gas and finally the district heating demand connected to the grid based on the building owners' investment decision.

Figure 2.1 shows an overview of the model.

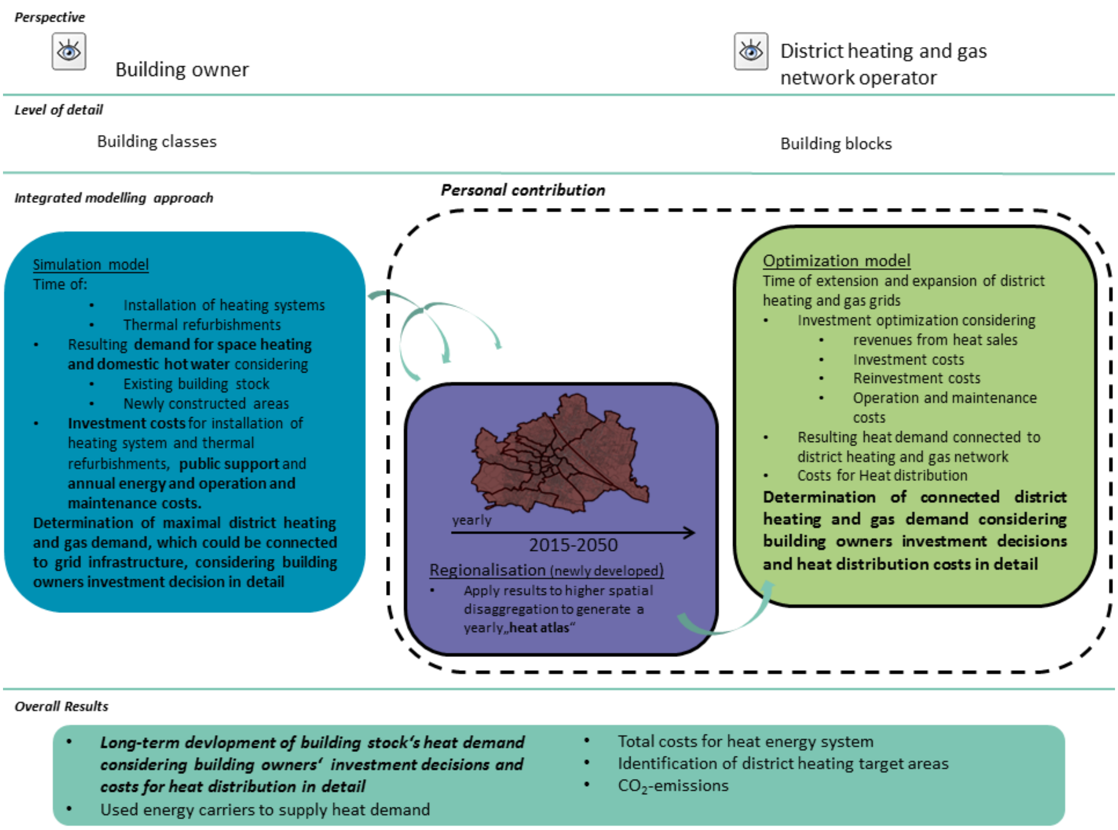

Figure 2.1: Overview of the integrated modelling approach. Source: own illustration

The existing simulation model is shortly described in 2.2, the regionalisation is described in 2.3 and the investment optimization model for the extension and expansion of the existing district heating and gas grid is formulated in 2.4.

2.2 Simulation of building stock's heat demand

The long-term development of the building stock's demand for space heating and domestic hot water is conducted with the existing techno-socio-economic bottom-up modelling tool Invert/EE-Lab. The following section shortly describes the main functions of the model as well as the main input and output parameters. A full description can be found in Kranzl et al. [2013] or Müller [2015]. The existing simulation model considers the investment decisions of building owners for heating technologies and for thermal refurbishments of buildings. The consumers' decisions for a specific heating system depend strongly on the total costs of a technology which cover investment costs as well as yearly energy and operation and maintenance costs. As the yearly costs influence the investment decisions, the interdependencies with the investments in thermal refurbishments are also taken into account. These cost-based decisions are endogenously modelled with a nested logit approach. Figure 2.2 gives an overview of the model structure.

The data aggregation level in this model is on a higher level (less disaggregated) than the data resolution in the optimization model. The analysis is conducted for the whole building stock within one area, whereas the building stock is further divided into (1) building categories, (2) building classes and (3) building segments. Building segments are the most detailed units within the model and describe the buildings with their information about the categories (e.g. single family house or office buildings), their building class (age of building and thermal quality of buildings' envelope) and the used heating system and energy carrier. Furthermore, all buildings are assigned to an energy carrier region. This region determines the costs for the connection to grid-bound heat supply. Blesl [2002], Neuffer and Witterhold [2001] or Hausladen and Hamacher [2011] showed in their analysis that different types of settlement allow to use different costs for the connection to the existing district heating network for buildings, dependent on their location and the structure of the area like number of buildings per m^2, main building categories and size of buildings.

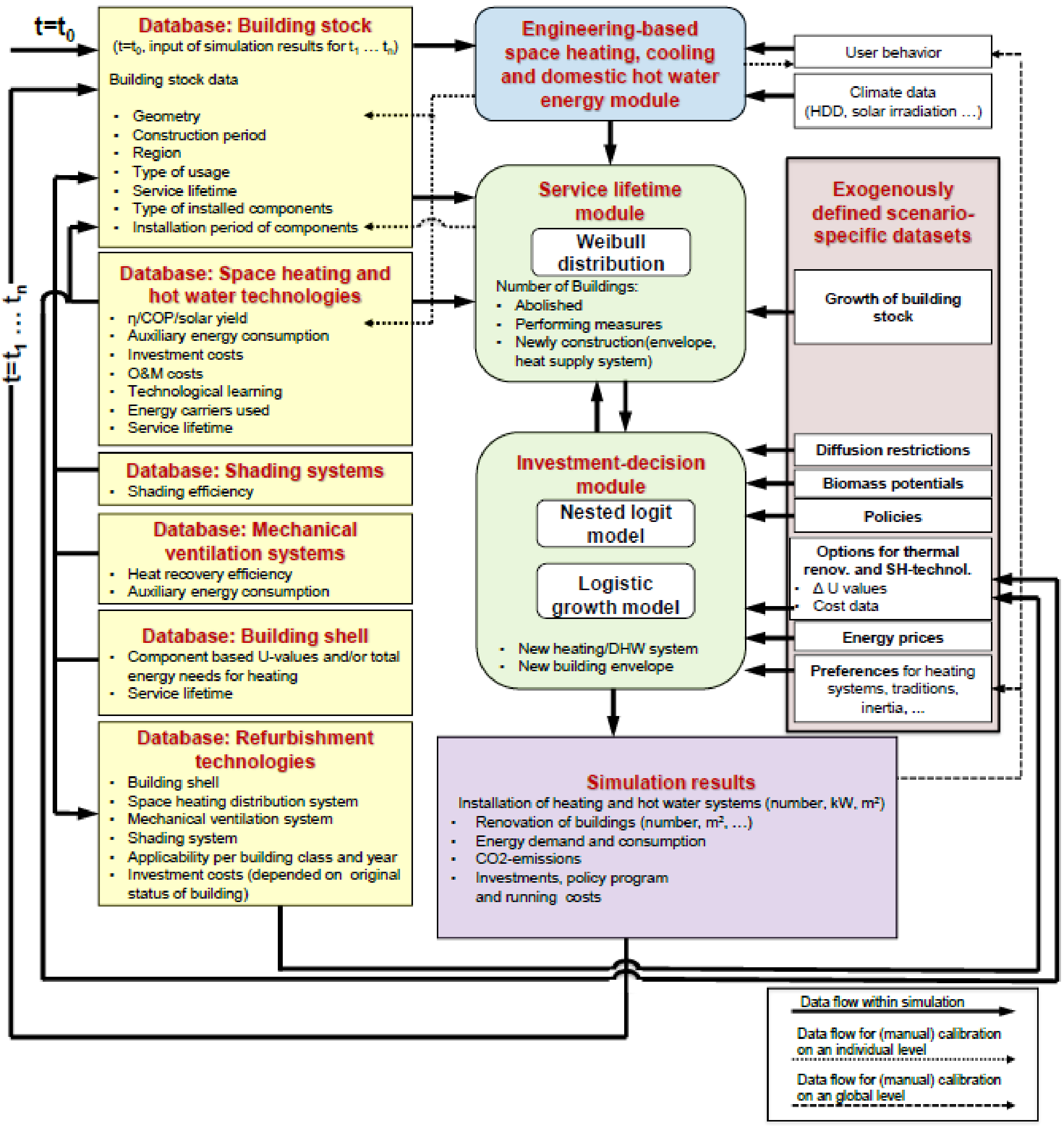

Figure 2.2: Overview about the general structure of the existing simulation tool Invert/EE-Lab. Source: Müller [2015]

The main simulation results used for the integrated analysis of the demand and distribution of a heat energy system are the information about the energy demand, the investments in heating technologies and thermal refurbishments and the replacement rate of existing heating technologies as well as the gross floor area and the used energy carriers to supply the heat demand with. Additionally, the information on the public costs is used as well.

Change of heating technologies and thermal refurbishments Depending on the lifetime of heating technologies and building components like facade and windows, the yearly share of buildings, where investments are required, is determined by the model. If heating technologies exceed their lifetime, the investment-decision model determines if the system is replaced by a newer system of the same type or if another type is used and thus the used energy carrier for domestic hot water and heat demand changes for this building. Furthermore, if the building components exceed their lifetime, the same model decides, if maintenance is conducted to extend the lifetime of the buildings without any influence of the buildings' heat demand or if renovation activities with an influence on the thermal quality of the building are conducted. Depending on which renovation activity is selected, the reduction of the buildings' heat demand is calculated. Possible activities are inter alia just thermal refurbishment of the facade, refurbishment of the facade and change of windows or just the change of windows.

Energy demand The investment decisions of the building owners for the heating technologies, the used energy carriers and the thermal refurbishments of the building influence the buildings' energy demand. The determination of the economically best investment strategies for the extension and expansion of the existing district heating and gas infrastructure requires the information about the year in which an investment is conducted and which energy carrier is used. If building owners decide to invest in district heating or gas technologies for the first time, the related heat demand for this building could be supplied by the grid-bound energy carrier if the grid-operator evaluates this as economically beneficial. Thus, the decisions of the building owners serve as upper bound of the demand, which could be connected to the existing district heating or gas network. In the following sections, the demand resulting from the building owners investment decisions is denoted as $FED^{DH,1}$ resp. $FED^{Gas,1}$, where FED abbreviates the term Final Energy Demand and DH is the short form of district heating. This district heating and gas potential does not consider the distribution costs in detail. The demand which is connected to the existing grid infrastructure due to economic decision of the grid-operator then is denoted as $FED^{DH,2}$ resp. $FED^{Gas,2}$. The ratio $\frac{FED^{DH,2}}{FED^{DH,1}} \in [0,1]$ resp. $\frac{FED^{Gas,2}}{FED^{Gas,1}} \in [0,1]$ indicates the share of the theoretical district heating and gas potential, which is actually connected. The integrated analysis of the heat energy systems' demand and distribution is based on the energy term Final Energy Demand, which is defined in the (Directive 2009/28/EC on the promotion of the use of energy from renewable sources, 2009). A detailed description of the different types of energy terms is displayed in figure 2.3. This energy term can be used as the required energy which has to be supplied by the grid operator.

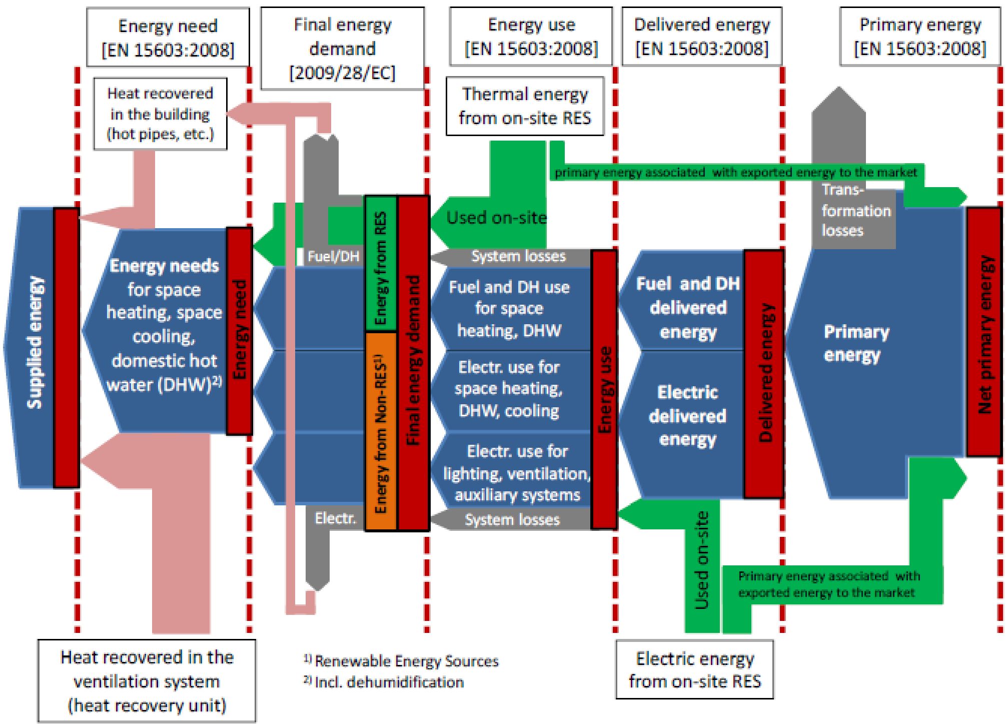

Figure 2.3: System boundaries for different types of energy terms used. Source: Müller [2015]

2.3 Regionalisation of the long-term heat demand

The usage of two different spatial resolutions of the input data within the integrated analysis is required to convert the data and assign it from a more general data aggregation level to higher disaggregated resolution. As the results of the existing simulation model are grouped by different attributes of the buildings, no specific information about the location of the building is available. The adequate usage of the optimization model requires the information about the long-term development of the buildings' heat demand for smaller units within the city and also the distance of these units to the existing grid-infrastructure is essential. Thus the demand for the whole city has to be divided into these smaller units.

The results of the existing simulation model can be interpreted as follows: For every simulation year, a specific share in each building segment performs an action regarding the heating technologies and/or the thermal refurbishments. This action can lead to a decrease in the heat demand general and subsequently can change the relative and absolute share of the used energy carriers. The regionalisation assumes that this change can be distributed to all buildings with the same attributes. These attributes are the building category, building class, construction year and the energy carrier region, which defines the structure of different areas within the city. All these attributes are immutable for all existing buildings and every building of the building stock can be assigned to exactly one group. Furthermore, the absolute change in the usage of gas and district heating has to be determined for all these groups and thus the demand has to be assigned to the buildings. Since the calculation for every single building could be inaccurate due to missing or incomplete data and uncertainties regarding the future development, the information for the buildings is an aggregate for every building block. The following calculation steps are conducted:

- Initialization of the demand in the base year: The results of the existing simulation model are assigned to each building block, depending on the available infrastructure (gas/district heating)

- For every simulation year and group of building[1]: Calculation of the new gas and district heating demand. A distinction of cases is required:
  - Increase of the gas and/or district heating demand within the group: The absolute change is uniformly assigned to all buildings within this group.
  - Decrease of the gas and/or district heating demand within the group: The absolute change is subtracted from the demand of the already connected buildings to the corresponding energy carrier. Thus, the absolute change is divided by the share the connected buildings have in the whole connected demand within this group.

The same procedure is conducted for the total gross floor area for the energy carriers gas and district heating and the connected load or the load that could be connected (this is denoted as $P^{DH,1}$ resp. $P^{Gas,1}$ where P indicates the load).

2.4 Optimization of investments in grid-bound heat infrastructure

The investment optimization for extension and expansion of existing grid infrastructure is formulated as mixed integer optimization (MIP) model. The mixed integer formulation allows to identify the units, which are connected to the existing district heating network. The units differ for the two modelling approaches, which are developed and used: First, an approach where the building owners' investment decision an the resulting final energy demand for district heating and gas serve as upper bound for the extension and expansion potential of the existing district heating network (see section 2.4.1). Secondly, a variation of the modelling approach analyses the benefits, if a switch between grid-bound energy carriers from a gas and district heating networks operators point of view is possible. Here, additional constraints are used to limit the yearly new demand, which can be connected to

[1] The group of building is defined by building category, building class, construction year and energy carrier region

the existing infrastructure (see section 2.4.2). All the modelling approaches are modelled in Matlab using the YALMIP Toolbox and the GUROBI solver.

2.4.1 Optimization model considering the building owners' investment decisions in detail

This approach considers the building owners' investment decision in detail. Thus, the results of the existing simulation model (see section 2.2 for the description of the method and section 4.1 for the simulation results) serve as upper bound for the yearly potential of the extension and expansion of the existing district heating and gas network. Additionally to the distribution costs for district heating and gas the connected demand $\mathrm{FED}_{b,1}^{\mathrm{DH},2}$ and $\mathrm{FED}_{b,1}^{\mathrm{gas},2}$, the connected load $P_{b,1}^{\mathrm{DH},2}$ and $P_{b,1}^{\mathrm{gas},2}$ and the connected gross floor area $\mathrm{GFA}_{b,1}^{\mathrm{DH},2}$ and $\mathrm{GFA}_{b,1}^{\mathrm{gas},2}$ for the simulation years $t \in T$ serve as main outputs. All these parameters are restricted with the results of the existing simulation model. Thus the inequality $\mathrm{FED}_{b,1}^{\mathrm{DH},2} \leq \mathrm{FED}_{b,1}^{\mathrm{DH},1}$ holds for all these parameters. The units, where the model decides whether they are connected or not are here formulated as building blocks $b \in B$.
The model is formulated as dynamic model and considers several investment periods $t \in T$ with the objective to maximize the district heating and gas network operator's profit Π. The profit Π results from the difference of the total revenues R_t^{tot} and the total costs c_t^{tot} for every time step $t \in T$. The objective function is formulated in equation (2.1),where r is the interest rate and T the considered horizon

$$\max \Pi = \sum_{t \in T} \frac{R_t^{\mathrm{tot}} - c_t^{\mathrm{tot}}}{(1+r)^t} \tag{2.1}$$

The model considers the costs for the grid extension/expansion $c^{\mathrm{Inv,DH}}$ resp. $c^{\mathrm{Inv,gas}}$ and reinvestments in the existing grid $c^{\mathrm{ReInv,DH}}$ resp. $c^{\mathrm{ReInv,gas}}$, as wells as the costs for heat generation $c^{\mathrm{g,DH}}$ and operation costs $c^{\mathrm{op,DH}}$ resp. $c^{\mathrm{op,gas}}$. The revenues R^{tot} respect the base price for district heating $p^{\mathrm{base,DH}}$ dependent on the blocks heat load $P_{b,t}^{\mathrm{DH},2}$ in MW and the demand charge for district heating $p^{\mathrm{dc,DH}}$, which arise from the connected heat demand $\mathrm{FED}_{b,t}^{\mathrm{DH},2}$ in MWh as well as the network charge for gas $p_t^{\mathrm{netcharge,gas}}$ depending on the connected gas demand $\mathrm{FED}_{b,t}^{\mathrm{gas},2}$. The cost and revenues are formulated in equations (2.2) to (2.3), where P_b^{DH} denotes the connected heating load in MW of the building block and $FED_{b,t}^{\mathrm{DH},2}$ the heat demand in MWh per block.

$$
\begin{aligned}
c_t^{\mathrm{tot}} = & c_t^{\mathrm{op,DH}} + c_t^{\mathrm{InvDH}} + c_t^{\mathrm{ReInv,DH}} + c_t^{\mathrm{g,DH}} + c_t^{\mathrm{op,gas}} + \\
& c_t^{\mathrm{Invgas}} + c_t^{\mathrm{ReInv,gas}}
\end{aligned}
\tag{2.2}
$$

$$
\begin{aligned}
R_t^{\mathrm{tot}} = & \sum_{b \in B} p_t^{\mathrm{dc,DH}} \, \mathrm{FED}_{b,t}^{\mathrm{DH},2} + p_t^{\mathrm{base,DH}} \, P_{b,t}^{\mathrm{DH},2} + \\
& p_t^{\mathrm{netcharge,gas}} \, \mathrm{FED}_{b,t}^{\mathrm{gas},2}
\end{aligned}
\tag{2.3}
$$

The economic evaluation is conducted by calculating the Net Present Values of the future Cash Flow. As the model considers changes in the buildings' heat demand over the time as well as changes in the costs for heat generation, the given period T consists of two parts, the investment period T_{Inv} and the payback period T_a. The investment period T_{Inv} consists of pre-defined time-steps, where investments in the extension/expansion of the heating network are allowed. In the payback period T_{a} the investments have to be recovered and no new buildings are connected. The Cash Flows in this period consist of the revenues and the costs for distribution whereas the future heat demand and the change in the heat demand is given as a result of the existing simulation model. The optimization-model determines the buildings, which are profitable to be connected to the existing district heating network in the Investment period T_{Inv}.

Hence the detailed objective function can be reformulated:

$$\max \Pi = \sum_{t=1}^{T^{\text{Inv}}} \frac{R_t^{\text{tot}} - c_t^{\text{tot}}}{(1+r)^t} + \sum_{t=T^{\text{Inv}}+1}^{T^{\text{a}}} \frac{R_t^{\text{tot}} - c_t^{\text{op}} - c_t^{\text{g}}}{(1+r)^t} \tag{2.4}$$

General constraints The binary decision variables $x_{b,t}^{\text{DH}}$ and $x_{b,t}^{\text{gas}}$ are introduced and indicate if a building block is connected to the district heating or gas network or not, see equation (2.5).

$$x_{b,t}^{\text{DH}} = \begin{cases} 1, & \text{if block } b \text{ is connected to district heating network in period } t \\ 0, & \text{else} \end{cases}$$
$$x_{b,t}^{\text{gas}} = \begin{cases} 1, & \text{if block } b \text{ is connected to gas network in period } t \\ 0, & \text{else} \end{cases} \tag{2.5}$$

As the model also considers already connected building blocks, the variables defined in equation (2.5) need to be to set to one, if a block is initially connected, $b \in B^{\text{con,DH}}$ resp. $b \in B^{\text{con,gas}}$ (see equation (2.6)).

$$\begin{aligned} x_{b,t}^{\text{DH}} &\geq 1 \quad t = 1, \forall b \in B^{\text{con,DH}} \\ x_{b,t}^{\text{gas}} &\geq 1 \quad t = 1, \forall b \in B^{\text{con,gas}} \end{aligned} \tag{2.6}$$

For the base year the initial connected demand $\text{FED}_{b,1}^{\text{DH},2}$ and $\text{FED}_{b,1}^{\text{gas},2}$, as well as the connected load $P_{b,1}^{\text{DH},2}$ and $P_{b,1}^{\text{gas},2}$ and gross floor area $\text{GFA}_{b,1}^{\text{DH},2}$ and $\text{GFA}_{b,1}^{\text{gas},2}$ are determined by the binary variables $x_{b,t}^{\text{DH}}$ and $x_{b,t}^{\text{gas}}$, see equations (2.7) to (2.9). In the following paragraphs all the constraints are just formulated for district heating and can be used for gas as well.

$$\mathrm{FED}_{b,1}^{\mathrm{DH},2} = \mathrm{FED}_{b,1}^{\mathrm{DH},1}\, x_{b,1}^{\mathrm{DH}} \quad \forall b \tag{2.7}$$

$$\mathrm{P}_{b,1}^{\mathrm{DH},2} = P_{b,1}^{\mathrm{DH},1}\, x_{b,1}^{\mathrm{DH}} \quad \forall b \tag{2.8}$$

$$\mathrm{GFA}_{b,1}^{\mathrm{DH},2} = \mathrm{GFA}_{b,1}^{\mathrm{DH},1}\, x_{b,1}^{\mathrm{DH}} \quad \forall b \tag{2.9}$$

For all investment periods $t \in T, t > 1$, the actual connected demand $\mathrm{FED}_{b,t}^{\mathrm{DH},2}$ is determined by the demand from the previous period $t-1$ $\mathrm{FED}_{b,t-1}^{\mathrm{DH},2}$ and the change in the demand between two simulation periods $\Delta\mathrm{FED}_{b,t}^{\mathrm{DH},1}$. The definition of the parameter $\Delta\mathrm{FED}_{b,t}^{\mathrm{DH},1}$ is described in equation (2.10) and is an input parameter for the model received as a result of the existing simulation model.

$$\Delta\mathrm{FED}_{b,t}^{\mathrm{DH},1} = \mathrm{FED}_{b,t}^{\mathrm{DH},1} - \mathrm{FED}_{b,t-1}^{\mathrm{DH},1} \quad \forall b, t > 1 \tag{2.10}$$

The demand $\Delta\mathrm{FED}_{b,t}^{\mathrm{DH},1}$ can either be positive or negative, depending on the fact, if the efficiency measures for the building block exceed the investment decision for district heating resp. gas technologies in the building stock or not. Therefore, two inequality are introduced, see equations (2.11)-(2.12). These inequality also ensure, that an already connected block cannot be disconnected, as long as there is an positive demand exogenously given for it . If the reduction in the building block's heat demand is higher as the new demand, inequality (2.11) together with inequality (2.13) ensures, that the block is disconnected.

$$\mathrm{FED}_{b,t}^{\mathrm{DH},2} \geq D_{b,t-1}^{\mathrm{DH}} + \Delta\mathrm{FED}_{b,t}^{\mathrm{DH},1}\, x_{b,t-1}^{\mathrm{DH}} \quad \forall b, t > 1 \tag{2.11}$$

$$\mathrm{FED}_{b,t}^{\mathrm{DH},2} \leq D_{b,t-1}^{\mathrm{DH}} + \Delta\mathrm{FED}_{b,t}^{\mathrm{DH},1}\, x_{b,t}^{\mathrm{DH}} \quad \forall b, t > 1 \tag{2.12}$$

$$\mathrm{FED}_{b,t}^{\mathrm{DH},2} \geq 0 \quad \forall b, t \tag{2.13}$$

The equations (2.10) - (2.13) are also valid for the connected load $P_{b,t}^{\mathrm{DH},2}$ and the connected gross floor area $\mathrm{GFA}_{b,t}^{\mathrm{DH},2}$

Cost components The following equations describe the considered costs for the investment optimization in expansion and extension of district heating and gas networks. These costs here are formulated as functions from various variables and parameters. The actual used parameters are explained in the section 3.3.3.
The heat generation costs $c^{\mathrm{g,DH}}$ are determined by the exogenously given costs for the heat production hc_t and the required demand $\mathrm{FED}_{b,t}^{\mathrm{DH},2}$, which needs to be supplied. Therefore the heat losses need to be considered and the heat generation costs can be written as a function from the total connected demand $\mathrm{FED}_{t}^{\mathrm{DH},2} = \sum_{b \in B} \mathrm{FED}_{b,t}^{\mathrm{DH},2}$, the heat losses hl^{DH} and the costs for heat hc_t, see equation (2.14).

$$c_t^{\mathrm{g,DH}} = f(\mathrm{FED}_t^{\mathrm{DH}}, hl^{\mathrm{DH}}, hc_t) \quad \forall t \in T \tag{2.14}$$

The operation costs $c^{\mathrm{op,DH}}$ are the sum of the pumping costs and the maintenance costs for the grid. Therefore it also can be formulated as a function from the total connected demand $\mathrm{FED}_{b,t}^{\mathrm{DH},2}$ including heat losses hl^{DH}, the length of the grid $\mathrm{grid}_t^{\mathrm{length,DH}}$ at time period t, the costs for the maintenance of the grid $c^{grid,DH}$ and the electricity price c_t^{el}, displayed in equation (2.15).

$$c_t^{\mathrm{op,DH}} = f(\mathrm{grid}_t^{\mathrm{length,DH}}, c^{\mathrm{grid,DH}}, \mathrm{FED}_t^{\mathrm{DH},2}, hl^{\mathrm{DH}}, hc_t, c_t^{el}) \quad \forall t \tag{2.15}$$

In contrast do equation (2.15), the operation costs for gas are just dependent on the total connected demand $\mathrm{FED}_{b,t}^{\mathrm{gas},2}$, the length of the grid $\mathrm{grid}_t^{\mathrm{length,gas}}$ and the costs for the maintenance of the grid $c^{grid,gas}$ as described in equation (2.16).

$$c_t^{\mathrm{op,gas}} = f(\mathrm{grid}_t^{\mathrm{length,gas}}, c^{\mathrm{grid,DH}}, \mathrm{FED}_t^{\mathrm{gas},2}) \quad \forall t \tag{2.16}$$

The length of the grid $\mathrm{grid}^{\mathrm{length,DH}}$ is determined by the initial grid length in the first period $t = 1$ and the additional length l_b^{DH} required to connect each block in the investment periods $t > 1$. The determination of the length of the grid is formulated in equations (2.17) to (2.18).

$$\mathrm{grid}_t^{\mathrm{length,DH}} = \mathrm{grid}^{\mathrm{lengthInital,DH}} \quad t = 1 \tag{2.17}$$

$$\mathrm{grid}_t^{\mathrm{length,DH}} = \mathrm{grid}_{t-1}^{\mathrm{length,DH}} + \sum_{b \in B} x_{b,t}^{\mathrm{DH}} \, l_b^{\mathrm{DH}} \quad \forall t > 1, \forall b \tag{2.18}$$

The investment costs are also considered as an function of the length l_b^{DH} which is required to connect each block to the existing district heating network, the connected load $P_{b,t}^{\mathrm{DH}}$ in each investment period $t \in T$, the costs per meter depending on the connected load $c_{P_{b,t}}^{\mathrm{GridInv,DH}}$ and the variable $nC_{b,t}^{\mathrm{DH}}$, formulated in equation (2.19).

$$nC_{b,t}^{\mathrm{DH}} = \begin{cases} 1, & \text{if block } b \text{ is newly connected in period } t \\ 0, & \text{else} \end{cases} \tag{2.19}$$

This variable indicates, whether a block is newly connected in this period or not and results from equation (2.20).

$$nC_{b,t}^{\mathrm{DH}} = x_{b,t}^{\mathrm{DH}} - x_{b,t-1}^{\mathrm{DH}} \quad \forall t > 1 \tag{2.20}$$

The function for the investment costs are displayed in equation (2.21).

$$c_t^{\mathrm{Inv,DH}} = f(P_{b,t}^{\mathrm{DH}}, l_b^{\mathrm{DH}}, c^{\mathrm{GridInv,DH}}, nC_{b,t}^{\mathrm{DH}}) \quad \forall t \tag{2.21}$$

As the connected load $P_{b,t}^{\mathrm{DH}} \forall t$ of one block influences the used pipe diameter and subsequently the costs per meter $c_{P_{b,t}}^{\mathrm{GridInv,DH}}$ it has to be ensured, that the used diameter is suitable for the connected load over the whole simulation period. Thus, the costs per meter $c_{P_{b,t}}^{\mathrm{GridInv,DH}}$ are linearised and the investment costs dependent on the load can be displayed as in equation (2.22) formulated. This formulation ensures, that investment costs $c_{P_{b,t}}^{\mathrm{GridInv,DH}}$ just incur, if the building is newly connected up to the considered simulation period t. If a building is not connected, the load $P_{b,t}^{\mathrm{DH}}$

equals zero.

$$c^{\text{GridInv,DH}}_{P_{b,t}} = P^{\text{DH}}_{b,t}\,\text{lin}^{\text{DH}}_{x} + \sum_{t' \le t} nC^{\text{DH}}_{b,t}\,\text{lin}^{\text{DH}}_{y} \quad \forall b, t > 1 \tag{2.22}$$

To ensure that the pipe diameter is suitable also in case that the connected load increases over the simulation horizon, equations (2.23) and (2.24) are introduced. Therefore the auxiliary variable $c^{\text{InvHilf,DH}}_{b,t}$ is needed to ensure, that the costs incur in the simulation year where the building block is initially connected. The parameter M, a big number, ensures, that the constraint isn't used (resp. has no influence on the model) if the block b isn't connected in up to the considered period t.

$$(c^{\text{GridInv,DH}}_{P_{b,t}})\,l^{\text{DH}}_{b} \le \sum_{t' \le t}(c^{\text{InvHilf,DH}}_{b,t} + (1 - nC^{\text{DH}}_{b,t})) * M \quad \forall b \in b, \forall t \in T \tag{2.23}$$

$$c^{\text{InvHilf,DH}}_{b,t} \le nC^{\text{DH}}_{b,t} * M \quad \forall b \in b, \forall t \in T \tag{2.24}$$

Beside the investments in the connection of building blocks, the model assumes, that an increase in a building blocks' connected demand within the time horizon can occur, if the owners of not connected buildings within this already connected block decide to invest in the connection. In this case not the total length for the connection is required, but additional pipes to connect the buildings within this block are required. These extension costs are formulated as function from the new possible heat demand $\Delta\text{FED}^{DH,1}_{b,t} > 0$, the perimeter of the building block Per_b and a corresponding factor f[2], the costs per meter $c^{\text{GridInv,DH}}$ and whether the block is already connected or not. The function for the extension costs is formulated in

[2]the factor to describe the costs was determined in coordination with experts from the Wiener Stadtwerke Holding AG

equation (2.25).

$$c_t^{\text{Ext,DH}} = f(D_{b,t}^{new,DH}, \text{Per}_b\, f, c^{\text{GridInv,DH}}, (x_{b,t}^{\text{DH}} - nC_{b,t}^{\text{DH}})) \tag{2.25}$$

The reinvestment costs regard the age structure of the current network. Based on this, the required reinvestments can be formulated as a function in equation (2.26) depending on the required length for the pipes assigned to the building block l_b^{DH} the age of the pipeline section assigned to this block $\text{age}_{b,t}^{\text{DH}}$, the costs per meter $c^{\text{GridInv,DH}}$ and the binary variable $x_{b,t}^{\text{DH}}$.

$$c_t^{\text{ReInv,DH}} = f(\text{age}_{b,t}^{\text{DH}}, l_b^{\text{DH}}, c^{\text{GridInv,DH}}, x_{b,t}^{\text{DH}}) \tag{2.26}$$

Finally, The yearly investments for the expansion and extension of the existing grids are restricted with a maximum amount, as depicted in equation (2.27).

$$c_t^{\text{InvNeu,DH}} \leq \text{Inv}_t^{\text{max,DH}} \quad \forall t \tag{2.27}$$

2.4.2 Flexible change of grid-bound energy carriers from grid operators point of view

As the formulation in the previous section 2.4.1 mainly respects the view of the grid (gas and district heating) operator, this formulation focus on the reduction of the costs (operation, maintenance, investments and reinvestment costs) for all networks as a whole. In the previous formulation the investment decisions of the building owners ($\text{FED}_{b,t}^{\text{DH},1}$ and $\text{FED}_{b,t}^{\text{gas},1}$) exogenously prescribed the maximum demand of district heating and gas, which can be connected to the existing network ($\text{FED}_{b,t}^{\text{DH},2}$ and $\text{FED}_{b,t}^{\text{gas},2}$) and the optimization model determines the best expansion and extension plans. In this modellings approach it is assumed, that building blocks, where the owners decide to invest in grid-bound energy supply can be supplied either by gas or by district heating. Furthermore a flexible change from already connected blocks from one energy carrier to another is possible. As the revenues and the costs for the expansion and extensions are still the same, the same objective as formulated in (2.1) is considered. This approach required adapted and additional constraints.

The exogenously given district heating and gas demand, which is determined by the investment decisions of the building owners $\mathrm{FED}_{b,t}^{\mathrm{DH},1}$ and $\mathrm{FED}_{b,t}^{\mathrm{gas},1}$ here is added up to $\mathrm{FED}_{b,t}^{\mathrm{both},1} = \mathrm{FED}_{b,t}^{\mathrm{DH},1} + \mathrm{FED}_{b,t}^{\mathrm{gas},1}$. This forms the base for the determination of the demand for district heating $\mathrm{FED}_{b,t}^{\mathrm{DH},2}$ or gas $\mathrm{FED}_{b,t}^{\mathrm{gas},2}$ which is connected from a network operators economic point of view. Therefore the binary variable $x_{b,t}^{\mathrm{con}}$ is introduced, explained in equation (2.28).

$$x_{b,t}^{\mathrm{con}} = \begin{cases} 1, & \text{if block } b \text{ is connected either to gas and/or district heating in period } t \\ 0, & \text{else} \end{cases} \tag{2.28}$$

To ensure that the variable is 1 if and only if at least one grid-bound energy carrier is connected to building block, the following equations (2.29)- (2.31) have to be formulated. The binary variables $x_{b,t}^{\mathrm{DH}}$ and $x_{b,t}^{\mathrm{Gas}}$ are defined as in equations (2.5).

$$x_{b,t}^{\mathrm{con}} \geq x_{b,t}^{\mathrm{DH}} \quad \forall b,t \tag{2.29}$$

$$x_{b,t}^{\mathrm{con}} \geq x_{b,t}^{\mathrm{Gas}} \quad \forall b,t \tag{2.30}$$

$$x_{b,t}^{\text{con}} \leq x_{b,t}^{\text{DH}} + x_{b,t}^{\text{Gas}} \quad \forall b,t \tag{2.31}$$

The initial demand is determined as in equation (2.7). The demand for the periods $t > 1$ can be expressed as in (2.32) and (2.33). $\Delta\text{FED}_{b,t}^{\text{both},1}$ is determined as in equation (2.10).

$$\text{FED}_{b,t}^{\text{DH}} + \text{FED}_{b,t}^{\text{Gas}} \geq \text{FED}_{b,t-1}^{\text{DH}} + \text{FED}_{b,t-1}^{\text{Gas}} + \Delta\text{FED}_{b,t}^{\text{both},1}\, x_{b,t-1}^{\text{con}} \quad \forall b, t > 1 \tag{2.32}$$

$$\text{FED}_{b,t}^{\text{DH}} + \text{FED}_{b,t}^{\text{Gas}} \leq \text{FED}_{b,t-1}^{\text{DH}} + \text{FED}_{b,t-1}^{\text{Gas}} + \Delta\text{FED}_{b,t}^{\text{both},1}\, x_{b,t}^{\text{con}} \quad \forall b, t > 1 \tag{2.33}$$

As the demand for district heating and gas has to be non-negative (see equations (2.34)), these constraints ensure that the building block is supplied by grid-bound heat supply, as long as there is a demand in the block. In comparison to the modelling approach described in section 2.4.1 it is possible that one of the two grid-bound energy carriers isn't used any more to supply the building blocks' heat demand.

$$\begin{aligned} D_{b,t}^{\text{DH}} &\geq 0 \quad \forall b,t \\ D_{b,t}^{\text{Gas}} &\geq 0 \quad \forall b,t \end{aligned} \tag{2.34}$$

To respect the slackness of investments in the building stock resp. the slackness of the investments in the change of heating system, a diffusion barrier has to be introduced, expressed in equation (2.35), where v represents a share in percent which has to be supplied by the same energy carrier as in the previous period and $\Delta\text{FED}^{\text{both,neg}}$ just stands for the negative change in the heat demand for both energy carriers, as the positive change can be assigned independent to one of the two possible grid-bound energy carriers.

$$D_{b,t}^{\text{DH}} \geq (D_{b,t-1}^{\text{DH}} + \Delta\text{FED}^{\text{both,neg}}) * v \quad \forall b, t \tag{2.35}$$

$$D_{b,t}^{\text{Gas}} \geq (D_{b,t-1}^{\text{Gas}} + \Delta\text{FED}^{\text{both,neg}}) * v \quad \forall b, t \tag{2.36}$$

To avoid the connection and reconnection of one block to one or both energy carrier in every period, it is assumed, that just one new connection per energy carrier within the simulation horizon is allowed, displayed in equation (2.37). The variable $nC_{b,t}^{\text{DH}}$ is defined as in equations (2.19) and (2.20).

$$\begin{aligned} \sum_{t \in T} nC_{b,t}^{\text{DH}} \leq 1 \quad \forall b \\ \sum_{t \in T} nC_{b,t}^{\text{Gas}} \leq 1 \quad \forall b \end{aligned} \tag{2.37}$$

To determine the investments, operation, reinvestments and heat generation costs[3], it is required to know, if a block b is connected to district heating in the period t ($x_{b,t}^{\text{DH}} = 1 \quad , \forall b, t$) or to gas ($x_{b,t}^{\text{Gas}} = 1 \quad , \forall b, t$) or to both ($x_{b,t}^{\text{DH}} = 1 \wedge x_{b,t}^{\text{Gas}} = 1, \forall b, t$). These variables are defined as in equation (2.5). These variables are one if and only if there is a positive demand for the corresponding energy carrier. This is explained by the following equations (2.38) to (2.41). The values M, a big number, ensures that $x_{b,t}$ is one, if the demand is greater zero.

$$x_{b,t}^{\text{DH}} \geq \text{FED}_{b,t}^{\text{DH,2}} / M \quad \forall b, t \tag{2.38}$$

[3] heat generation costs are just considered for district heating

$$x_{b,t}^{\mathrm{Gas}} \geq \mathrm{FED}_{b,t}^{\mathrm{Gas},2}/M \quad \forall b,t \tag{2.39}$$

$$x_{b,t}^{\mathrm{DH}} \leq \mathrm{FED}_{b,t}^{\mathrm{DH},2} \quad \forall b,t \tag{2.40}$$

$$x_{b,t}^{\mathrm{Gas}} \leq \mathrm{FED}_{b,t}^{\mathrm{Gas},2} \quad \forall b,t \tag{2.41}$$

All these constraints together allow to determine the costs as described in the previous section (equations (2.14), (2.15), (2.21)). In contrast to the district heating optimization model (section 2.4.1), in this model the allocation of the load ($P_{b,t}^{\mathrm{Gas}}$, $P_{b,t}^{\mathrm{DH}}$) and gross floor area ($GFA_{b,t}^{\mathrm{Gas}}$, $GFA_{b,t}^{\mathrm{DH}}$) cannot be done exactly and is allocated depending on the demand for the corresponding energy carrier.

2.5 Cost calculation and iterative adaptation of results of the integrated analysis

The following sections shortly describe the methodology to calculate the distribution costs for district heating and gas, the cost and CO_2-emission calculation to compare the scenarios and the iterative adaptation of the results of the integrated analysis.

2.5.1 Calculation of distribution costs for gas and district heating

The district heating and gas distribution costs are determined by the Investment costs, the reinvestment costs and the operation costs. The costs for district heating and gas distribution are expressed as levelized costs of heat. The following assumptions are made to calculate these costs, the underlying equations are written in equations 2.42 and are applicable for gas and district heating. As the investments and reinvestments just occur for the investment periods $t \in T$, the operations costs and demand for the whole amortisation period $t' \in T_a$ has to be considered.

1. reinvestment costs DC^{ReInv}: The discounted cumulative reinvestment costs for each simulation step up to 2050 are divided by the discounted cumulative demand for the simulation steps and the amortisation period (initial connected and newly connected).

2. investment costs DC^{Inv}: The discounted cumulative investment costs for expansion are divided by the discounted cumulative newly connected demand. In addition, the discounted cumulative costs for extension are divided by the cumulative total demand.

3. operation costs DC^{op}: The discounted cumulative operation costs up to the year 2050 for all years within the simulation horizon are divided by the discounted cumulative demand.

$$
\begin{aligned}
DC &= DC^{\text{Inv}} + DC^{\text{ReInv}} + DC^{\text{op}} \\
DC^{\text{Inv}} &= \frac{\sum_{t\in T} c_t^{\text{Inv}}\,(1+r)^t}{\sum_{t\in T}\sum_{b\in B}\sum_{t'=0}^{T_a-1} D_{b,t+t'}^{\text{new}}\,(1+r)^{t+t'}} \\
DC^{\text{ReInv}} &= \frac{\sum_{t\in T} c_t^{\text{ReInv}}\,(1+r)^t}{\sum_{t\in T}\sum_{b\in B}\sum_{t'=0}^{T_a-1} D_{b,t+t'}\,(1+r)^{t+t'}} \\
DC^{\text{op}} &= \frac{\sum_{t\in T}\sum_{t'=0}^{T_a-1} c_{t+t'}^{\text{op}}\,(1+r)^{t+t'}}{\sum_{t\in T}\sum_{b\in B}\sum_{t'=0}^{T_a-1} D_{b,t+t'}\,(1+r)^{t+t'}}
\end{aligned}
\tag{2.42}
$$

The calculation of the mean costs for the investment periods is conducted as described in equations 2.43, whereas $n(t)$ indicates the years between the two investment periods.

$$\text{costs}_t = \frac{(c_t^{\text{Inv}} + c_t^{\text{ReInv}}) * (1+r)^t + \frac{1}{n(t)}(\sum_{t'=0}^{n(t)} c_{t+t'}^{\text{op}} * (1+r)^{t+t'})}{\frac{1}{n(t)}(\sum_{t'=0}^{n(t)} \sum_{b \in B} D_{b,t+t'} * (1+r)^{t+t'})} \tag{2.43}$$

2.5.2 Adaptation of the simulation output due to the results of the optimization model

The optimization model, described in 2.4.1 assumes, that the building owners' investment decision in the building stock and the resulting district heating and gas demand serve as upper bound for the potential of extension and expansion of the existing grid infrastructure. Thus, the share $\frac{\text{FED}^{\text{DH},2}}{\text{FED}^{\text{DH},1}} \in [0,1]$ resp. $\frac{\text{FED}^{\text{gas},2}}{\text{FED}^{\text{gas},1}} \in [0,1]$ determines the share of district heating and gas, which is connected from a grid-operator's economic point of view. As the integrated analysis shall provide information about the energy mix considering the building owners' investment decision as well as the grid-operators' investment decisions, the results of the existing simulation model have to be adapted. Therefore, the share of district heating resp. gas, which is not connected due to the grid-operators' economic point of view is splitted and added to the other energy carriers, which are used in the building stock to supply the space heating and domestic hot water demand. The weighted share is displayed in equation (2.44), whereas $\text{FED}_t^{\text{ec},2}$ describes the final energy demand for all considered energy carriers without grid-bound supply $ec \in EC^{\text{dec}}$ considering the grid-operators' investment decisions and $\text{FED}_t^{\text{ec},1}$ are the results of the existing simulation model for those energy carriers.

$$\text{FED}_t^{\text{ec},2} = (\text{FED}_t^{\text{DH},1} - \text{FED}_t^{\text{DH},2}) \frac{\text{FED}_t^{\text{ec},1}}{\sum_{ec \in EC} \text{FED}_t^{\text{ec},1}} \tag{2.44}$$

Based on this adaptation, the resulting cost indicators and CO_2-emissions can be defined.

CHAPTER 3

Data and model calibration

3.1 Building stock Vienna

The main datasets used in this thesis to describe the current building stock of Vienna are the Vienna Heat registry [Wiener Wärmekataster] (WWK) and the GIS building data (GisData), provided by the Viennese municipal department 39 [Magistratsabteilung 39 der Stadt Wien] (MA39) and the Viennese municipal department 41 [Magistratsabteilung 41 der Stadt Wien] (MA41). In addition, data from "‘Open Government Data"’[1] and the national statistical bureau ("‘Statistik Austria"’) is used. In the following subsection 3.1.1, the used data bases are described in detail. In subsection 3.1.2, the data conversion and preparation to receive the required data structure for the submodels, pointed out in section 2, is explained in detail.

3.1.1 Data base

Heat registry The WWK is a table data set provided by Pöhn [2011] and includes each building in Vienna with additional information about the location (no Geographic information system (GIS) information available), the geometry of the building (ground area, number of floors, total gross floor area, etc.) and the

[1]Datenquelle: Stadt Wien – `data.wien.gv.at`

calculated needs for space heating and domestic hot water. The information on the connection to the existing gas or district heating network is also included for some buildings, as well as the construction year of the building. All buildings are listed with their effective area for different usages. The following classifications for the effective area are included:

1. living
2. office
3. schools and other public buildings
4. public accommodations
5. hospitals
6. care home
7. commercial
8. others

All the buildings are identified with a unique primary key (called „GACD “), and are assigned to a building block, also named with an unique key. The allocation to building blocks is required for two reasons: on the one hand, it is necessary for the investment optimization model, where the expansion and extension planning is conducted for building blocks, see section 2.4.1. On the other hand, building blocks are the common key for the data exchange in the USCA of URBEM^{DK}. The base year of the heat registry is the year 2008.

Open Data Wien and Statistik Austria Especially the following data is used for the calibration of the building stock:

1. Stadt Wien – data.wien.gv.at
2. Buildings census 2001 where all the buildings in Vienna were captured Statistik Austria [2004]
3. information about the used heating systems for Vienna for the years 2003 - 2012 Statistik Austria [2013d]
4. census 2011 Statistik Austria [2014b]

This data is used to add missing information for the analysis to the data listed in the WWK.

3.1.2 Data conversion and preparation

For the integrated analysis for the development of the buildings' energy demand and the interdependencies to the existing heat infrastructure, additional information on the building stock is required. The existing simulation model Invert/EE-Lab (see section 2.2) has a predefined data structure, which have to be generated before the analysis. In addition, as the investment optimization model (see section 2.4) uses another data aggregation level, some additional information is also required, whereas the regionalisation (see section 2.3) covers most of the parts of data preparation. This section shortly describes the data conversion and preparation steps which has to be conducted before the data serves as input data for the existing simulation model Invert/EE-Lab. All this pre-modelling conversion and preparation affects the base data, mainly the WWK, and uses additional input data.

Classification of the buildings

The classification of the buildings' utilisation is necessary for the assignment to the building categories and the generation of the building classes within the existing simulation model Invert/EE-Lab. This is among other things necessary to consider the effects of subsidies on different building classes (for a detailed description see e.g. Müller [2015]).
The classification in the WWK corresponds to the classification provided in the data by Statistik Austria. Each building contains the information about the compilation of the effective area per classification. As the whole effective area of one building can be divided into multiple classifications, the main classification has to be defined. For residential buildings, the definition of the Statistik Austria is used (see [Statistik Austria, 2011, p.2]), which implies that buildings with more than 50% of the effective area for living are classified as residential buildings. For the other categories, the dominant classification, i.e. the category with the highest share in the effective area, defines the classification of the whole building.
In figure 3.1 the differences between the number of buildings per classification according to Statistik Austria (Sources: Statistik Austria [2004] and Statistik Austria [2013b]) and WWK are displayed. As the data from Statistik Austria

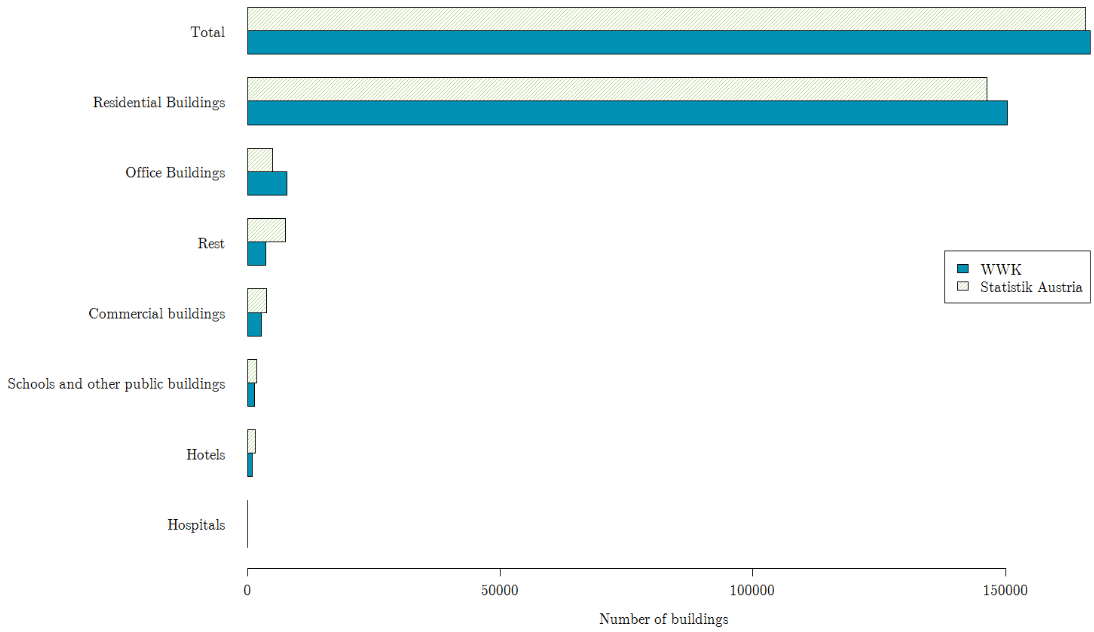

Figure 3.1: Number of buildings: Comparison data WWK and calculations on data of Statistik Austria, Source: own illustration, based on Poehn [2012], Statistik Austria [2004] and Statistik Austria [2013e]

is only available for the years 2001 and 2011, the number of buildings for the year 2008 are linearly interpolated. The differences in the single classifications are justified by the differences in the total number of buildings in the base year of the building stock's data base 2008. That's the reason why all following calculations and conversions are not conducted with absolute values of the number of buildings but with the shares in the total number of buildings.

The analysis of the impacts of different policy frameworks in the existing simulation model requires a further division: As the buildings within a building class (for definition see 2.2) are aggregated, it is necessary to divide the buildings into different sizes, depending on their total gross floor area. In addition, especially for residential buildings it is required to introduce additional usages, namely: single family houses, apartment buildings (with division into small and large apartment buildings) and residential buildings with offices inside. The information about the

Table 3.1: Share of different usages in building stock, source: own calculations, based on „WWK“, Poehn [2012]

Usage	Share [%]	Usage	Share [%]
Office Building large	1.04%	Hotels small	0.51%
Office Building small	3.58%	Hospitals	0.01%
Offices in residential buildings	10.05%	Apartment Buildings large	16.75%
Single family houses	51.58%	Apartment Buildings small	11.83%
Commercial Buildings large	0.06%	Schools and public Buildings	0.86%
Commercial Buildings small	1.52%	Mechanical workshop, halls, etc. large	0.08%
Hotels large	0.05%	Mechanical workshop, halls, etc. small	2.09%

buildings within each usage is provided for the year 2001 and 2011 in Statistik Austria [2004] and Statistik Austria [2013e]. The sources provide the data for the year 2001 in more detail. The distinction in the buildings' usages are provided per registration districts[2] in Vienna for the year 2001. For the year 2011, data is only provided for the Viennese districts. As each building in the WWK contains information about the registration district it is located in, the accuracy of the calibration can be improved by considering this level of detail. Therefore it is assumed that the growth rate of the building stock between 2001 and 2011 is the same for all registration districts within one district. With this information, the data for the year 2008 is linearly interpolated.

In table 3.1, the shares of all used classifications and usages within this thesis are displayed.

[2]Registration districts divide the 23 districts in Vienna into smaller units. There is a direct link between registration district and districts. Each registration district is member of only one district.

Geometry of buildings and calculation of gross floor area

The calculation of the (area) specific heat demand [in kWh/m^2] and thus of the final energy demand [in kWh], explained in section (2.2), requires some information about the geometry of the building. This required information includes amongst others the length and width of the building as well as the number of floors. To receive the length and width of the building, the following steps have to be conducted:

- Determine length and width: The WWK just contains information about the area of the building's basement and the perimeter. With this information, the length and width of the building are calculated.
- Calculate the proper ground area (area of the basement ceiling in WWK) for each single building: In the WWK, some attached buildings are grouped together for the heat demand calculations conducted in the WWK. In this case, the conditioned gross floor area of each single building, and the cumulative gross floor area of all attached buildings is given. The conditioned gross floor area is defined as the area, which is thermal-conditioned and which is enclosed by the gross volume (for detailed description see Pöhn [2012]). The segmenting of the basement ceiling requires knowing the share of each single building in the whole basement ceiling. With the presumption that the ratio between the gross floor area of each single building and the cumulative gross floor area of the attached buildings is the same as the ratio between the basement ceiling of single buildings and the whole basement ceiling of all attached buildings, the share of one building in the basement ceiling is determined.
- Length and width of each single building, if buildings are grouped: If multiple buildings are combined, as mentioned, the length and width of all buildings is calculated under the assumption that the proportion between length and width for each single building is the same as for all buildings grouped together.

The geometry of the building defines the total gross floor area in the existing simulation model, as this is calculated as product of length, width and height.

As the existing simulation model doesn't use each single building as input data but building classes, defined by the building category, the age of the building and the envelope quality due to thermal renovations, the buildings has to be grouped. Thus, the input data of the existing simulation model considers the average values within one building class for the length, width and height of a building. Figure 3.2 shows the cumulative results for the total gross floor area of the calculations on the aggregated and averaged results as input for the existing simulation model Invert/EE-Lab and the initial data in the WWK for each introduced building classification.

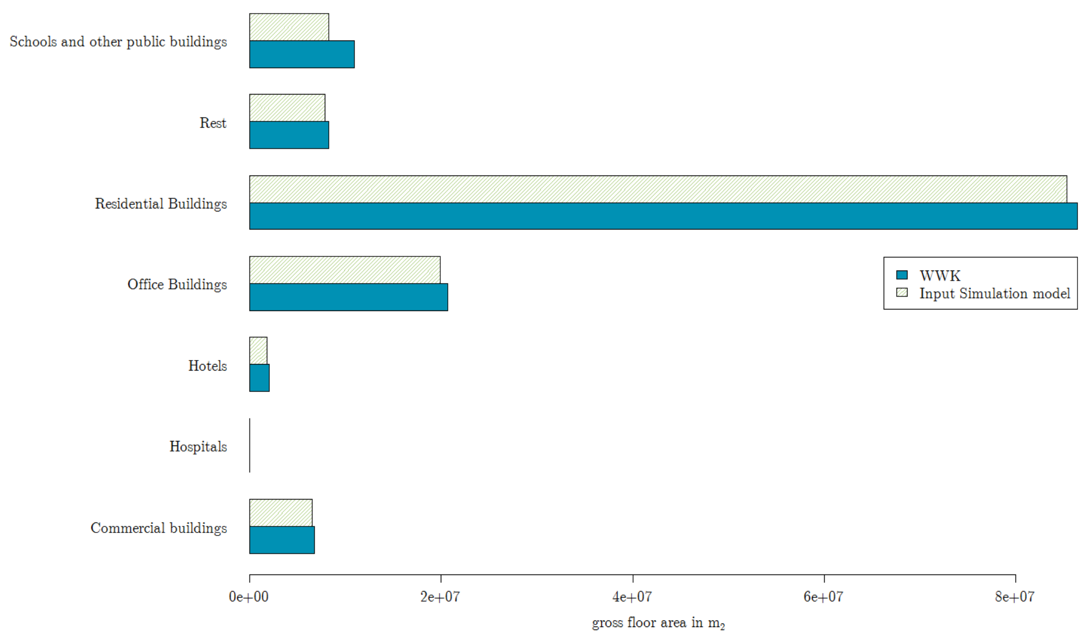

Figure 3.2: Comparison data WWK and results of existing simulation model Invert/EE-Lab, Source: own illustration

Number of residential dwellings

The numbers of dwellings per residential building are required for two reasons: First, the information which is necessary to validate the calibration of the used heating systems in the building stock is provided for the number of main residences in Statistik Austria [2013d]. Second, the number of dwellings also influences the calculations of the heat demand and the impacts of policies on the investment behaviour of building owners and is required for the input data for the existing simulation model Invert/EE-Lab. For each district, the average number of dwellings per usage (single family houses, small and large apartment buildings) are calculated from the data of Statistik Austria for the year 2001 Statistik Austria [2004] and the number is assigned to the corresponding buildings within in the WWK. The number of dwellings per building for single family houses varies from 0.83 dwellings per building in one of the districts in Vienna up to 1.64 dwellings per building in another district. As the buildings are grouped by building classes to serve as input for the existing simulation model, table 3.2 shows the differences of the data assigned to the buildings according to the source of Statistik Austria and the average results used as input in the existing simulation model.

Table 3.2: Number of dwellings in Vienna (Source: Statistik Austria [2004] and Statistik Austria [2013e]) compared to the average results as input for the simulation model

number of dwellings according to Statistik Austria	average input value for simulation model
961 911	1 024 939

Buildings under national heritage

In Vienna, the buildings under national heritage influence the development of the buildings' heat demand, as the renovation of these buildings isn't that easy. The source provides information about all monuments in Vienna which are under national heritage. Filtering this list for the keywords "buildings" and variations of it result in 1300 buildings in Vienna that are under national heritage (Source: Bundesdenkmalamt [2013] and own assumptions regarding the monuments). These buildings are grouped by districts and then randomly assigned to the oldest buildings within this district. The existing simulation model considers a longer lifetime of the facade for this building class to consider the renovation barriers due to the national heritage. Figure 3.3 shows the number of buildings under national heritage per district in Vienna.

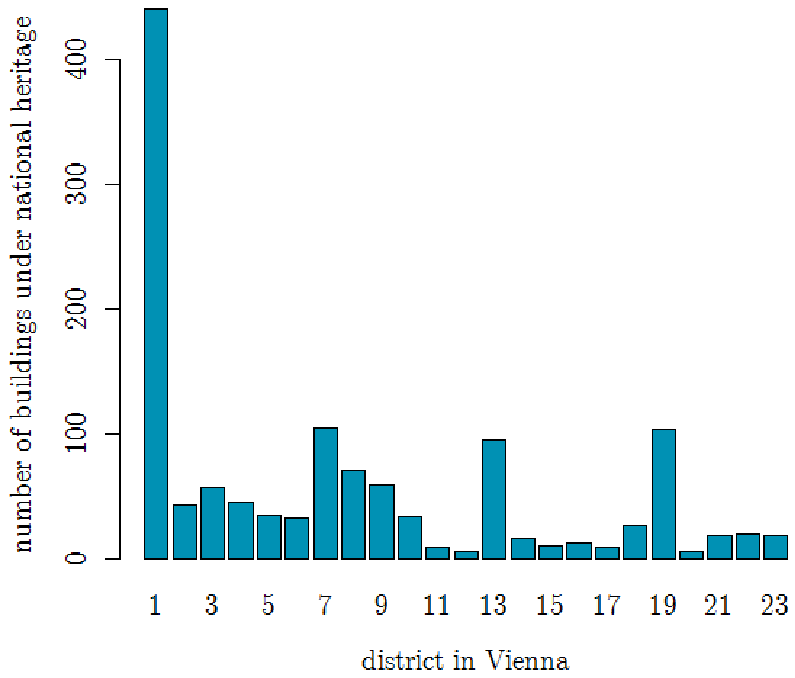

Figure 3.3: Number of buildings under national heritage per district in Vienna, Source: Bundesdenkmalamt [2013] and own calculations

Used energy carrier and heating system

The information about the used energy carrier and heating system considers multiple data sources. The information in the WWK, if a building is connected to the existing grid infrastructure (district heating and gas), information from „Wien Energie “ about the number of dwellings and buildings connected to the existing district heating network and information from Statistik Austria about the used energy carriers and heated effective buildings' area (Statistik Austria [2013d] and Statistik Austria [2013c]). This section shortly describes the data preparation steps, the calibration and comparison with the energy balance is explained in section 3.2.1.

The information of Statistik Austria is provided for the main residence dwellings. The data provided by „Wien Energie " is available for census areas within Vienna. This area is a smaller unit of the registration districts and so allows a more detailed assignment of the information. The assignment is conducted in two steps.

- Comparison of the number of dwellings supplied by district heating per census area with the information available in the WWK. Differences are changed, either new buildings are determined, where district heating is used for heat supply or another energy carrier is determined according to the next step.

- The energy carrier of the remaining buildings is randomly determined using the share of each energy carrier for Vienna provided by Statistik Austria [2013d] and Statistik Austria [2013c].

Table 3.3 shows the share of energy carrier in the year 2008, the base year of the WWK.

Table 3.3: The used energy carriers as share of residential dwellings for Vienna for the base year of the WWK 2008. Source: Statistik Austria [2013c]

Energy carrier	Share
Wood, wood chips, pellets	2.22 %
Oil	3.51 %
Electricity	6.84 %
Gas	50.75 %
Solar, heat pumps	0.23 %
District heating	36.47 %

3.2 Data calibration

The following sections describe the data calibration for the building stock from the years 2008 to 2013.

3.2.1 Description of the building stock by modelling the Year 2013

The initial year for the building stock data, where the data serves as input for the simulation model (see section 2.2), is the year 2008. This is motivated by the fact that the publishing year of the WWK is the year 2008. For the correct data calibration, two main characteristics are used: On the one hand, the historic renovation activities are calculated based on assumptions from Müller and Kranzl [2015] and assigned to the existing building stock. This is done with the provided information of Statistik Austria and other literature sources. On the other hand, the resulting and calculated final energy demand for the period 2008-2014 are compared with the useful energy analysis Statistik Austria [2014c].

Renovation Activities

The used database for this thesis, the WWK, doesn't provide information about measurements regarding the building's envelope during the buildings' lifetime, it only contains information about the construction year of the buildings. As different measurements can influence the heat demand of the building in general on the one hand and can also influence further investment decisions on the other hand, assumptions regarding the historic measurements are required. These assumptions include activities regarding the facade, activities which include the change of windows and investments in the change of heating systems.
Müller [2015] discusses the approach for this calibration and the required parameters for the used Weibull distribution to describe the service lifetime of building components like the facade, windows and heating systems. The Weibull distribution describes the expected lifetime of the components and the failure probability of the components. The distribution is described by two parameters, the shape k and scale parameter λ. The distribution function $F(t)$ is displayed in equation 3.1:

$$F(t) = 1 - e^{-(\lambda\, t)^k} \quad t > 0 \tag{3.1}$$

As it is assumed that there are no failures within the first years a component is used, the Weibull distribution is modified and years with a zero failure rate are introduced (see [Müller, 2015, p. 84]).

The calibration considers different lifetimes of the buildings and the components, dependent on the construction year and usage. The parameters are taken from ([Müller, 2015, p. 265]). The algorithm, described in detail in [Müller, 2015, p. 83 ff.]) is used and implemented in the statistical software R Core Team [2013].
As there ise little data available about the historic renovation activities in Austria and in Vienna, the results of the calibration are compared to the information contained in Statistik Austria [2004]. This source contains information about the building stock in Vienna in the year 2001, where all the buildings and additional information are captured. Among other things, it also contains the information about the number of buildings, where the building owners decide to exchange some building components in the time period between 1991 and 2001 and provides information about the change of windows, maintenance of the facade and thermal refurbishments of the facade. For the evaluation of the assumptions regarding the parameters applied on Vienna's building stock, the input data is grouped and analysed as follows:

1. All buildings
2. Small houses[3]
3. Apartment buildings[4]
4. All residential buildings[5]

The structure of the underlying data for the building stock is displayed in figure 3.4.

Table 3.4 displays the comparison of the data provided by Statistik Austria and the results of the calibration using the above mentioned approach. As for the number

[3] buildings with one or two dwellings
[4] buildings with three or more dwellings
[5] A building is declared as residential building if more than 50 % of the effective floor space is declared for living.

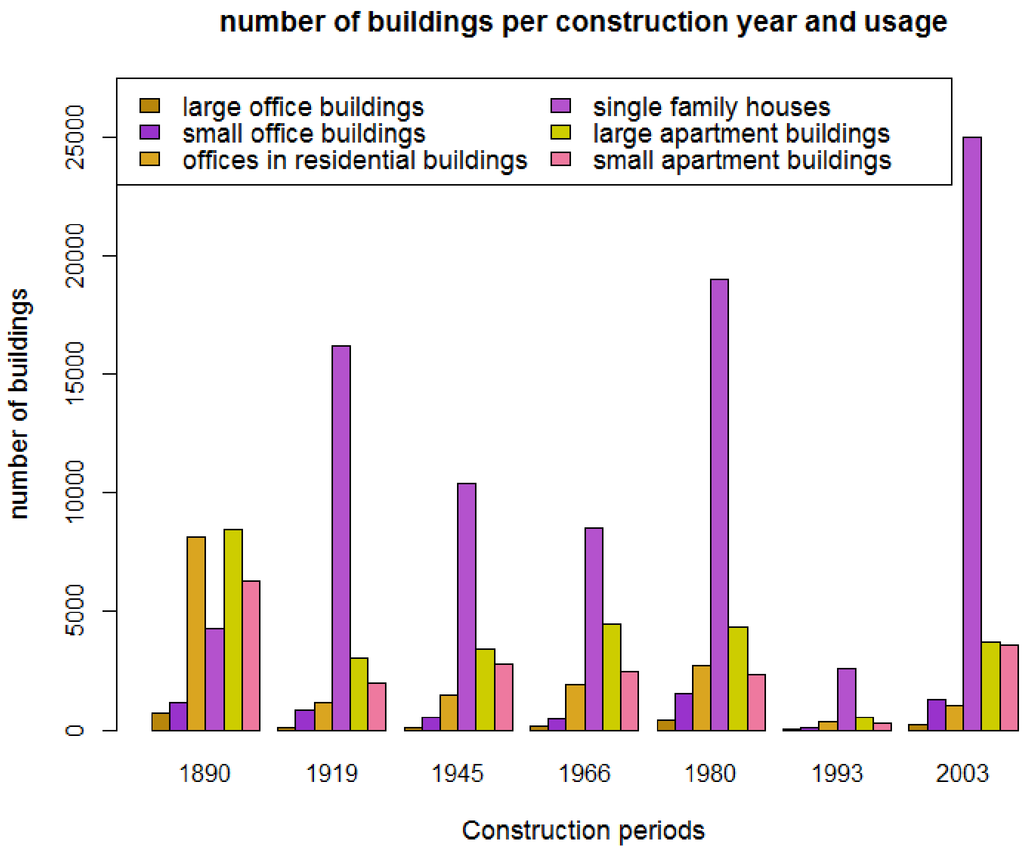

Figure 3.4: Number of buildings per construction year and usage for Vienna, Source: own illustration, based on WWK

of buildings in the used data base, the WWK, differs slightly from the number provided in the data of Statistik Austria (see 3.1), the results are compared as share of the total number of buildings in the year 2001. This means that the values are compared $\frac{\sum_{1991}^{2001} \text{measurement}_{\text{facade/window}}}{\text{number of buildings}_{2001}}$ first for the statistical data and second for the results of the modelled calibration. The results show, that the assumptions regarding the historic measurements match quite towel with to the observed data. The highest deviation is in the changing rate of windows for small and apartment buildings, whereas the deviation of the shares for the facade is modest for this building groups. The renovation rates between 1980 and 2008 for the different

[6]includes maintenance as well as thermal refurbishments

Table 3.4: Comparison Data from Statistik Austria [2004] (Number of buildings investing in measurement, share of all buildings invest in measurement) and results of calibration regarding the investments in the change of building components for the period 1991-2001

Measurement	Building group	Number of buildings invest in measurement	Share of all buildings invest in measurement	Results calibration
Change windows	all	23866	14.19 %	15.18%
Refacing[6]	all	24337	14.47 %	15.38%
Change windows	small buildings	9095	11.05 %	13.50%
Refacing	small buildings	10873	13.21%	13.71%
Change windows	apartment buildings	12819	22.58 %	17.99%
Refacing	apartment buildings	11296	18.19%	18.24%
Change windows	residential buildings	21914	15.76 %	15.48%
Refacing	residential buildings	22169	15.94%	15.71%

building groups are splitted into the renovation rates for the facade and the windows are displayed in figures 3.5 and 3.6. Based on the assumption that the yearly renovated buildings within the period 1991-2001 are uniformly distributed, the resulting annual renovation rate for facade of accounty by 1.31% (including maintenance and thermal refurbishments). The renovation rate for thermal refurbishments is about 0.71%. For the period from 2001 to 2008,these values increase to 1.61% for all facade relating measurements resp. 0.88% for thermal refurbishments.
Figure 3.7 shows the share of not-renovated buildings in the year 2008 per construction period and usage.

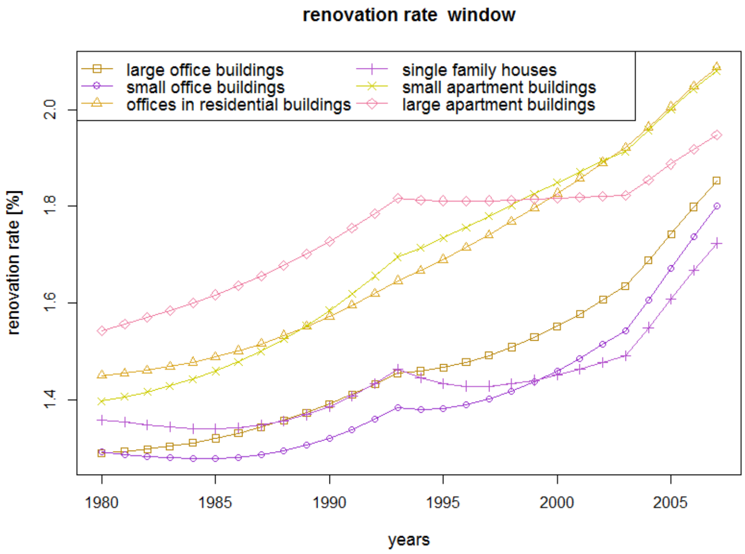

Figure 3.5: Calculated historic renovation rates of windows for different building groups, Source: own illustration, based on WWK and assumptions regarding historic renovation from Müller [2015]

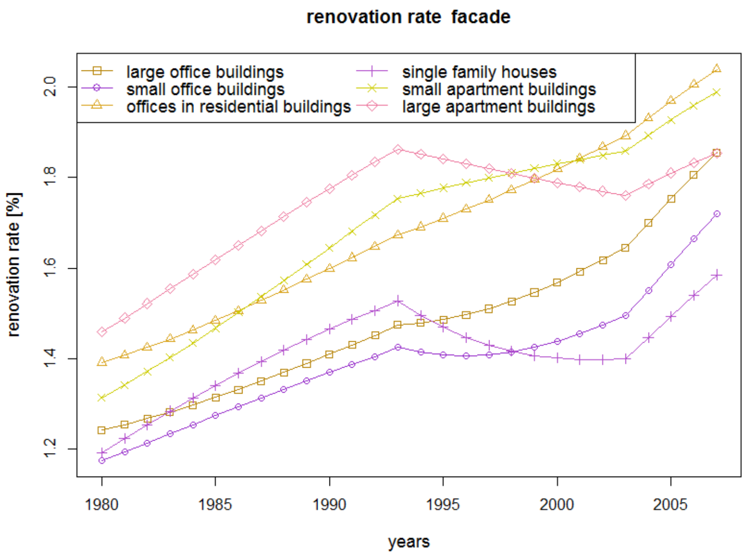

Figure 3.6: Calculated historic renovation rates of facade for different building groups, Source: own illustration based on WWK and assumptions regarding historic renovation from Müller [2015]

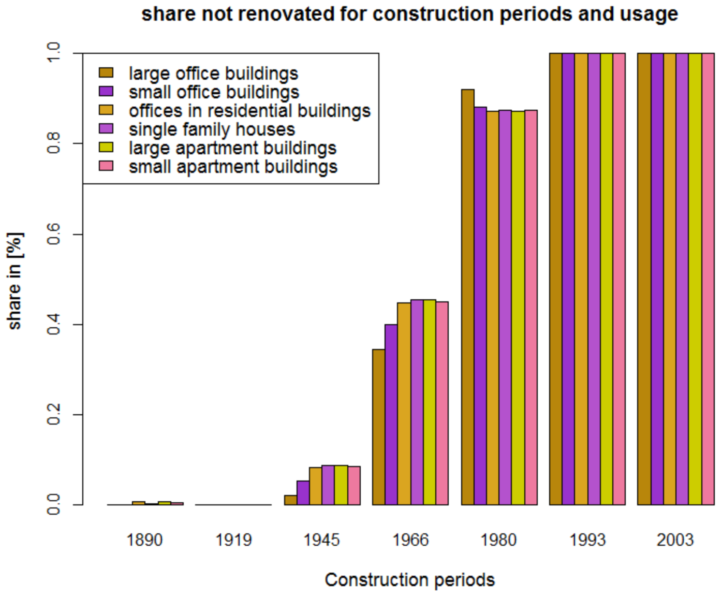

Figure 3.7: Share of buildings per construction period and usage which were not renovated in the year 2008, Source: own illustration based on WWK and assumptions regarding historic renovation from Müller [2015]

Final Energy Demand for the period 2008 - 2014 and used energy carriers

In this section, the input data of the simulation model is validated for the years 2008 - 2014. Therefore the data about the useful energy demand in Vienna Statistik Austria [2014c] is compared with the results of the simulation model for the different energy carriers used for space heating and domestic hot water supply. In the useful energy demand balance, the consumption for space heating and conditioning, as well as the data of the domestic hot water demand of private households and public and private services is provided. These values are adjusted for the heating degree days[7]. The heating degree days are only used for the space heating part of the useful energy demand and not applied to the share of domestic hot water, which is assumed to be independent from the climate of the observation years.
The simulation results are mainly influenced by the assumptions regarding the used heating systems, the age of the building stock and the corresponding historic

[7]The actual heating degree days for the years 2005-2014 were received by „Wiener Stadtwerke“.

renovation rates (see 3.2.1 for description of the assumptions regarding the historic measures for the building components). The main input data for the simulation of the final energy demand for the period 2008 - 2014 is:

1. Information from „Wiener Stadtwerke "about the number of buildings per district connected to the district heating network
2. Useful area and number of buildings connected to district heating in the year 2001 Statistik Austria [2014c]
3. The information about used energy carriers and useful area for households from 2003 to 2013 Statistik Austria [2013c]
4. The information about the number of main residences and used heating system from 2003 to 2012 Statistik Austria [2013d]
5. The number of completed buildings within the years 2005 and 2013 to consider the newly constructed buildings after the base year of the WWK Statistik Austria [2014a]

In the main input data base, the WWK, the buildings are just classified by determining if they are connected to the gas / district heating network or if the connection is unknown. This calibration, as well as the assignment of the remaining energy carriers and heating systems is insufficient. That's the reason why the data is merged with the data sources mentioned above (see also the previous sections about the data preparation and calibration for more details).
Three indicators are used for this calibration: (1) The number of residential dwellings per energy carrier, (2) the share of useful area per energy carrier in the total useful area of residential buildings and (3) the absolute final energy demand for space heating and domestic hot water.

In figure 3.8, the results of the existing simulation model Invert/EE-Lab for the years 2008-2013 and the data from Statistik Austria [2014c] are displayed and compared for each energy carrier used for space heating and domestic hot water. The data from Statistik Austria is adjusted by the heating degree days for the share of space heating. For District heating (DH), two curves are displayed, as the information from Statistik Austria about the district heating demand and the data from „Wiener Stadtwerke (WSTW) " differs within the considered horizon. The figure shows that for gas, the results of the existing simulation model overestimate the share of gas. For District heating it can be observed that the results of the existing simulation model are within the limits of the data provided by Statistik Austria and the information provided by „Wiener Stadtwerke (WSTW) “. Figure 3.9 shows the result for all energy carriers in total.

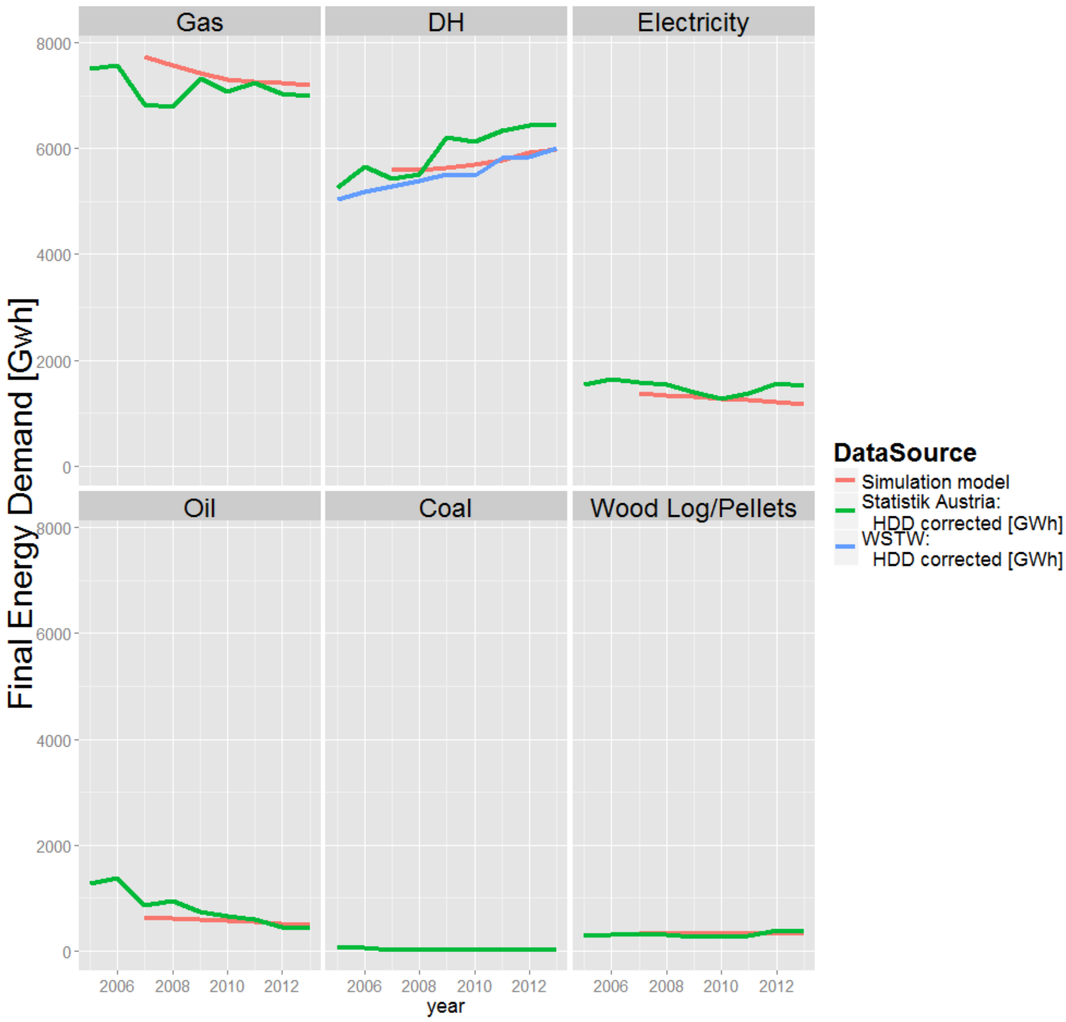

Figure 3.8: comparison of information about final energy demand provided by Statistik Austria and simulation results for each of the used energy carriers; The results of Statstik Austria are adjusted for the heating degree days, Source: own illustration

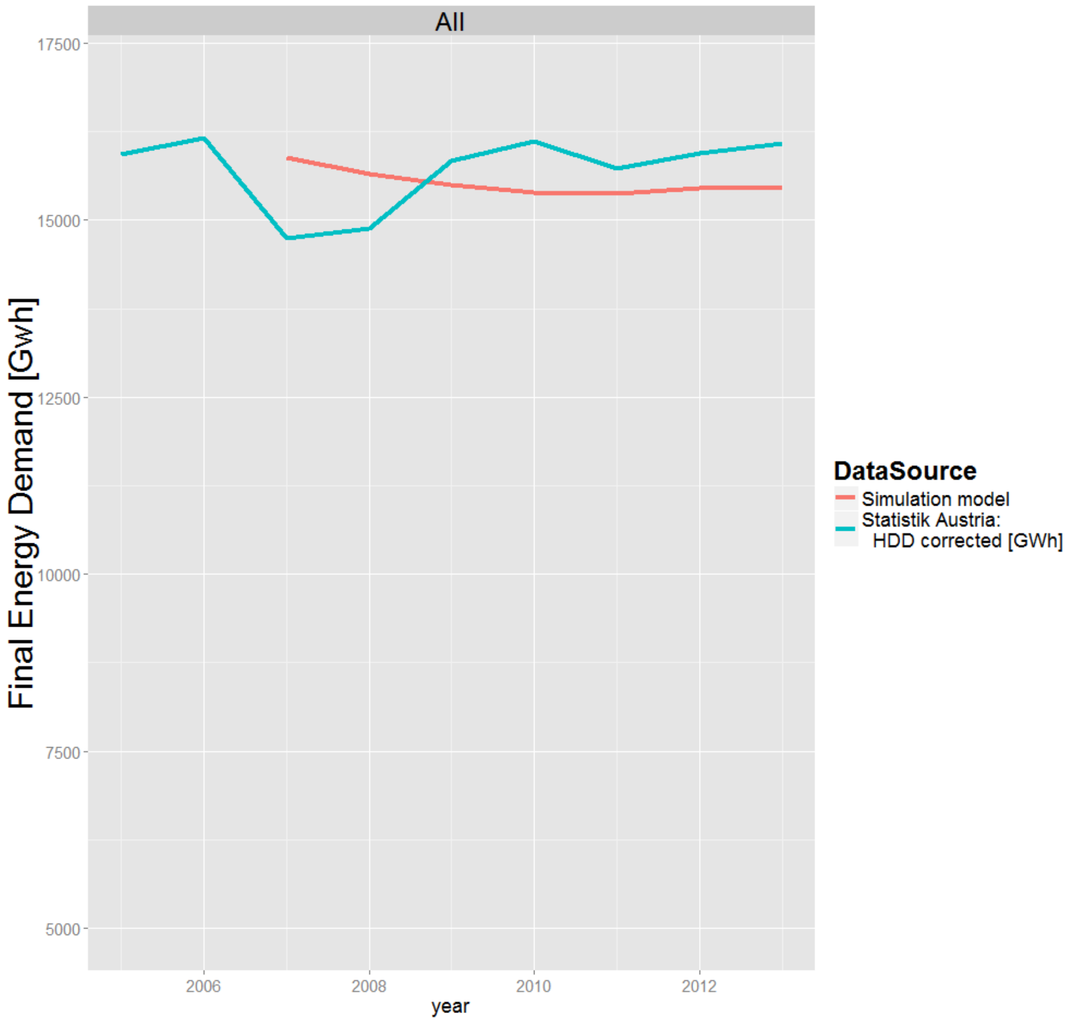

Figure 3.9: comparison of information about final energy demand provided by Statistik Austria and simulation results for all energy carriers in total; The results of Statstik Austria are adjusted for the heating degree days, Source: own illustration

3.3 Input Data of the integrated modelling approach

The input data of the integrated modelling approach consists of the required input data for the existing simulation model and the input data required for the investment optimization model for investments in the extension and expansion of the existing district heating and gas infrastructure. Besides the building stock data (described in section 3.1), additional information is required. This section describes the input data for either the existing simulation model or the optimization model, which are the same for all scenarios. The scenario-dependent input data is described in the next section 3.4.

3.3.1 Population growth and newly constructed buildings

The assumptions regarding population growth and thus the newly constructed areas don't vary for the different scenarios. The development of Viennese population assumed for this thesis is based on a study from the city of Vienna, where the expected growth of population up to 2044 is pointed out Magistratsabteilung 23 - Wirtschaft, Arbeit und Statistik [2011]. This study provides the information about the expected future population on three different aggregation levels: First, on registration district up to 2024 (for the years 2014, 2019 and 2024), second on district level up to 2034 (for the years 2024, 2029, 2034) and last, for all of Vienna up to 2044. The detailed information is displayed in table 3.5. For the years 2045-2050, the same growth as in the decade before is assumed. In general, the development of the population growth drops from 2015-2050.

Table 3.5: The population growth in Vienna. Source: Magistratsabteilung 23 - Wirtschaft, Arbeit und Statistik [2011]

Year	Population
2014	1 774 829
2024	1 952 394
2034	2 043 411
2044	2 110 212

The population growth and demolition of existing buildings leads to newly constructed buildings within the city of Vienna. Determining the future development of the current building stock is based on an interdisciplinary analysis within the PhD-course URBEM^{DK}. Based on the inner-development potential, calculated by Forster [2016], the future gross floor area and the prospective number of buildings dependent on the expected population within the time horizon can be calculated. Therefore the following distinction to calculate the future building stock is done:

1. Increasing the gross floor area of existing buildings: due to the current legal framework, the potential for existing buildings can be raised according to the actual height of each building, the required average storey height and the maximum allowed height of a building. Based on a GIS analysis, this potential is provided for each single building in Vienna (base year 2008).
2. Construction of new buildings: In addition, all areas within Vienna which are declared as potential construction sites by the city of Vienna Magistratsabteilung 21 - Stadtteilplanung und Flächennutzung [2013] are analysed to define the potential ground area for new buildings. It is assumed that green areas are going to stay constant and brown field usage is neglected due to missing information.

The theoretical potential for increasing the gross floor area of existing buildings serves as input parameter for an analysis concerning the future building stock. This potential for increasing the gross floor area of the buildings is about 19.81 km^2 for all of Vienna and can be exploited by extending the attic of a building. As this can be very costly, it is assumed that the potential is actually exploited if a thermal refurbishment of a building is conducted. As the refurbishment rates are endogenously modelled within this analysis and the development for the future building stock serves as input parameter for the analysis, the calculation of the potential for increasing the gross floor area of the buildings is determined with an exogenously assumed refurbishment rate about 1.4 %. Additionally, an average living area per building category for the extension of the attic is used, based on the calculations of Julia Forster. This leads to an extension potential of attic per registration district up to 2024 resp. per district up to 2034.

Based on the population growth and assumptions of floor area per capita until 2050, the yearly required additional living space can be calculated[8]. Thus, the comparison of the required additional living space with the potential of the extension of the attics results in the required additional living space of newly constructed buildings. Finally, the determination of the required buildings is based on following assumptions: The ratio between the construction of single family houses and apartment buildings is assumed with 6, that is, for every single family house, 6 apartment buildings are built[9]. Figure 3.10 shows the results, which serve as input for the following analyses. The differences within the considered horizon, especially for the gross floor potential within existing buildings, can be explained by the varying population increase within single registration districts over the years.

The annual development regarding non-residential buildings is assumed to be the same as the average annual development in the period 2009-2013 Statistik Austria [2014a] and doesn't vary for the different scenarios. Thus, the effects of changes in the GDP on the floor area aren't considered in this analysis.

3.3.2 Climate Data

The assumed climate data and the development of the climate are the same for all three considered scenarios. As the assumed weather and climate data influences the buildings' heat demand, the existing simulation model requires information about the average outdoor temperature, solar radiation and the change of the heating degree days up to 2050. Therefore, and to ensure consistency within the URBEM^{DK} - context, the climate data from Kranzl et al. [2014] is considered.

3.3.3 Costs regarding the extension and expansion of district heating and gas

The following section shortly describes the general assumptions regarding the extension and expansion of the existing district heating and gas network. In this

[8] Assuming a constant average living area per person about 37.9 m^2 and a constant average area per dwelling about 75.2 m^2 for Vienna up to 2050 Statistik Austria [2014d].

[9] Source: Own calculations based on the recent development, quoted in Statistik Austria [2014a]

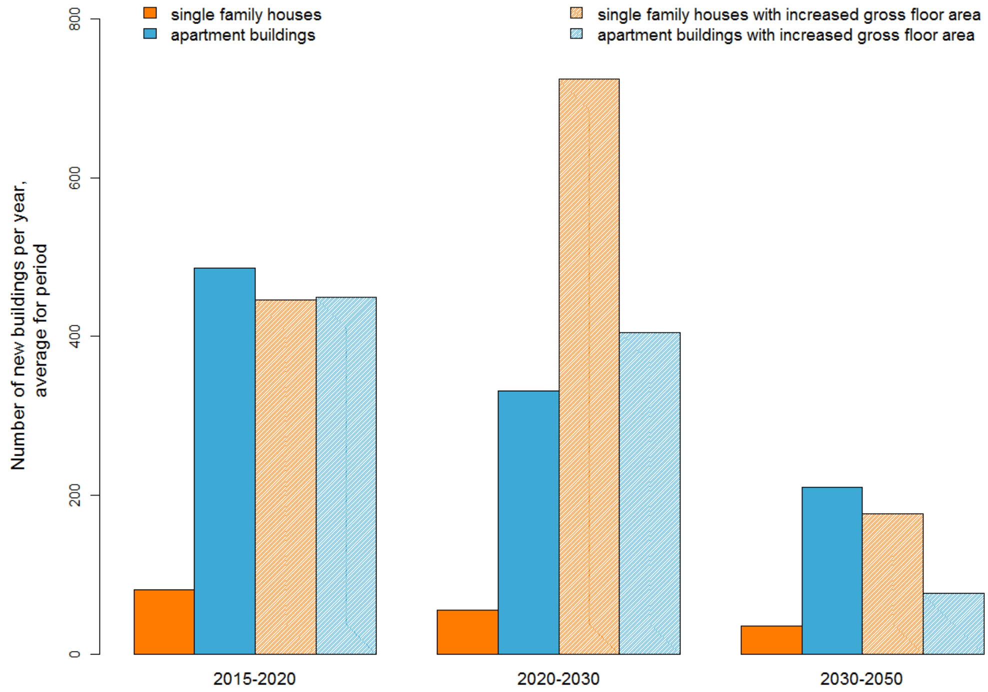

Figure 3.10: Calculated number of new buildings and buildings with increased gross floor area per year as an average of the periods, divided in single family houses and apartment buildings[10], Source: own illustration

research work, extension is defined as the increase in the district heating demand of building blocks already connected, whereas expansion is the connection of new building blocks.

If building owners decide to connect to the district heating grid, they have to pay for the house connection. In this thesis it is assumed that these costs differ for different settlement types[11]. The main difference of the settlement types is the composition of the building stock and the plot ratio of the corresponding area. The costs for the house connection vary from 1,920 € to 11,700 € (Source: Lutsch et al. [2004]).

[10]As the development of the population growth is just disaggregated up to 2034, the potential for increasing the gross floor area of existing buildings is only considered up to 2034.

[11]For more information about the assumed settlement types in Vienna see 3.3.5

Table 3.6 displays the assumptions for the district heating expansion model.

Table 3.6: General assumptions and input data for economic assessment of the extension and expansion of district heating network

Interest rate	6 % per year
Amortisation horizon	15 years
Max. yearly investments	20 Mio. Euro
Length network base year 2013 [12]	1192 km
Lifetime of grids	40 years
Pumping	15 $kWh_{\mathrm{el}}/MWh_{\mathrm{th}}$
energy demand	([Hensel, 2013, p.61])
Operation cost	18 Euro/m ([Hensel, 2013, p.201])
Heat generation costs	35 €/ MWh

The costs for the extension of the district heating network are provided by „Wien Energie“ and are linearized. The values of the linearisation dependent on MW are listed in Table 3.7.

Table 3.7: Costs for expansion of district heating network.

MW	Euro / linear metre	MW	Euro / linear metre
0.5	1325	5	1550
1	1350	10	1800

The investment costs for the connection of new building blocks mainly determine the decision whether a block is connected or not. As these costs are determined from the required pipe length, the distance of each building block to the existing district heating network in the base year is assigned. The information about the distance of buildings to the existing district heating is provided by „Wien Energie“.

The considered cost components to determine the district heating distribution consist of costs for investments in expansion, investments in extension, reinvestment costs depending on the age of the network and operation costs, which consist mainly of the pumping costs and the maintenance costs depending on the length of the

[12] Source: `http://www.nachhaltigkeit.wienerstadtwerke.at/oekologie/energieerzeugung-bereitstellung/fernwaerme.html`, accessed 1.11.2016

grid. Additionally, the heat generation costs and spatially resolved grid losses[13] applied on the district heating demand $FED^{DH,2}$[14] determine the costs for heat supply, which are required to do the investment planning. The heat generation costs are exogenously given and include the long-term investment costs in heat generation sites and the fuel costs[15].

For the investment planning of the existing gas network, the heat generation costs and the costs for gas are neglected. Rather, the network charges are used to determine if the network operator should invest.

3.3.4 Assumptions regarding the existing grid infrastructure

For the present research work, no detailed information about the existing district heating and gas grid infrastructure is available. Besides the information about the used heating technologies and thus used energy carriers in the building stock (see section 3.1.2), information on the current length of the networks, as well as the age structure of the networks is required. Both parameters are required to be able to determine the future re-investment costs of the existing infrastructures. The information about the current length of the networks is available and displayed in table 3.8.

Table 3.8: Information about the current length of the district heating and gas grid in Vienna for the year 2012, Source: Wiener Stadtwerke

Energy carrier	length [km]
Gas	3500
District heating	1169

The detailed information about the age structure of the grids isn't available, neither is the information about the pipe length, which is assigned to one building block.

13 As a result of Dissertation 5 within the $URBEM^{DK}$ Bothe [2016]

14 $FED^{DH,2}$ denotes the district heating demand connected to the existing grid from a grid operator's economic point of view, FED = final energy demand, DH = district heating

15 These costs are results from Dissertation 2 Rab [2017] within the $URBEM^{DK}$

As different information is available for district heating and gas, the assumptions and calculations to receive the required information vary.

Gas Based on the information about the total length of the gas network, the pipe length is uniformly distributed to all connected building blocks in the analysis. For all connected building blocks, assumptions regarding the age of the assigned pipe meters are made: Thus, a random number between 1973 and 2013 is assigned to each building block. This corresponds to the underlying assumptions regarding the technical lifetime of the grid infrastructure mentioned in table 3.6. It is assumed that if a section of pipeline exceeds the technical lifetime, reinvestments are required.

District heating For the district heating grid, more information about the development of the infrastructure is available. On the one hand, information about the distance for all buildings to the transport pipes of the district heating network is provided by „Wien Energie “. Thus, this information is used to assign the corresponding length of the district heating network to each building block. On the other hand, Wiener Stadtwerke provides information about the past development of the district heating network[16], displayed in table 3.9. The assumptions for the

Table 3.9: Development of the district heating network in Vienna from 1980-2012, Source: Wiener Stadtwerke

Year	Length [km]	Year	Length [km]
1980	118	2010	1139
1990	339	2011	1149
2000	904	2012	1169

age structure of the existing grid is based on this information: The newly built district heating network per period and length mentioned in table 3.9 is related to the total length of the network in the year 2012. This share is applied to the number of building blocks connected to district heating. That means that up to 1980, 118 km of the network were built, which corresponds with 10 % of the total network (related to the year 2012) and thus 10 % of the connected buildings in

[16] http://www.nachhaltigkeit.wienerstadtwerke.at/oekologie/energieerzeugung-bereitstellung/fernwaerme.html

the year 2012 are connected up to 1980. As historic maps of the district heating networks show that the construction and installation of the grid started in the city centre, it is assumed that the districts in the city centre were first connected. Thus, 10 % of the buildings from the city centre are chosen and a random installation year between 1960 and 1980 is assigned. In the following years, more and more buildings from the bordering districts are connected as well. That means that the share of the next period is defined and connected buildings from the city centre or bordering districts are chosen and random numbers of this period are assigned.

3.3.5 Areas of Settlement: Classification of Vienna's registration districts

The areas of settlement are introduced, as this classification of an area allows to relate the building structure of areas with the profitability of district heating and thus also with the investment costs for the extension and expansion of an existing district heating network. There are two characteristics of this approach. 1) The profitability of district heating mainly is influenced by the heat densities and the linked investment costs for district heating. In general, areas with high heat densities have lower specific distribution costs for district heating and this leads to a higher profitability of district heating. As densely built areas often come with high heat densities, the classification of the areas of settlement allows to classify regions with higher heat densities. 2) The number of buildings per usage and unit allows to estimate the average investment costs for district heating, depending on the required pipe length and length of the house connection.
The second interpretation of the approach is used and explained in this section: It is assumed that areas with higher building densities require less investments in the district heating infrastructure, as less meters of pipes are required per building. This is also stated and used in various research works regarding the economic feasibility of district heating networks, like in Blesl [2002], Hensel [2013], Lutsch et al. [2004], Hausladen and Hamacher [2011] or Roth and Häubi [1980]. In this section, the classification applied to Vienna's building stock is explained. This is used for the input data of the existing simulation model: With the classification of settlement areas, it is possible to assign different costs for the house connection of

district heating technologies to different areas within the city. These costs occur if the building owners decide to change the used energy carrier for space heating and domestic hot water and use district heating instead. In highly populated areas, which also have high building density, the investment costs are lower than for areas with many single family houses.
The used level of detail for the classification in settlement areas respects the 250 registration districts of Vienna, which subdivide the 23 districts of Vienna. This scale was chosen since most of the accessible data base, especially the detailed buildings description „Wiener Wärmekataster “, is class-divided in these registration districts. The following data bases are further used for the classification:

1. WWK; table data set (Source: Poehn [2012])
2. Land development plan (Flächenwidmungsplan); GIS-based Magistratsabteilung 21 - Stadtteilplanung und Flächennutzung [2013]
3. Information about registration districts Magistratsabteilung 21 - Stadtteilplanung und Flächennutzung, Stadt Wien [2016]; GIS-based Magistratsabteilung 23 - Wirtschaft, Arbeit und Statistik [2011]; table data set
4. Real land allocation (Realnutzungskartierung) Magistratsabteilung 18 - Stadtentwicklung und Stadtplanung [2012]; GIS-based
5. Buildings and Dwellings Censuses and Register-based Census from Statistik Austria Austria [2013b], Austria [2013a]; table data set

Results Types of Settlement

The classification of the areas of settlement is based on the introduced settlement types in Blesl [2002]. The suitable settlement types are taken for the analysis of the building stock in Vienna. The classification in [Blesl, 2002, p. 147], considers multiple factors like the usage of buildings, building age, range of base area and average base area of buildings, number of buildings per km^2, range of distance of buildings and streets and average of it, number of single building blocks and also some additional characteristics regarding the streets. As this information is not provided in the available data, a cluster analysis is conducted. This analysis allows to find similarities of all single registration districts automatically and furthermore assign the registration districts to the corresponding settlement types. For the assignment, visual and manual steps are required, which are based on information provided by the map of Vienna. The criteria for the clustering are the share of buildings per usage and registration district. With this information, it is possible to consider the average size of all buildings as well, as the usage of the buildings contains this information (see also table 3.1). Thus, the classification of areas of settlement requires the following steps:

- Assigning all buildings to exactly one registration district in Vienna
- Filtering registration districts which are not appropriate for the analysis (excluding outliers)
- Determining the share of each usage of buildings per registration district
- Conducting a cluster analysis to define the settlement type for all registration districts.

The assignment of the buildings to the registration district is already conducted in the WWK. For the filtering, all registration districts with a population density lower than 100 persons per km^2 are excluded (5 registration districts).
The classification itself is done with the statistical software R (R Core Team [2013]). A defined clustering function „kmeans“ within the package „stats“ is used. The starting point of the analysis is the definition of the number of clusters. For the analysis, 12 clusters are introduced. The reason is the classification in [Blesl, 2002, p. 147]. The comparison of the sum of squares within the cluster, an indicator for the cluster analysis, shows that an increase of the number of cluster at a reasonable degree (up to 18 settlement areas) would improve the clustering of 20 %. With the predefined number of clusters, the analysis is conducted according to the description of the statistical packages, 12 observations (=number of clusters) are taken and serve as center of the clusters. Then, the distance from each of the other observations is calculated for each of the k clusters, and observations are put into the cluster to which they are the closest. After each observation has been put in a cluster, the center of the clusters is recalculated, and every observation is checked

to see if it might be closer to a different cluster, now that the centers have been recalculated. The process continues until no observations switch clusters anymore. This leads to the result, that every registration district can be assigned to one cluster, which corresponds to the area of settlements. Here, the silhouette width can be taken as an indicator: This indicator is a measure of how well a registration district fits into the cluster that it is assigned to (indicator $\in [0,1]$). The average silhouette width of the cluster analysis for the 245 considered registration districts in Vienna results in 0.57, which means that a reasonable structure of the clustering has been found. Table 3.10 provides additional information about the classification for the areas of settlement. The table contains information on the total area, number of buildings, number of blocks of all registration districts assigned to one of the settlement areas as well as the average base area of the buildings, average number of buildings and average number of blocks within one area of settlement, based on the clustering.

Table 3.10: Information about the classificaton of the areas of settlement done for Vienna, source: own calculations

Name	Description	Number of registration districts	total area [km^2]	Total number of buildings	total number of blocks	average base area	average number of buildings	average number of blocks
ST 1	low housing density, primary single family houses	16	11	10383	511	230	850	36
ST 2	settlements with single family houses	34	30	42758	1729	153	1302	47
ST 3	old center of village, higher housing density than in ST 2	21	15.81	17810	881	238	946	44
ST 4	serial houses	36	31	35887	1492	183	1020	39
ST 5a	settlement with small apartment buildings	15	7	6783	456	352	725	46
ST 5b	settlement with small and medium apartment buildings	13	4	4363	304	322	660	41
ST 6	settlement with large and high apartment buildings	32	9	13484	1158	373	927	78
ST 7a	settlement with low buildings blocks density	9	4	4305	216	231	755	3
ST 7b	settlement with high buildings blocks density	30	10	14714	11583	357	1052	81
ST 8	City centre	32	8	12069	1008	452	972	78
ST 9	history city centre	7	1	1447	247	608	670	100
ST 10a	*public special buildings not whole registration districts, just single buildings in each district*							

3.4 Description of the scenario input parameters

Three scenarios, the Business as usual (BAU)-scenario, stagnation-scenario and climate protection-scenario, are used and formulated to compare the impacts on energy demand, supply mix, resulting CO_2-emissions, costs, etc. of different future developments regarding energy prices and policies. The scenarios are developed in an interdisciplinary URBEM^{DK}-context for the city of Vienna URBEM Scenario Taskforce [2016]. The BAU-scenario assumes that the currently implemented policy measures are considered. In the stagnation-scenario, it is assumed that the efforts regarding climate protection decrease. The climate-protection scenario is the most ambitious one, where additional support schemes to contribute to a higher reduction of the energy demand are implemented. In the following sections, the assumptions and scenario frameworks regarding population growth, newly constructed buildings, energy prices and policies are described. The base year of this analysis is 2013.

3.4.1 Energy Prices

The development of the households' energy prices differs for the various scenarios. The underlying assumptions are taken from the interdisciplinary URBEM^{DK} scenarios and are based on the WIFO price scenarios ([Kratena et al., 2014, p. 44]). The wholesale energy prices for the three scenarios are displayed in Figure 3.11. The determination of the household energy prices starts with the current household energy prices provided in Statistik Austria [2015]. These prices are broken down to net prices, taxes and additional fees. In a first step, the net prices without taxes and additional fees are taken. Based on the relative change in the wholesale energy prices, these net prices are adapted for the period up to 2050. As there are no underlying assumptions on the development of the fees for every energy carrier, an average value for taxes and fees for the period 2007 - 2014 is assumed to remain constant until 2050. The values are displayed in table 3.11.

As the CO_2-emission certificate prices also influence the household prices for district heating and electricity, these values are added to the wholesale energy prices. Additionally, it is assumed that the district heating price development is

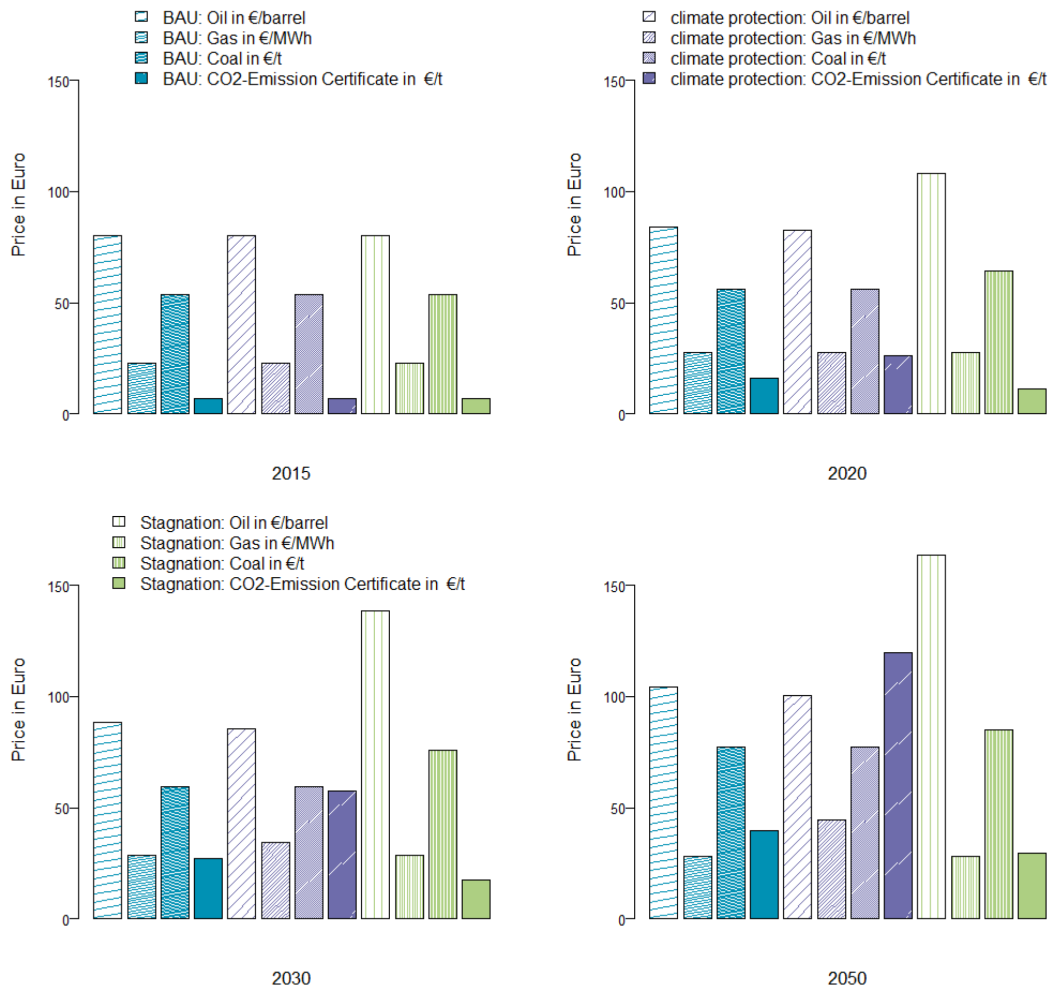

Figure 3.11: Development of the wholesale energy prices and CO_2-emission certificates until 2050

Table 3.11: General price data for the average surcharge, consisting of taxes and additional fees, on household energy prices divided into the different energy carriers, Source: own calculations, based on Statistik Austria [2015]

Energy carrier	Average surcharge
Gas	34.71 %
Coal	42.45 %
Oil	43.22 %
Electricity	42.19 %

linked to the gas price development for the Business as Usual (BAU)-scenario and the stagnation-scenario. For the climate protection-scenario it is assumed that the district heating price is linked to the development of the biomass wholesale prices. The initial values for district heating household prices are provided by „Wien Energie “. The final household energy prices for gas, oil, coal and electricity are displayed in Figure 3.12.

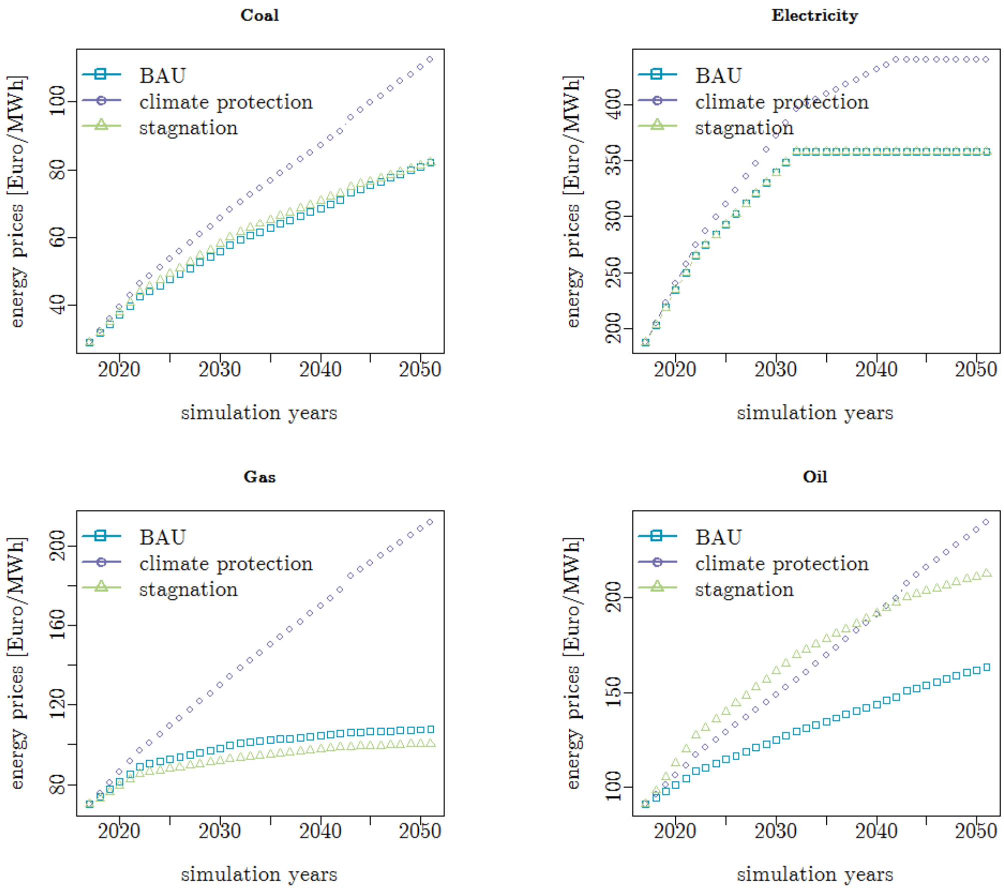

Figure 3.12: The development of the household energy prices, Source: own calculations, based on Statistik Austria [2015] and Kratena et al. [2014]

3.4.2 Energy policies and subsidies

The three scenarios differ in their assumptions regarding energy prices, energy policies and subsidies. The BAU-scenario is mainly derived from the with existing measures (WEM)-scenario described in Müller and Kranzl [2015], where energy demand scenarios for space heating and domestic hot water for Austria were developed up to 2050. The assumptions regarding the population growth (see section 3.3.1), the energy prices (see section 3.4.1), the subsidies and the amount of the total subsidies for thermal refurbishments and the change of heating systems are adapted for Vienna. The total amount of budgets for subsidies for thermal refurbishments and the change of heating systems is divided into those for residential and those for non-residential buildings. Therefore the budget foreseen in Müller and Kranzl [2015] is multiplied by the factor $\frac{\text{number of residential dwellings in Vienna}}{\text{number of residential dwellings Austria}}$ respectively $\frac{\text{number of non-residential dwellings in Vienna}}{\text{number of non-residential dwellings Austria}}$, data provided in Statistik Austria [2013a]. The amount of subsidies in Mio. Euro is displayed in Figure 3.13. For the stagnation-scenario, a 50 % reduction of the subsidies is assumed.

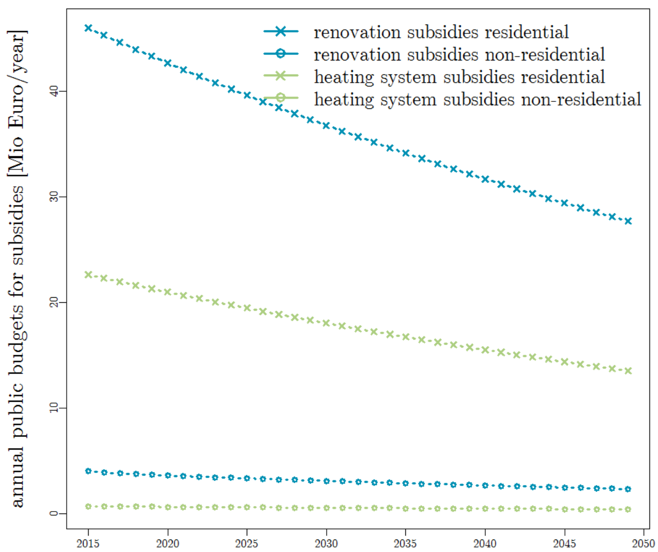

Figure 3.13: Annual budget for subsidies for thermal refurbishments and change of heating systems in Mio. Euro, Source: own illustration based on Statistik Austria [2013a] and Müller and Kranzl [2015]

3.4.3 Specific CO_2-emissions

The calculation to determine the CO_2-emissions is based on the emission-factor of the single energy carriers used for space heating and domestic hot water. The underlying assumptions for the base year are displayed in table 3.12. For district heating, the development of the CO_2-emissions are influenced by the used capacities for heat generation, which are endogenously determined within the URBEM-PhD course by dissertation 2 (see Rab [2017]). Thus, as a result from dissertation 2, it is assumed, that the CO_2-emissions of district heating evolve as follows up to 2040 in comparison to the base year 2015 (specific district heating emissions: 0,19 kg/kWh):

- BAU-scenario: reduction of 53 %
- climate protection-scenario: reduction of 63 %
- stagnation-scenario: reduction of 58 %

As the calculation of the CO_2-emissions for the whole simulation horizon up to 2050 requires information about the period after 2040, it is assumed, that the same yearly reduction occurs within the considered horizon resp. after 2040 up to 2050.

Table 3.12: CO_2-emissions factors for different energy carriers. Source:Umweltbundesamt [2015]

energy carrier	spec. CO_2-emissions spec. [kg/kWh]	energy carrier energy carrier	spec. CO_2-emissions [kg/kWh]
Gas	0.252	dec mix	0.3
Oil	0.299	Electricity	0.157
Coal	0.34	Pellets	0.052
Wood log	0.025	Wood chips	0.025
district heating	0.19		

The specific emissions for electricity are also taken from Umweltbundesamt [2015] and are kept constant up to 2050. These values are based on the Austrian electricity generation technologies. Thus, electricity imports are neglected.

CHAPTER 4

Scenario Results Vienna

The following chapter summarizes the results of the integrated analysis for Vienna. It's structured as follows: First, the results of the existing simulation model for the three URBEM^{DK}-scenarios are described in section 4.1. These results serve as input for the optimization model, which is described in sections 4.2 and 4.3. Section 4.2 identifies the future demand for district heating and gas, considering the building owners' investment decisions for energy carriers as limitation. These scenarios are denoted as BAU-, stagnation- and climate protection scenario. Section 4.3 analyses the effects if this constraint is relaxed, and the district heating and gas network operators are allowed to substitute a certain share of the gas demand by district heating and vice versa, if it is economically viable. These scenarios are denoted as adapted BAU- and adapted climate protection scenario and are based on the same output data of the existing simulation model. Finally, section 4.4 points out the additional costs and the decrease of CO_2-emissions for the substitution of the whole remaining gas demand in 2050 by either district heating or decentralized renewable energy sources for heating (RES-H). Therefore, no optimization is conducted, the results of the previous analysis serve as input for the post-analysis. Figure 4.1 shows the interactions of the scenarios.

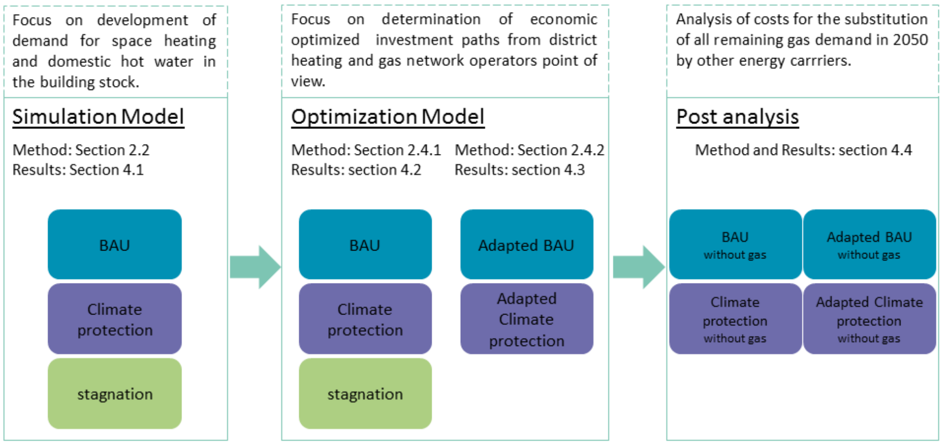

Figure 4.1: The results in this chapter are based on the three URBEM^{DK}-scenarios, defined in URBEM Scenario Taskforce [2016] and adapted for this thesis in 3.4. For the optimization model, the model-based scenario results of the existing simulation model serve as output for all analysis, even if a variation of the modelling approaches is used. Furthermore, the post-analysis is based on the outputs of the optimization model. Thus, a prefix for the scenarios is introduced. Source: own illustration

4.1 Long-term development of the buildings' heat demand

This section describes the results of the existing simulation model, which serve as input for the district heating expansion and extension investment optimization model. The main data used for the investment optimization is the development of the buildings' heat demand in general, the development of the district heat demand and the replacement rate of heating technologies. These results are mainly determined by the yearly renovation rates and the building owners' investment decisions for the used energy carrier. Additionally, effects of the different scenarios on the final energy demand are pointed out.

Figure 4.2 displays the development of the buildings' space heating and domestic hot water demand in comparison to the base year. It contains all energy carrier used for space heating and domestic hot water, as well as ambient heat for heat pumps and auxiliary energy for space heating and domestic hot water. For the

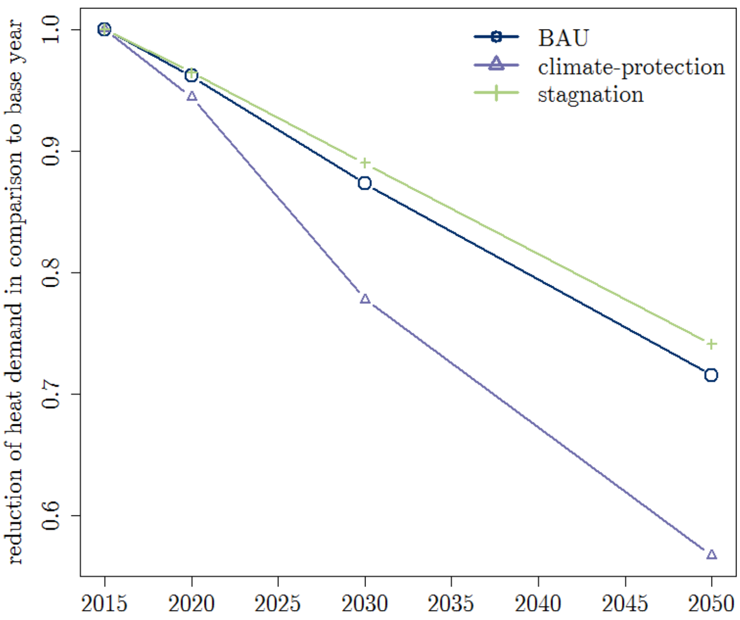

Figure 4.2: Development of the buildings' space heating and domestic hot water demand in comparison to the base year based on the building owners investment decisions for the three scenarios, Source: own illustration

BAU-scenario, the development of the demand in general, and the share of the specific energy carriers are pointed out in table 4.1. These results contain the information about the existing building stock as the results of the newly constructed buildings are excluded[1]. The initial share of district heating in the existing building

[1]This arises from the assumption, that in newly constructed areas, the network operator may influence the decision if this area should be connected to district heating or gas. Thus, the upper bound $FED^{DH,1}$ resp. $FED^{Gas,1}$ for the optimization model is the whole demand for space heating and domestic hot water of the newly constructed buildings.

stock in 2015 is about 39 % and increases up to 51 % in 2050. It contains the yearly share of energy carriers [in %] and the sum of the buildings' space heating and domestic hot water demand of the existing building stock, as well as the sum of the demand of newly constructed buildings. The total decrease of the demand for space heating and domestic hot water due to investments in thermal refurbishments and efficiency measures until 2050 exceeds 32 %[2]. The position "Rest" contains the energy carriers oil, coal, wood log/chips, pellets, electricity and electricity for heat pumps. The detailed information about all used energy carriers can be found in Table A.1.

Table 4.1: The shares of each energy carrier on the final energy demand for space heating and domestic hot water, not considering the distribution costs in detail.

Energy carrier	2015	2020	2030	2050
Gas	46 %	45 %	41 %	31 %
District Heating	39%	41 %	45 %	51 %
Rest	14 %	13 %	11 %	10%
Solar	1 %	1 %	3 %	8 %
Sum existing building stock [GWh]	14878	14049	12494	9775
Sum newly constructed buildings [GWh]	-	703	901	1207

The renovation rates influence the decrease in the demand up to 2050[3], displayed in figure 4.3. It is assumed that the policies regarding subsidies for thermal refurbishment will increase in the year 2017 and thus, the climate protection scenario shows substantially higher renovation rates for the whole considered horizon. Here, the renovation rates are averaged for all considered building categories. Figure 4.4 points out the renovation rates including maintenance[4]

The reduction in the overall energy demand also leads to a fundamental decrease in the share of gas, which is mainly influenced by energy prices, but also the share of district heating in the total energy demand is lower for the climate protection scenario shown in Table 4.2 and 4.3. The reduction of the share of district heating

[2]Here, the calculation includes both, the existing and the newly constructed building stock.
[3]The average rates for the corresponding periods are displayed in Table A.3.
[4] Maintenance of the building envelope is defined as measures to extend the lifetime of the building but without consequences on the thermal quality of the building.

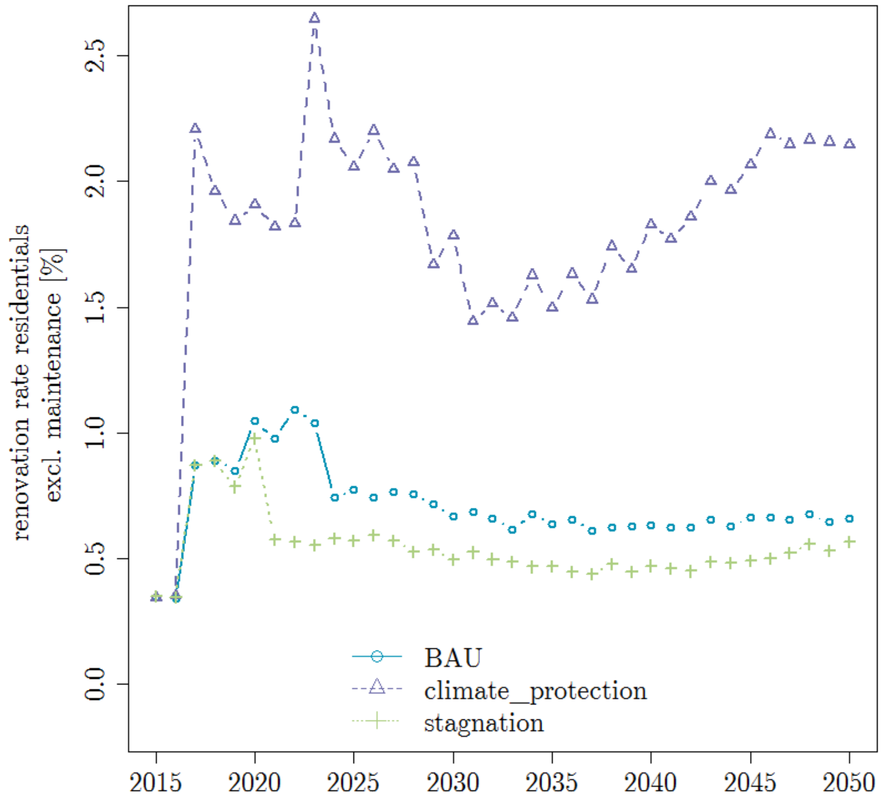

Figure 4.3: Thermal renovation rates of the building stock (without maintenance)for the three scenarios, Source: own illustration

arises from the fact that the full load hours of connected buildings decrease within the simulation horizon. Thus, the lower district heating household prices with the same base prices lead to a lower district heating demand, as the efficiency measures of the renovation are not economically viable.

Figure 4.5 points out the number of dwellings, which are supplied by district heating in the three scenarios. As the share of district heating is lowest for the climate-protection scenario, the number of buildings supplied by district heating is consequently lower in this scenario. Although the BAU- and stagnation-scenario have the same share of district heating, the number of dwellings in the stagnation-

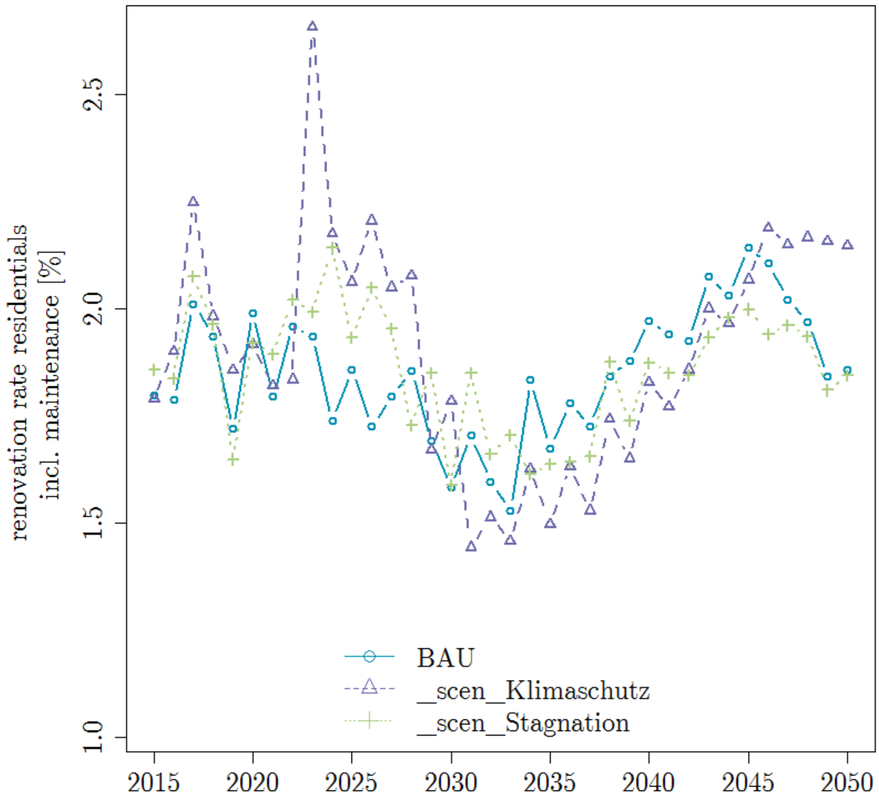

Figure 4.4: Renovation rates of the building stock (thermal renovation rates as well as maintenance)for the three scenarios, Source: own illustration

Table 4.2: Share of district heating in the different scenarios FED^{DH,1}.

	BAU	Climate protection	Stagnation
2015	39 %	39 %	39 %
2020	40 %	40 %	40 %
2030	44 %	42 %	44 %
2050	49 %	46 %	48 %

scenario is lower than in the BAU-scenarios. This is mainly due to the fact that the renovation rates in the stagnation-scenario are lower and thus lead to higher final energy demand of the buildings in the stagnation scenario.

Table 4.3: Share of gas in the different scenarios $FED^{Gas,1}$.

	BAU	Climate protection	Stagnation
2015	46 %	46 %	46 %
2020	45 %	46 %	45 %
2030	41 %	43 %	41 %
2050	31 %	25 %	33 %

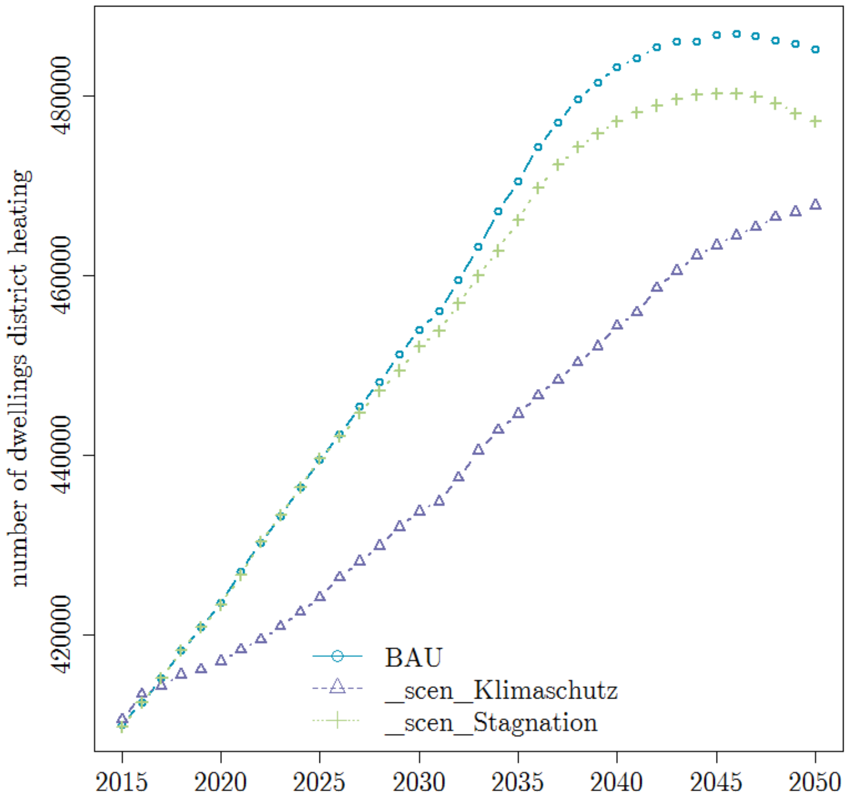

Figure 4.5: Number of dwellings, where the building owners decide to invest in district heating technologies within the simulation horizon for the three scenarios, Source: own illustration

Figure 4.6 shows the specific final energy demand for the different scenarios. The stagnation-scenario has the highest specific final energy demand. Furthermore, the figure displays the differences in the final energy demand for all energy carriers and for district heating. The reduction of the average specific final energy demand for district heating is lower than the average of all energy carriers. The difference in the year 2050 for all energy carriers accounts for 17 kWh/m^{2}a and for district heating for 23 kWh/m^{2}a. The decrease of the specific final energy demand for district heating in the BAU- and stagnation-scenario is also flatter than for the average of all energy carriers.

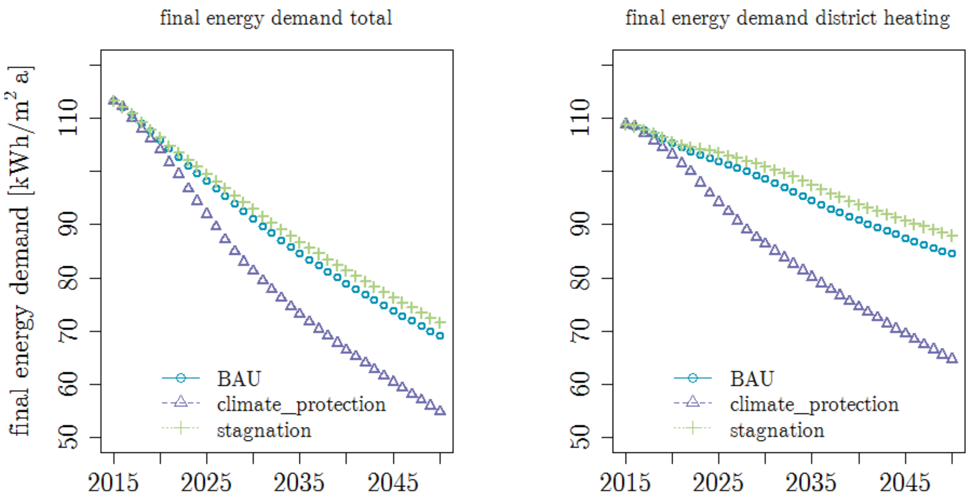

Figure 4.6: Development of the specific final energy demand based on the building owners' investment decisions for the three scenarios, averaged for all energy carriers (left) and averaged for district heating (right), Source: own illustration

In general, bigger buildings with a higher final energy demand are connected to district heating. The average final energy demand for all energy carriers starts with 89 MWh per building in 2015 an decreases to 38 MWh per building in 2050. The initial value for district heating is 163 MWh per building and decreases to 80 MWh per building.

Figure 4.7 displays the average replacement rate for all building categories and for all 5 years. It can be seen, that the scenario frameworks rarely influence the replacement rates.

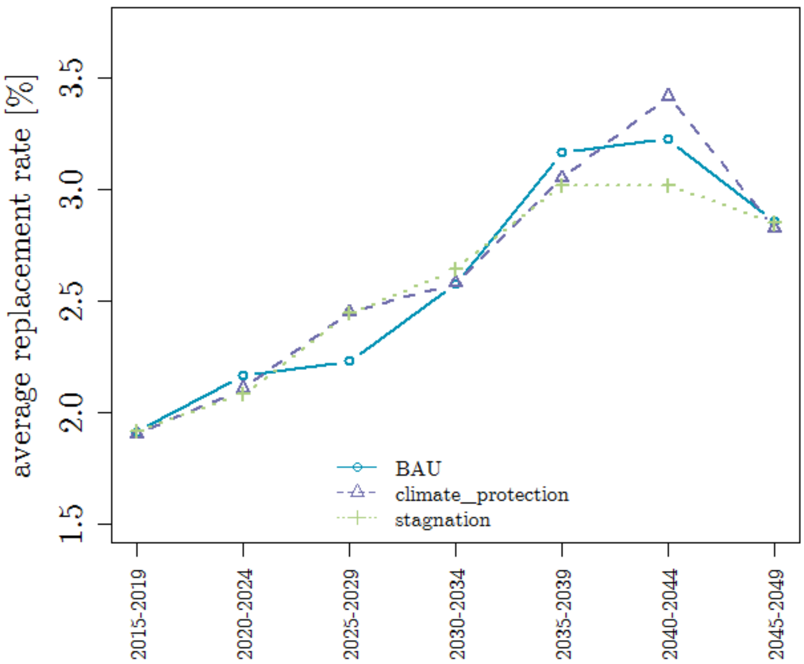

Figure 4.7: Replacement rate of heating technologies in the building stock; average for all building categories and all 5 years and the scenarios, Source: own illustration

4.2 Results: The impact of energy policies on the grid-bound energy supply

In the following sections, the results of the analysis are described. This contains a detailed description of the results of the BAU-scenario in 4.2.1, the comparison of the three scenarios in 4.2.2, a spatial analysis in 4.2.3 and a second modelling approach, which analyses the benefits, if a switch between grid-bound energy carriers from the network operators' point of view is possible in 4.3. All the results here are based on the integrated analysis, considering the results of the existing simulation model and thus the building owners' investment decision as well as the economically optimal investment strategies from a network operator's point of view.

4.2.1 Business as usual scenario

This section describes the results from the integrated model analysis for the BAU-scenario.

The investment optimization and evaluation model for the effects on the existing district heating and gas network is conducted for several years, namely 2015, 2020, 2025, 2030, 2035 and 2050. In 2050, no investments in the extension or expansion are possible in the model, but revenues from the heating sales are considered.

The results of the optimization model show, that the optimized investments consist of extension as well as expansion of the existing district heating network. Figure 4.8 displays the initial connection rate[5] of district heating per registration district and the growth (in %) up to 2050. It can be seen that an increase in the population also increases the rate of district heating.

Furthermore, the newly connected district heating demand $\mathrm{FED}_t^{\mathrm{DH,new}}$ can be divided into the share of extension and the share of expansion for all periods. The share of the extension in the newly connected district heating demand in the simulation years is about 21% in 2020, 45 % in 2025 and decreases to 20 % in 2035. The other part of the newly connected district heating demand arises from expansion, mainly due to newly constructed buildings.

As the existing simulation model doesn't consider the spatial aspects of the buildings in detail[6] and thus neglects the distance of the building blocks to the existing district heating/gas network, it is not possible to connect the whole demand $\mathrm{FED}^{\mathrm{DH,1}}$ resp. $\mathrm{FED}^{\mathrm{Gas,1}}$[7] from a district heating- resp. gas-grid operator's economic point of view. The shares $\frac{\mathrm{FED}^{\mathrm{DH,2}}}{\mathrm{FED}^{\mathrm{DH,1}}} \in [0,1]$ resp. $\frac{\mathrm{FED}^{\mathrm{Gas,2}}}{\mathrm{FED}^{\mathrm{Gas,1}}} \in [0,1]$ for the investment years are displayed in Table 4.4

[5] The connection rate is defined as the share of district heating in the total heat demand: $\frac{\mathrm{FED}^{\mathrm{DH,2}}}{\mathrm{FED}^{\mathrm{total}}}$

[6] The existing simulation model considers the different costs for the building owners to connect to the district heating network. These costs differ for the different settlement types, see 3.3.3.

[7] $\mathrm{FED}^{\mathrm{DH,1}}$ denotes the heating demand for district heating based on the building owners' investment decisions, $\mathrm{FED}^{\mathrm{DH,2}}$ denotes the district heating demand connected to the existing grid from a grid operator's economic point of view, FED = final energy demand, DH = district heating

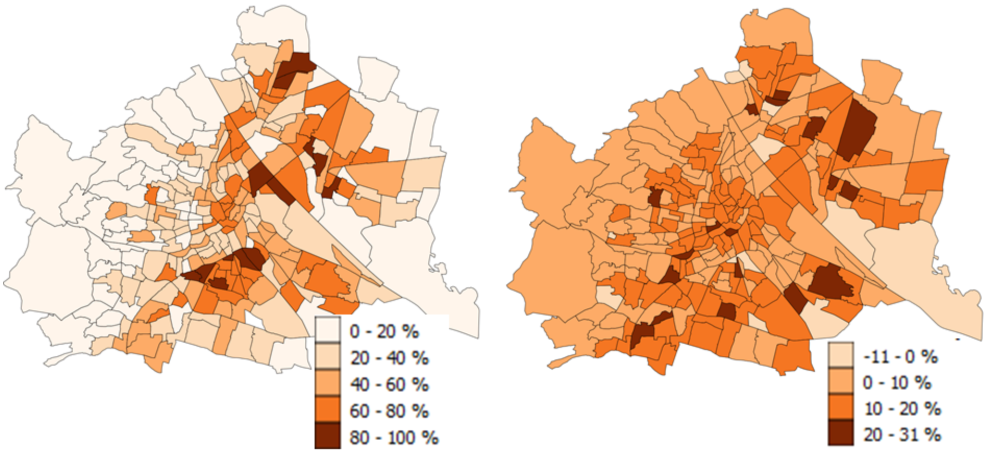

Figure 4.8: The initial connection rate of district heating per registration district (left) and change of the connection rate in percentage terms up to 2050 (right), Source: own illustration

Table 4.4: Share $\frac{FED^{DH,2}}{FED^{DH,1}}$ resp. $\frac{FED^{Gas,2}}{FED^{Gas,1}}$ 7 and the share of gas and district heating in the total energy carrier mix in the BAU-scenario

	2020	2030	2050
$\frac{FED^{DH,2}}{FED^{DH,1}}$ for building stock	98%	95%	93%
$\frac{FED^{Gas,2}}{FED^{Gas,1}}$ for building stock	96%	96 %	100%
District heating in newly constructed areas	65%	63%	61%
Gas in newly constructed areas	11%	17%	13%
Share district heating in total heat demand	40%	44%	49 %
Share gas in total heat demand	45 %	42 %	32%
Total demand district heating [GWh]	6051	5885	5236
Total demand gas [GWh]	6512	5347	3342

Table 4.4 shows that the share of district heating in the total buildings' heat demand considering the building owners' investment decision and the detailed cost

for distribution reaches 49 %, whereas the share of gas drops to 32 %. In contrast to district heating, most of the gas demand $FED^{Gas,1}$ is connected, especially in the last simulation period, i.e. $FED^{Gas,1} = FED^{Gas,2}$. This arises from the reduction of gas demand according to the simulation of the building owners' investment decision.

The methodology for the calculation of the distribution costs can be found in section 2.5.1. In total, the distribution costs for district heating are higher than the costs for gas[8]. A detailed analysis of distribution costs shows the investment costs for district heating grid as the largest share, whereas the operation costs have the highest share for the gas distribution costs (see Figure 4.9).

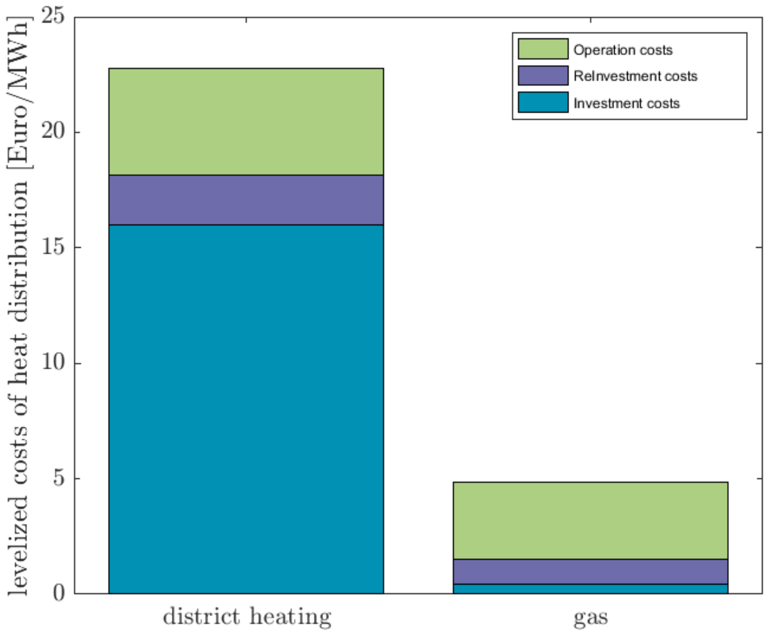

Figure 4.9: Levelized costs of energy distribution for district heating and gas per MWh, divided into the different cost components for the BAU-scenario, Source: own illustration

[8]The distribution costs don't take the heat supply costs in account, these costs are just considered for the grid investment planning

Figure 4.10 shows the trend of the yearly costs for the simulation years within the considered horizon and displays the weighting of the single cost components over time. The costs are not discounted and scaled to the costs in the year 2020. For both grid-bound energy carriers, district heating and gas, the reinvestment costs are the maximum costs within the horizon. The operation costs are almost constant over the period for both energy carriers, whereas the investment costs for district heating have their peaks in the year 2020 and 2030. This arises from the population growth in these years.

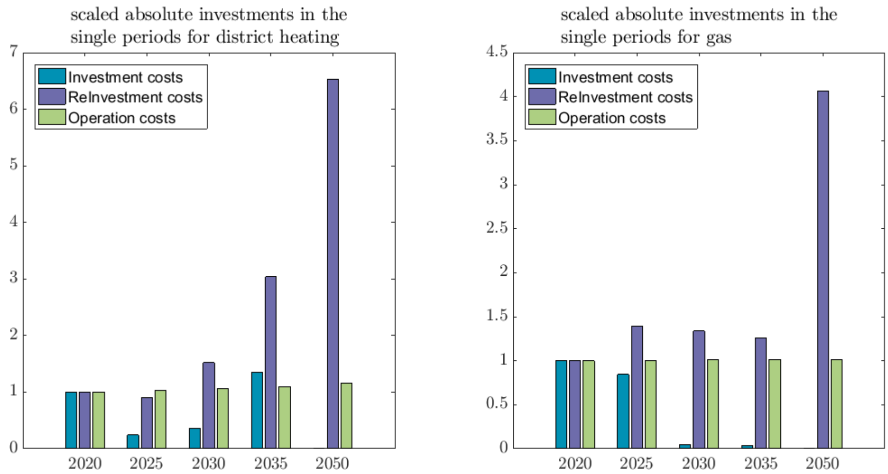

Figure 4.10: Scaled costs for energy distribution in €, not discounted, for cost components within the simulation horizon for the BAU-scenario, Source: own illustration

Furthermore, the consideration of the mean costs per MWh of sold heat for the investment periods shows a massive increase in the costs for gas in contrast to the costs for district heating, displayed in Figure 4.11. This substantial increase in the mean costs for gas arises from the fact that the gas demand is reduced within the considered simulation horizon, but the gas infrastructure has to be maintained and thus high costs per MWh of sold heat occur. The calculation is described in equation 2.43 in section 2.42.

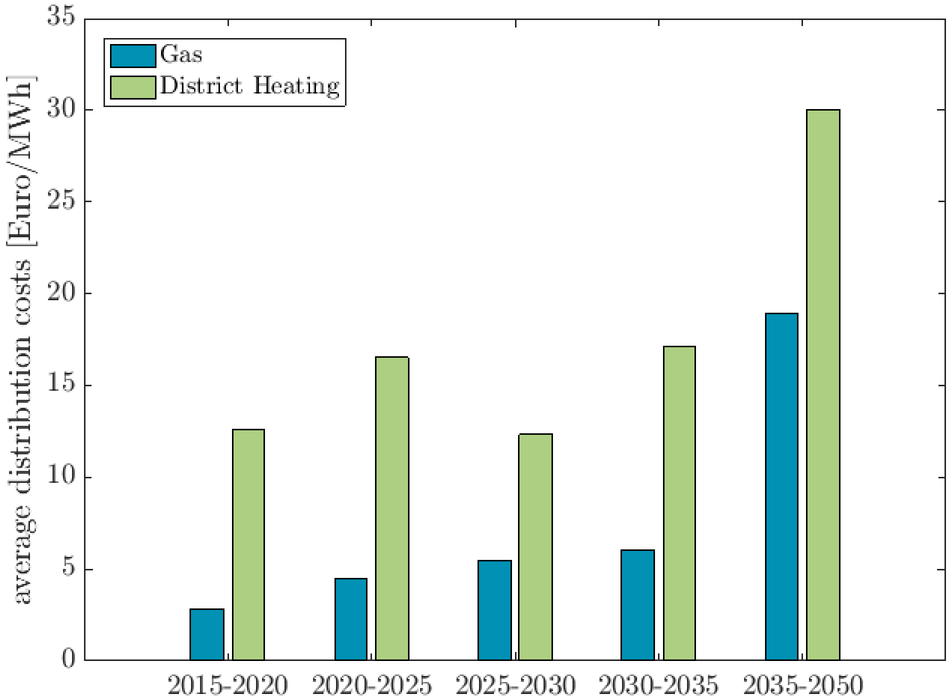

Figure 4.11: Mean distribution costs for district heating and gas for the investment periods in the BAU-scenario, Source: own illustration

4.2.2 Comparison of various scenarios and indicators

This section points out the difference for the climate protection and the stagnation scenario in comparison to the BAU-scenario. The main differences within the scenario parameters are the energy prices and the assumptions regarding the subsidies, described in 3.4.2. The focus here is on showing the differences within the scenarios and the comparison of the CO_2-emissions and the total costs for district heat and gas distribution in the building sector and the public costs from support programmes.

The total energy carrier mix as a result from the optimization model considering the costs for distribution in detail is shown in Table 4.5. Even though the share of district heating $FED^{DH,1}$ is lower in the climate protection-scenario just considering the building owners investment decision, the share after the optimization of the investments in the expansion and extension $FED^{DH,2}$ is nearly the same. The reason for this is that for the existing building stock, nearly all of the district heating demand $FED^{DH,1}$ is connected.

Table 4.5: Share of energy carriers in the scenarios including the detailed analysis of the heat and gas distribution costs

	2020	2030	2050
Climate protection - Gas	43 %	38 %	25 %
Climate protection - District Heat	42 %	45 %	47 %
Climate protection - Rest	13 %	12 %	16 %
Climate protection - Solar	2 %	5 %	11 %
Stagnation - Gas	42 %	39 %	33 %
Stagnation - District Heat	42 %	45 %	47 %
Stagnation - Rest	14 %	13 %	14 %
Stagnation - Solar	2 %	3 %	6 %

The reduction of the final energy demand supplied by district heating in the climate reduction-scenario results in higher distribution costs. The specific levelized costs of heat [€/MWh] for the district heating distribution increase by 10 %. The reason for this is that the investment costs have the highest share of the distribution costs (see also figure 4.9 for the BAU-scenario) and the share of investments and new connected district heating demand remains almost the same. For the stagnation scenario, the specific levelized costs of heat [€/MWh] decrease by 4 %, based on the fact that the final energy demand generally is higher due to lower energy savings. In contrast, the costs for gas distribution per MWh increase by 9 % in the climate protection-scenario compared to the BAU-scenario and decrease by 1 % in the stagnation-scenario. The reason for the increase is that mainly the operation costs here influence the levelized costs for distribution. Thus, the reduction of the gas demand due to efficiency measures in the building stock and the same operation costs leads to higher levelized costs of heat per MWh.

The CO_2-emissions serve as an indicator to analyse the scenarios in the $URBEM^{DK}$-context in order to analyse scenarios for the way to a sustainable city[9]. It can be observed that the stagnation and the BAU-scenario almost have the same

[9] Soure: http://urbem.tuwien.ac.at/home/EN/

reduction of CO_2-emissions for space heating and domestic hot water in comparison to the base year. The climate protection-scenarios achieve a reduction of 73 %, the reduction in the BAU-scenario is 57 %, the one in the stagnation-scenario ise about 56 %. Even the climate protection-scenario can't reach the targets stated in the Paris agreement. The methodology for the calculation is described in 3.4.3.

The comparison in Figure 4.12 shows the differences in the cumulated, discounted costs for the three scenarios.

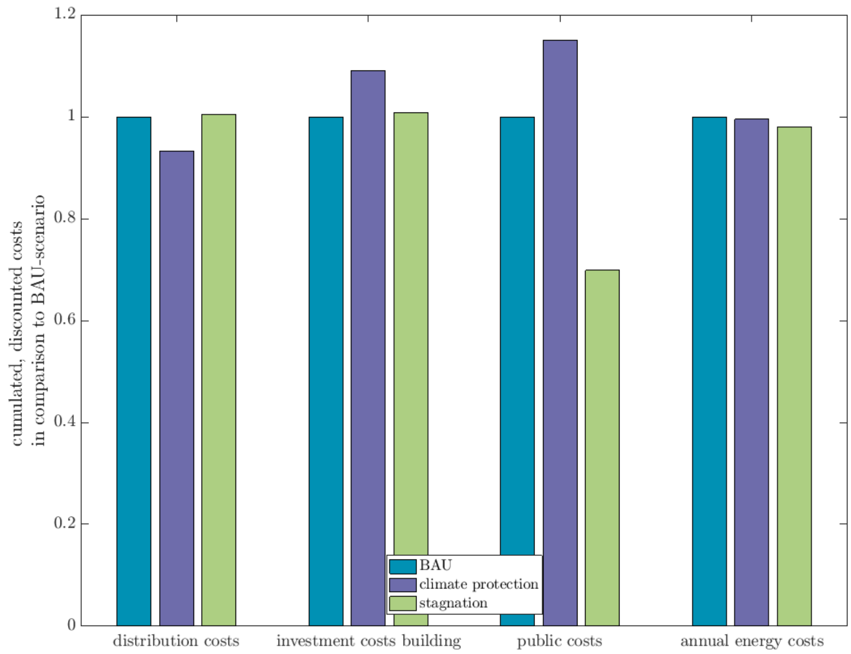

Figure 4.12: Comparison of the cumulated, discounted costs for the scenarios up to 2050, Source: own illustration

The costs are discounted and accumulated within the whole considered horizon and consist of the following components:

- Distribution costs: Costs for distribution of gas and district heating. These contain the costs for operation-, reinvestment- and investment as well as the costs for heat generation.

- Annual energy costs: These contain the total annual running costs for space heating and domestic hot water, consisting of energy costs and operation and maintenance costs in the buildings.
- Investment costs buildings: These costs consist of the investments in renovations and the change of heating systems.
- Public costs: These costs express the public costs for support programmes regarding subsidies for thermal refurbishments and the change of heating systems.

Figure 4.13 shows the composition of the cost components and their scale.

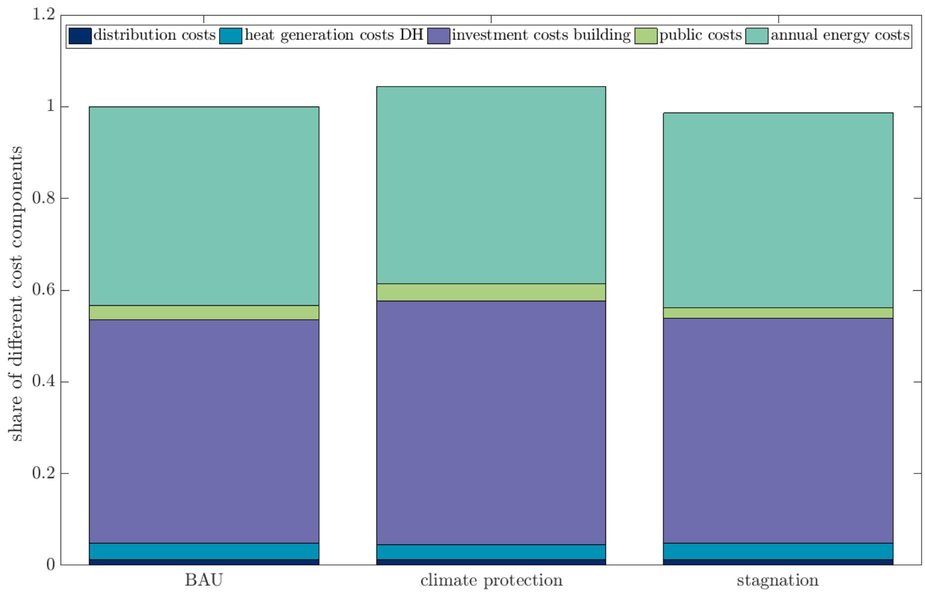

Figure 4.13: Comparison of the costs for the scenarios and their composition, Source: own illustration

The comparison of the three scenarios shows that the costs for distribution of district heating and gas are the lowest for the climate protection-scenario. The annual energy and operation and maintenance costs in the building stock hardly change for the three scenarios. This arises from the fact that the reduction in the buildings' energy demand for space heating and hot water starts to make an impact after 2030 due to higher renovation rates in the climate protection scenario. Additionally, the energy prices in the climate protection-scenario are higher (compare section 3.4.1) and thus the savings in the final energy demand lead to no cost increase. The main differences can be observed in the investment costs in the building sector for refurbishments and the change of heating system and in the expenses of the public domain. Based on this figure it could be concluded, that there are no savings in the ambitious climate protection scenario, as the higher costs for investments in the buildings and the higher public costs exceed the savings for the distribution and annual energy costs. But the high energy prices in the climate protection-scenario compared to those in the BAU-scenario would lead to substantial higher annual energy costs, if no efficiency measures would take place. A comparison of the annual energy costs in the year 2050 for the here discussed scenarios and the values displayed in figure 4.12 show, that the savings in the climate protection-scenario compared to the BAU-scenario (expressed as discounted annual energy costs) account for less than 2 % in the year 2050. If the energy prices from the BAU-scenario are assumed in the climate protection-scenario (applied on the results mentioned above), the savings in the discounted annual energy costs would be more than 22 % in the year 2050. Thus, the higher total costs, displayed in figure 4.13 for the climate protection-scenario and accounting 3.6 % could be decreased to 2.7 %.

4.2.3 Spatial Analysis

The analysis of the development of the buildings' heat demand and the impacts on the economy of the existing grid-bound heat supply in this thesis also contains spatial information, as all the building blocks are assigned to the correspondent registration district in Vienna. Thus, this section shortly highlights the impact of the spatial differences for district heating within the city area.

Figure 4.14 shows the share $\frac{\mathrm{FED}^{\mathrm{DH},2}}{\mathrm{FED}^{\mathrm{DH},1}}$[10], which expresses the connected demand to the

[10] $\mathrm{FED}^{\mathrm{DH},1}$ denotes the heating demand for district heating based on the building owners' investment decisions, $\mathrm{FED}^{\mathrm{DH},2}$ denotes the district heating demand connected to the existing grid from a grid operator's economic point of view, FED = final energy demand, DH = district

district heating network considering the upper bound determined by the building owners' investment decision. It can be observed that the analysis with higher resolution makes sense, as the differences in the share for the registration districts vary in a broad range. This arises from assumptions regarding the population growth for registration districts and the different renovation activities within these areas. Based on this, target areas for high investments and/or promotion of district heating can be identified.

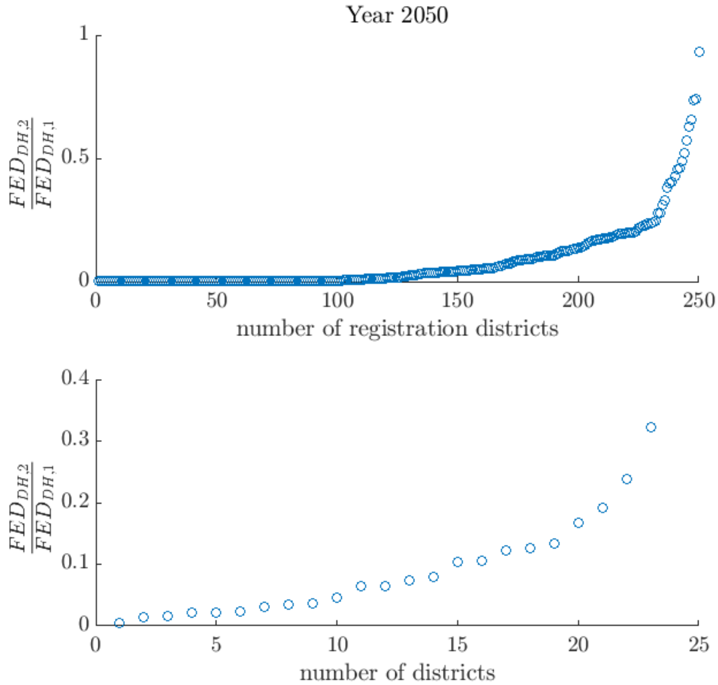

Figure 4.14: Spatial differences of the share $\frac{\mathrm{FED}^{\mathrm{DH},2}}{\mathrm{FED}^{\mathrm{DH},1}}$[10] for the registration districts (top) and districts (bottom) in Vienna for the BAU-scenario, Source: own illustration

The spatial differences of the final energy demand for space heating and domestic hot water development and the development of the district heating demand is displayed in Figures 4.15 and 4.16. These figures show the ratio $\frac{\mathrm{FED}^{\mathrm{all},2035}}{\mathrm{FED}^{\mathrm{all},2015}}$ resp. $\frac{\mathrm{FED}^{\mathrm{DH},2035}}{\mathrm{FED}^{\mathrm{DH},2015}}$[11] and express the rate of change for the considered scenarios for all

heating

[11] $\mathrm{FED}^{\mathrm{all},2035}$, $\mathrm{FED}^{\mathrm{all},2015}$ denotes the total final Energy demand in the corresponding year,

registration districts in Vienna. The rate of change consists of reduction for the final energy demand in general and a reduction and increase for district heating, depending on the registration district. The colours display the average specific final energy demand for all residential and non-residential buildings in kWh/m^2. It can be observed that the reduction due to thermal refurbishments exceed the new demand due to newly constructed areas. The BAU- and stagnation-scenario show the lowest decrease the in final energy demand, but the highest increase in district heating demand. Figure 4.16 explains the reason for the outlier with the highest increasefor district heating in the BAU- and stagnation-scenario: Although these registration districts have a high reduction of the final energy demand, the average specific final energy demand is still high and thus the incentives for connection to the district heating grid are present. However, the average reduction of the specific final energy demand due to thermal refurbishments and the lower average specific final energy demand of newly constructed buildings of these outliers leads to the significant reduction of the final energy demand.

The specific final energy demand also influences the decision if a building block is connected to the existing district heating network, as displayed in Figure 4.17 aggregated for districts. It can be observed that with increasing specific final energy demand the absolute new connected demand increases as well. The three outliers, the districts 12, 21 and 23 highly increased their demand due to the new connection $\text{FED}^{\text{DH},2}$ and a lower specific heat demand. It can be determined, that the average connection length for these buildings is also above average. These districts are development areas with a high rate of newly constructed areas. Thus, the expansion of the existing district heating grid is economically viable. Additionally, the linear heat density[12] in these districts is above average.

Another trend is shown in Figure 4.18: The higher the specific heat demand, the higher the share $\frac{\text{FED}^{\text{DH},2}}{\text{FED}^{\text{DH},1}}$. This trend is almost linear.

$\text{FED}^{\text{DH},2035}$, $\text{FED}^{\text{DH},2015}$ denotes the final energy demand for district heating in the corresponding year.

[12]The linear heat density is defined as the ratio $\frac{\text{FED}^{\text{DH},2}}{\text{length}^{\text{DH-grid}}}$

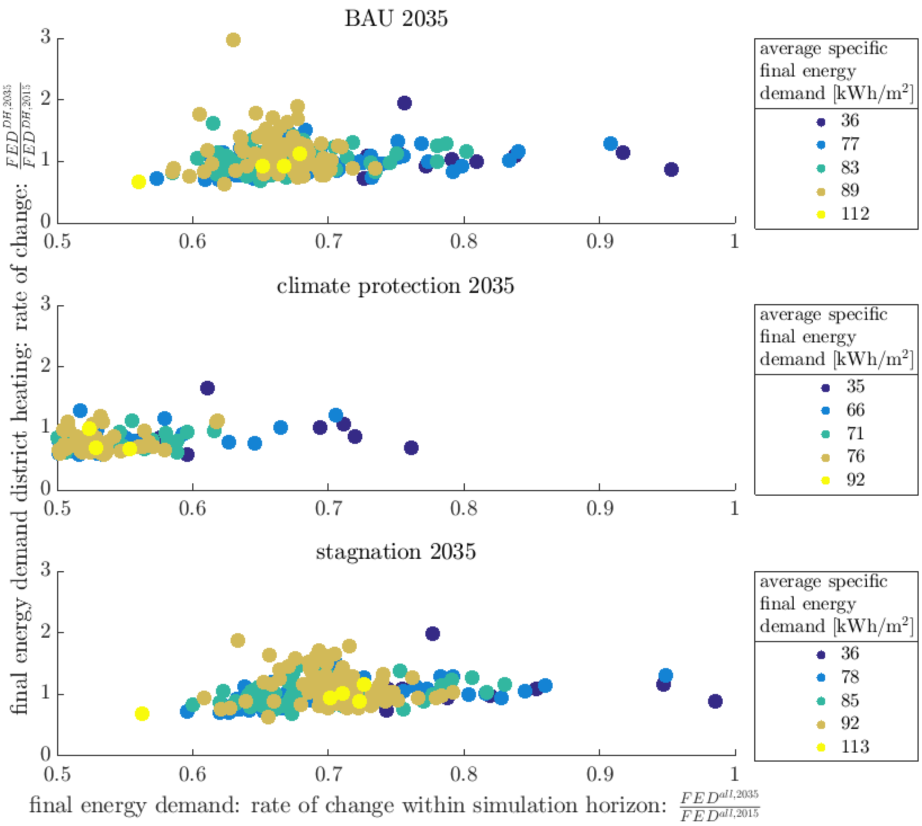

Figure 4.15: Spatial differences in rate of change of final energy demand and district heating for the registration districts and the average specific final energy demand for 2035 in comparison to the base year in [kWh/m2], Source: own illustration

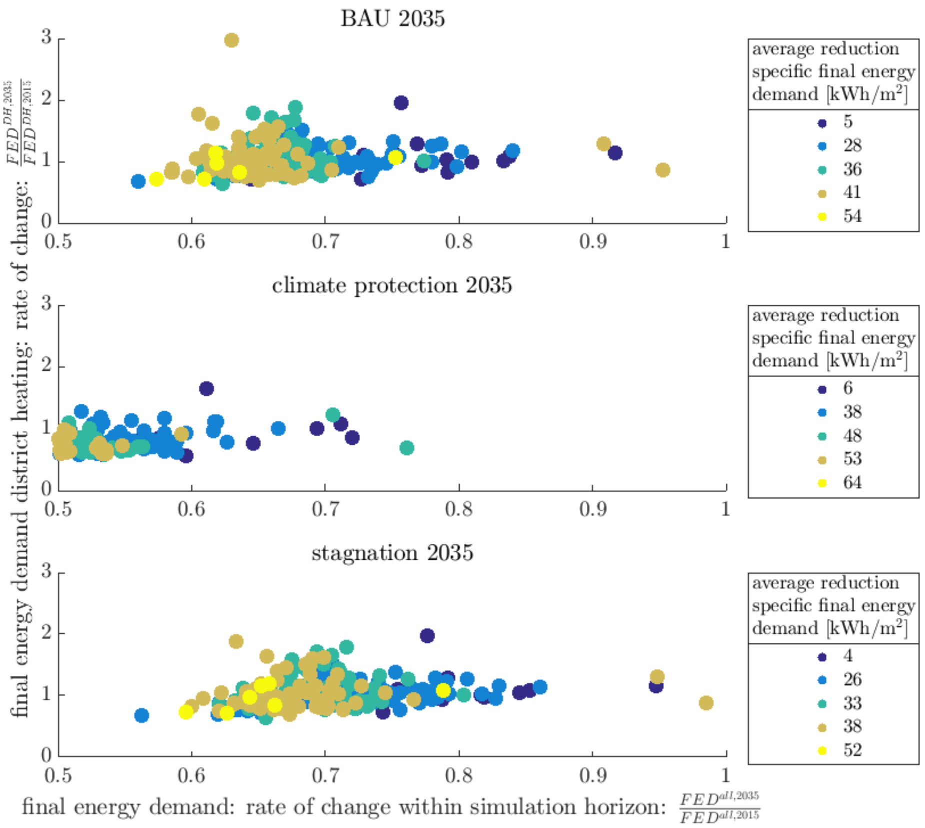

Figure 4.16: Spatial differences in rate of change of final energy demand and district heating for the registration districts and the average specific final energy demand reduction for 2035 in comparison to the base year in [kWh/m2], Source: own illustration

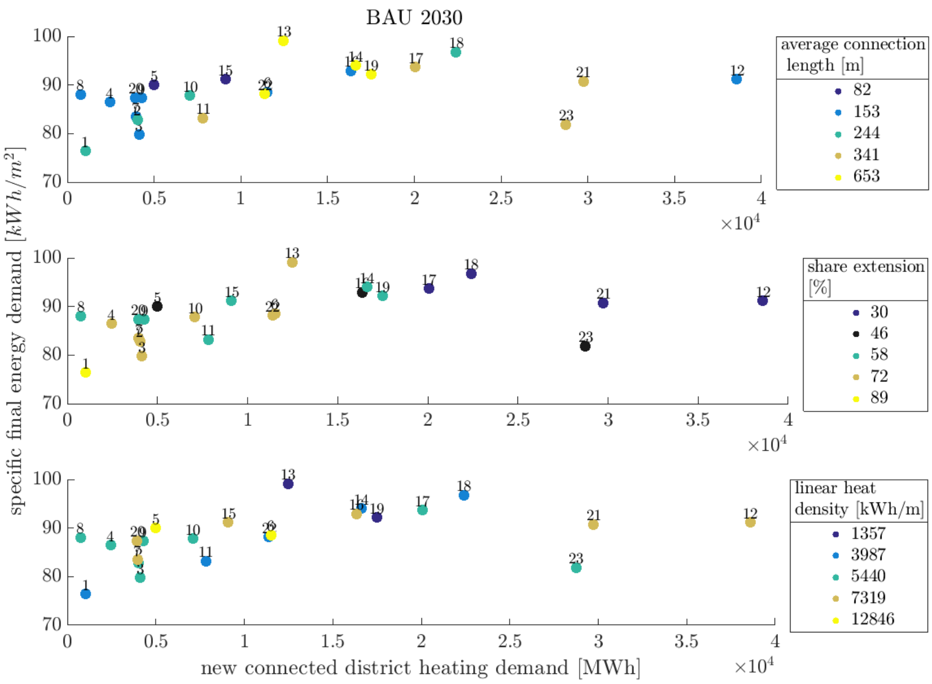

Figure 4.17: Spatial Differences of new connected demand in MWh and the average specific demand within districts, Source: own illustration

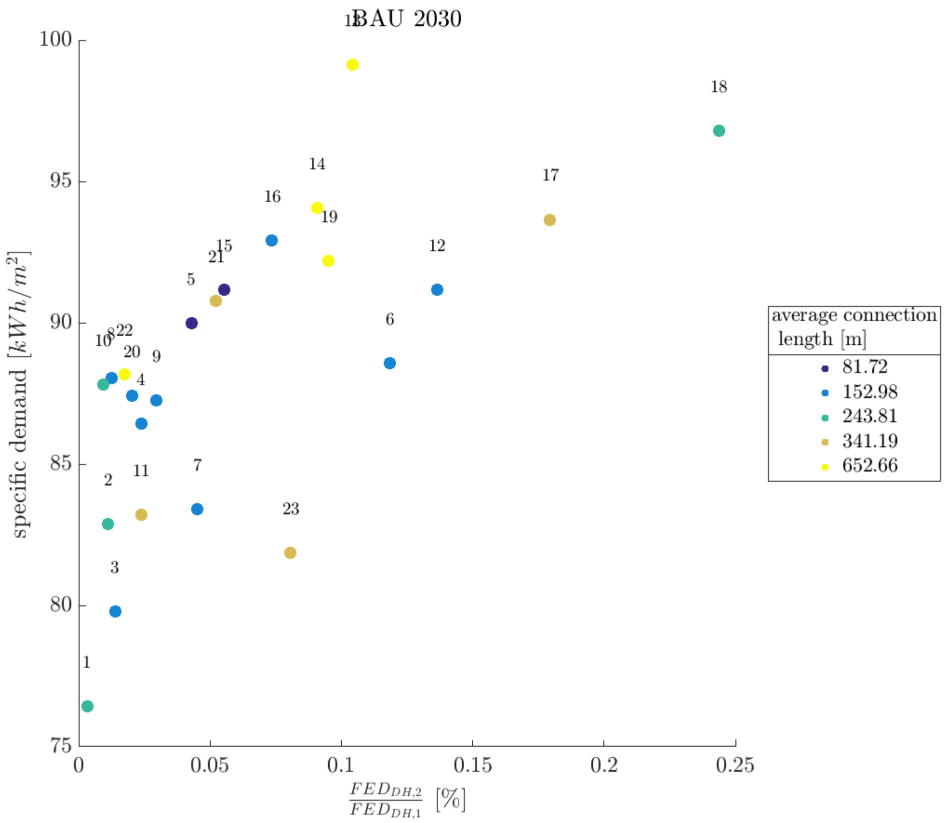

Figure 4.18: Relation of average specific heat demand and share of connected district heating demand $\frac{\text{FED}^{\text{DH},2}}{\text{FED}^{\text{DH},1}}$, Source: own illustration

4.3 Flexible change of grid-bound energy carriers

The current legislation in Austria obligates the gas distribution network operators according to § 59 GWG 2011 to contract consumers within their covered area if requested by the building owners or tenants. Thus, if a building is connected to the existing gas network, the operator is not allowed to cut the supply of natural gas for the consumer, even if e.g. another way of grid-bound heat supply like district heating would be guaranteed, if the consumer doesn't agree. Hence, in a lot of areas in Vienna (and also other cities/regions) two networks, gas and district heating, are still available and have to be maintained. Within the current legal framework the reduction of this double infrastructure is only possible, if the building owners decide to change the used energy carriers by investing in new technologies for space heating and domestic hot water. The following section analyses the hypothetical effects on the district heating and gas demand if this legal framework wouldn't exist. The objective is to maximize the revenues simultaneously from a gas and district heating network operators' point of view, including the costs for investments, reinvestments as well as for operation and maintenance. Thus, the costs for the maintenance of two grid-bound infrastructures should be reduced. Therefore it's assumed that the yearly replacement rate of heating technologies in buildings limits the demand per building block, where either district heating or gas can be substitute with the other energy carrier. This should guarantee that no additional costs for the building owners occur[13]. This replacement rate is a result from the existing simulation model for different building categories for all simulation years within the considered horizon. The replacement years for the scenarios are displayed in 4.7. The assumptions above imply that grid-bound heat supply is required, as long as the building owners demand for it, but the fictitious company operating both grid infrastructure may switch between the used energy carriers to supply customers with heat.

The analysis in this section is conducted for the climate protection-scenario and is

[13]This is not the case if no central heat distribution technology is installed in the building. Thus, in this case the switch wouldn't be possible without any additional investment in the required central distribution technology.

called adapted climate protection-scenario in the following. The used modelling approach is described in section 2.4.2.
Neglecting the current legal framework, the supplied district heating demand can be increased by 12 % in 2020 and up to 31 % in 2030. Figure 4.19 displays the absolute development of the connected district heating demand $FED^{DH,2}$. Thus, the share of district heating is 46 % in 2020 and 60 % in 2030. In general, there is a strong increase in the district heating demand up to 2020, a slow increase from 2020-2030 and after 2030, the reduction of the demand due to thermal refurbishments exceeds the additional potential of connection based on the substitution of gas by district heating. For the climate protection scenario, the reduction of the total connected district heating demand due to thermal refurbishments already starts after 2020.

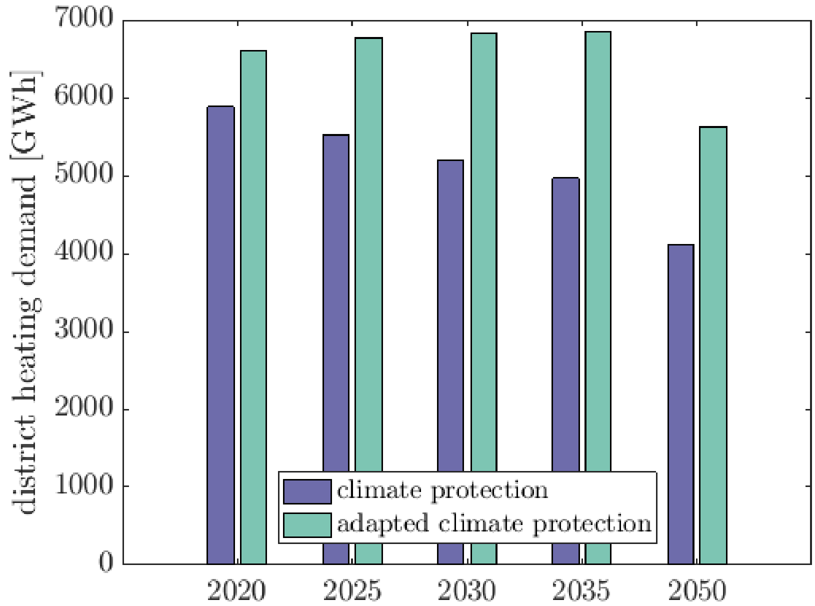

Figure 4.19: District heating demand $FED^{DH,2}$ for the climate protection-scenario and the adapted climate protection-scenario, Source: own illustration

Furthermore, the reduction of the CO_2-emissions can be increased to 81 % in comparison to the base year[14]. Switching from gas to district heating has advantages like reduced costs for the distribution of district heating. The levelized distribution

[14]The same emission factors as for the climate protection-scenario are assumed.

costs of heat for district heating can be reduced by 17 %, at the same time the costs for gas increase by 9 %. The comparison of the absolute values shows that the savings in the distribution costs for district heating (4.57 €/MWh) exceed the higher costs for gas distribution (0.48 €/MWh). This arises from the fact that a better utilisation of the existing district heating infrastructure and a better exploitation of the extension potential for district heating is possible. Overall, not required double infrastructure can be reduced. The higher costs for gas are due to higher specific operation and maintenance costs, as a big part of the infrastructure still has to be maintained by decreased demand. Considering the costs for both infrastructures simultaneously, the increased costs for gas can be balanced by the reduction for the distribution costs for district heating as the demand for district heating exceeds the gas demand.

In comparison to the previous versions of the scenarios, where the current legal framework is considered (see section 4.2.1), the share of extension and expansion of the existing district heating network changes within the considered horizon. Up to 2035, the share of extension in the adapted climate protection-scenario is quite high (54 % in 2020, 48 % in 2025, 44 % in 2035). The share of extension in the climate protection scenario is quite low, as the heat savings in the building stock exceed the extension potential (6 % in 2020, 7 % in 20, 14 % in 2035).

The spatial comparison of the two scenarios points out that under the given assumptions, most of the registration districts in Vienna are mainly supplied by district heating and the number of registration districts where the share of district heating in the total energy demand $\frac{\mathrm{FED}^{\mathrm{DH,2}}}{\mathrm{FED}^{\mathrm{Total}}}$ is above 80 % in 2050 increases from 55 to 100, shown in Figure 4.20. The figure also displays the dominating energy carrier (either district heating or gas). The dominating energy carrier per registration district is defined as the energy carrier with the higher share, e.g. if the share of district heating exceeds the share of gas, district heating is the dominating energy carrier. This visualization should support decision-makers, e.g. network operators, in identifying district heating target areas. These district heating areas are those areas where it is economically beneficial to support the extension and expansion of district heating.

Additionally, also the number of registration districts where no double infrastructure

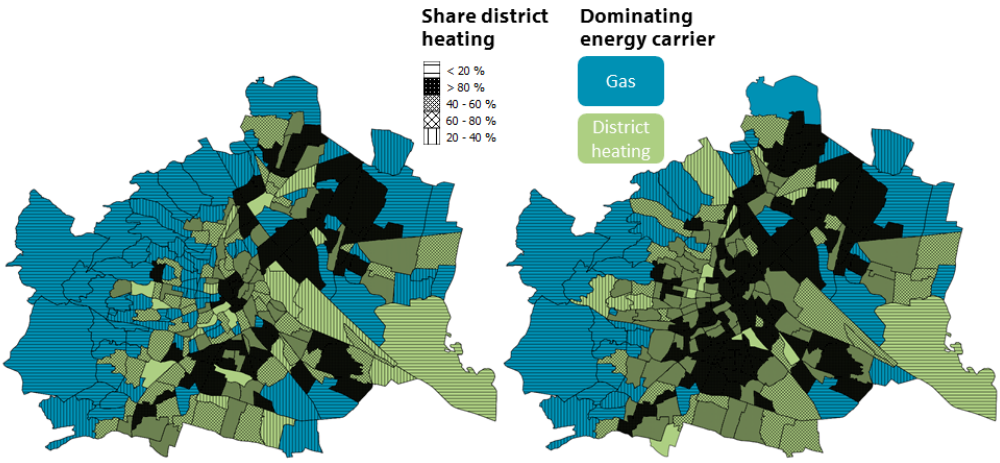

Figure 4.20: Registration districts in Vienna with their dominating energy carrier and the share of district heating for the climate protection (left) and the adapted climate protection-scenario (right), Source: own illustration

on block level has to be maintained increases. Table 4.6 displays these results. The table also shows the results for the adapted BAU-scenario. Even in the adapted version of the scenarios, no registration district can be supplied without gas in 2050, although the number of registration districts with a share of district heating above 80 % increases.

Table 4.6: Results regarding the reduction of double infrastructure for grid-bound heat supply on building block level in the year 2050 for the considered scenarios. Source: own calculations

	BAU	Climate protection	Adap. BAU	Adap. climate protection
Share building blocks with double infrastructure [%]	40	38	40	15
Share demand with double infrastructure [%]	58	30	53	4
Number of registration districts without double infrastructure on block level	7	13	9	61

4.4 Potentials and costs for further decrease of CO_2-emissions

With regards to the Paris Agreement, it is required to reduce CO_2-emissions dramatically up to 2050 and phase out fossil fuel consumption as far as possible. The analysis in the previous sections pointed out that even in the climate protection-scenario, the ambitious version of the considered scenarios, and the adapted climate protection-scenario, the decrease of CO_2-emissions from 2015 to 2050 is only 75 % resp. 81 % and still 25 % resp. 14 % of the total heat demand is covered by fossil fuels. In this context, this section deals with the following questions and evaluates the already analysed BAU- and climate protection-scenario and the adapted version of those scenarios as a post-analysis regarding the following research questions:

- Which share of gas demand can be replaced by other energy carriers from an economic point of view of the gas and district heating network operators?
- What costs would occur if the whole grid-bound gas demand should be supplied by other energy carriers?

- Where is an extension of the district heating grid useful and where is it better to replace gas by decentralized RES-H?

- To which extent could the CO_2-emissions be further reduced compared to the previous analysed scenarios, assuming that the whole grid-bound gas demand is supplied by other energy carriers?

4.4.1 Modelling approach and problem formulation

The current analysis is based on the results of the previous sections: First, on the results for the BAU- and climate protection-scenario (see section 4.2), where the problems regarding the current legislation, which does not allow gas suppliers to cut the supply of natural gas for consumers, even if e.g. another way of heat supply (e.g. district heating) would be guaranteed, were pointed out. Second, on the results of the adapted version of these scenarios (see section 2.4.2), where this constraint is relaxed and an annual replacement of the gas supply by district heating is allowed, if it is economically beneficial from the gas and district heating network operators' point of view. The limitation in this approach is given by the replacement rate of heating technologies in the building stock.

The level of detail of the analysis in this section is registration districts. The focus is on the identification of registration districts, where it is economically efficient from a gas and district heating network operators point of view to supply the remaining gas demand in 2050 by district heating and invest in the extension of the existing grid and which registration districts should be supplied by decentralized RES-H, i.e. heat pumps, solar thermal or biomass. From an economic point of view, assuming that the building owners' preferences for a certain energy carrier do not limit the network operators' investment decision, it can be economically viable to invest either in the extension of district heating or in decentral heating technologies in order to reduce the operation and reinvestment costs for the gas infrastructure. This means that a higher replacement rate of heating technologies in the building stock would be necessary. For the results in section 2.4.2 it is assumed that the replacement rate of heating systems in the building stock limits the change from natural gas to district heating. The economically viable potential of the gas demand, where a substitution by decentralized RES-H could be economically viable, was neglected. However, following the logic of what was said above, it could be rational for a fictitious gas and district heating grid operator to incentive the shift from gas to another energy carrier beyond this "natural" replacement rate.

The purpose of this analysis is on the one hand to point out the potential of cost reduction for district heating distribution[15] in general and on the other hand to show the additional costs if no grid-bound gas supply should occur for the supply of the buildings' heat and domestic hot water demand. The supply of the building stock's heat demand without gas also supports the goal to reduce the CO_2-emissions dramatically. The supply of the heat in the district heating grid and the options to decarbonise this supply in an economically optimal way e.g. was analysed in the URBEM^{DK}-context for the BAU- and climate protection-scenario by Nikolaus Rab Rab [2017]. The results of this study are taken into account in the study at hand.

The following steps are conducted and lead to new results for the already developed scenarios, the BAU- and climate protection-scenario and the adapted version of those scenarios (adapted BAU- and adapted climate protection-scenario).

- Identification of the remaining gas demand in 2050 for registration districts, where grid-bound gas supply is still available, for the BAU- and climate protection scenario according to section 4.2 and for the adapted BAU- and climate protection scenario according to section 2.4.2.
- Assume a gradual shift of this remaining gas demand between 2035-2050 to other energy carriers.
- Calculate the costs for district heating and decentral supply of this demand for each registration district.
- Identify registration districts where a change is economically beneficial under the condition that gas grid operators can cut the gas supply for some districts and replace it by e.g. district heating

[15] The reduction of the costs for gas distribution are out of scope as it is assumed in this analysis that the whole remaining gas demand has either been substituted by district heating or decentralized RES-H.

- Identify for each registration district the cheaper alternative - either extending the existing district heating infrastructure or investing in decentralized RES-H, assuming that natural gas supply is no option.

The costs for district heating and decentral supply are calculated as follows:

- District heating: The economic analysis compares the costs for investments in the extension of the existing district heating network, the required investments in district heating technologies in the buildings, the heat generation costs and the operation and maintenance costs for the new part of the district heating network on the one hand with the operation and reinvestment costs for the gas infrastructure and the gas price in each registration district on the other hand. The capital expenses for decentral gas boilers are neglected as the analysis assumes that these technologies are already installed in the building stock. A replacement is required in any case as the approach considers the substitution of all the remaining gas demand.
  - The specific levelized costs for district heating technologies in the buildings are assumed to be 16 €/MWh and include the costs for investments in the district heating technologies as well as the costs for the house connection for district heating.[16]
  - The heat generation costs for district heating are assumed to be 35 €/MWh. These values are taken from Rab [2017].
  - The remaining cost components (investments in extension, operation- and maintenance costs for district heating network, reinvestment costs for gas and operation and maintenance costs for gas grid) are calculated based on the output of the optimization model.
- Decentral Supply: The remaining gas demand of one registration district can be changed to decentral heat technologies from an economic point of view if the savings from the not required operation- and maintenance costs as

[16] Costs calculated based on the results of the existing simulation model. The average load of the remaining gas boilers is 40 kW, with an average final energy demand about 50 MWh. Interest rate: 4.5 %, investment costs 14000 €

well as reinvestment costs for the gas infrastructure are compensated with decentralized RES-H at the customer side. Thus, the customers would need to be financially supported by the gas grid operator to change their heating technologies before the lifetime of the system expires.

– Here, it is assumed to use pellets for the decentral supply. The specific levelized costs for decentral RES-H in the buildings are assumed to be 77 €/MWh for the scenarios and include the investment as well as the energy and operation and maintenance costs. The calculation is conducted as follows: The investment costs are assumed to be 20000 €%[17]. The investment costs are assumed for a heat load of 40 kW - this is the average heat load of the all building classes still connected to the gas infrastructure in 2050 as a result of the integrated modelling approach. Assuming a lifetime of 28 years, an interest rate about 4.5 %, the assumed average biomass energy prices between 2035 and 2050 (as input data of the simulation model) and an average gas demand in 2050 about 50 MWh per building[18], it results in specific levelized costs of heat about 77 €/MWh.

The specific CO_2-emissions for district heating and decentral supply are assumed resp. calculated as follows:

- District heating: The average values between 2035-2050 for the BAU- and climate protection scenario from Rab [2017] are used (see description in 3.4.3), where the options to decarbonise the district heating supply are analysed in an economically optimal way. The specific averaged CO_2-emissions are as follows:
  - (adapted) BAU-scenario: 0.07 kg/kWh
  - (adapted) climate protection-scenario:0.05 kg/kWh

[17] These values are based on the Invert/EE-Lab Input database, assuming a cost degradation of 27%, see i.a. Müller and Kranzl [2013], Müller and Kranzl [2015] and Müller [2015].

[18] The average gas demand of all building classes still connected to the gas infrastructure in 2050 is assumed as a result of the integrated modelling approach.

- Decentral Supply: For the decentralized RES-H option, the specific CO_2-emissions are calculated as weighted average for the renewable heating technologies used in the years 2035-2050, based on the results of the existing simulation model. Thus the specific CO_2-emission factors for the single energy carriers are used according to table 3.12 and are multiplied with the corresponding demand, simulated for the years 2035-2050.

4.4.2 Results

Under the assumed framework conditions, the economic potential to reallocate the whole gas demand from one registration district to either district heating is almost negligible. Table 4.7 displays the detailed numbers for the remaining gas demand before the reallocation in the year 2050 and the demand where a reallocation to decentralized RES-H is economically beneficial. That means that no additional costs are required to substitute the remaining gas demand. Additionally, the reallocation due to the objective to substitute the whole gas demand with either district heating or decentralized RES-H is shown.

The reason for the low potential, where district heating can be substituted from a district heating network operators' economic point of view, is that apart from the additional maintenance costs, investments in the decentralized district heating technologies in the building stock and the extension of the existing grid infrastructure are required. Under the assumptions in this analysis, these costs exceed the savings from the maintenance and reinvestment costs from the gas infrastructure. It only could be economically beneficial to substitute gas with district heating if a building block is connected to both infrastructures and just the costs for the decentral heating technologies for district heating and operation and maintenance occur.

Assuming that the whole remaining gas demand in 2050 has to be supplied by either district heating or decentralized RES-H, the highest potential for a reallocation to district heating occurs in the BAU- and climate protection scenarios, as these scenarios have the highest demand of gas remaining and a lot of building blocks are supplied by district heating and gas (see also table 4.6). In the adapted climate protection scenario, almost nothing of the remaining gas demand is reallocated to district heating. This means that the economic potential for district heating in the adapted climate protection-scenario is reached. The adapted BAU-scenario shows a minor district heating potential. That means that the assumed replacement rate of heating technologies as restriction in the previous analysis in the building stock is restrictive in this case.

Table 4.7: Economically viable energetic potential for reallocation of gas demand either to decentralized RES-H or district heating. Calculation based on registration districts and summarized. Source: own calculations

	BAU	Adap. BAU	Climate protection	Adap. climate protection
Remaining gas demand in 2050 [GWh]	3402	2293	2203	1203
Economic potential district heating [GWh]		1	5.6	3.5
Economic potential decentralized RES-H [GWh]	77	48	184	170
Reallocation district heating [GWh]	1796	237	98	8
Reallocation decentralized RES-H [GWh]	1605	1586	1762	1196

Table 4.8 points out the costs for the substitution of the remaining gas demand either by decentralized RES-H or by district heating. It can be determined, that the total levelized costs for heat generation (including demand, distribution and supply) in comparison to the BAU-scenario decrease for all scenarios. This is a result from the lower remaining gas demand in the other scenarios compared to the BAU-scenario, which has to be substituted. The additional costs in comparison to the grid-bound gas supply are lower for the adapted approaches for the scenarios. This is a result from the new perspective considered in the used modelling approach. The network operators are allowed to supply a share of the gas demand by district

heating and thus the utilization of the existing district heating infrastructure is more efficient (see also section 4.3 for more detailed results). The comparison of

Table 4.8: Comparison of the additional required cost for the substitution of the remaining gas demand in 2050 by the cost optimal option per registration district - either district heating or decentralized RES-H. Source: own calculations

	BAU	Adap. BAU	Climate protection	Adap. climate protection
Total discounted costs in Mio. €	240	137	201	92

the CO_2-emissions is displayed in figure 4.21. The figure shows the decrease of the CO_2-emissions from 2015 to 2050 for the scenarios. The potential of reducing the emissions is pointed out with (1) remaining gas demand in 2050 and (2) no remaining gas demand in 2050.

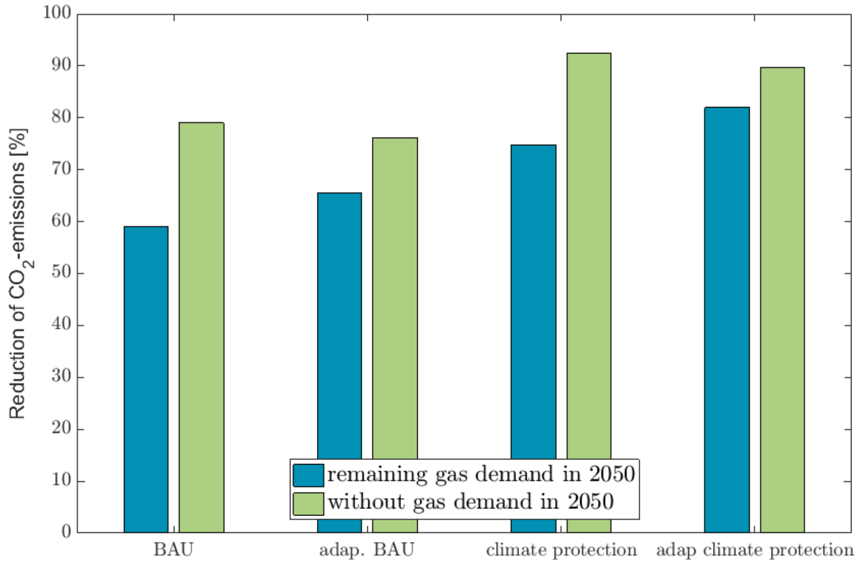

Figure 4.21: Decrease of the CO_2-emissions from 2015 to 2050 for the scenarios. The potential of reducing the emissions are pointed out with remaining gas demand in 2050 (results from the analysis in the previous sections) and without any remaining gas demand in 2050 (results of this section). Source: own illustration

Based on the results of this section, target areas for district heating can be identified. These are registration districts where the remaining gas demand is reallocated to district heating for both scenarios, the BAU- and climate protection scenario. That means that in both scenarios, the extension of the existing infrastructure is the economically viable alternative compared to decentralized RES-H supply, assuming that the whole remaining gas demand has to be supplied by another energy carrier. Figure 4.22 shows these target areas for both versions of the scenarios, the original version and the adapted version.

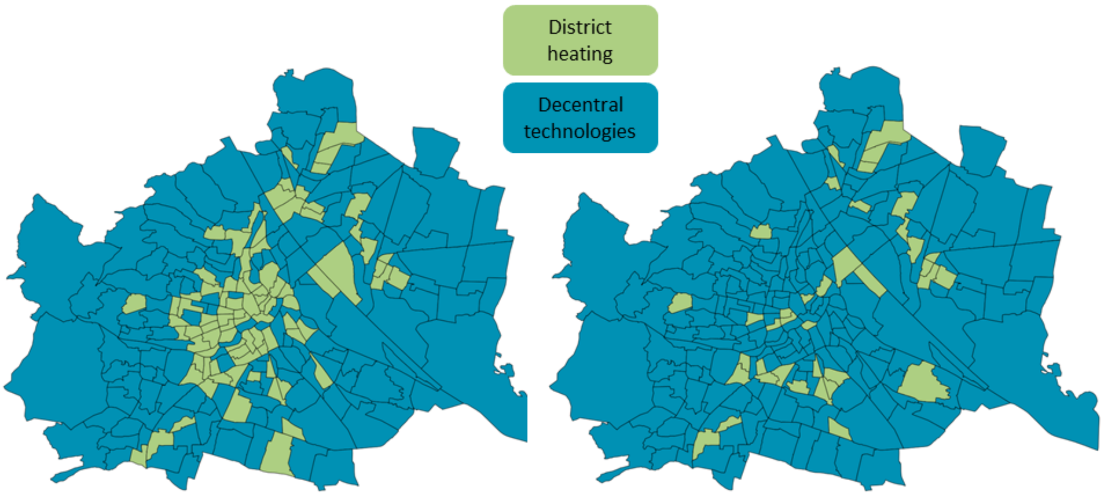

Figure 4.22: Spatial assignment of registration districts, where the remaining gas demand is allocated to district heating or decentralized RES-H for both scenarios, the BAU- and climate protection scenario. The figures differs in the assumptions regarding the legislative: the original versions of the scenarios, where the building owners investment decision limit the district heating potential (left) and the adapted version of the scenarios, where a change of the grid-bound supply is allowed (right). Source: own illustration

In the case of the adapted version of the scenario, the previous analysis in section 4.3 also pointed out district heating target areas (see figure 4.20). These target areas were defined as registration districts, where the efficiency of the existing district heating infrastructure can be increased by substituting remaining gas demand by district heating. The results of this previous analysis serve as input data for the adapted version of the scenarios in this analysis and thus also the target areas from the previous analysis have to be considered. A detailed list for all registration districts and scenarios with the share of district heating before and after the reallocation in 2050 can be found in the tables A.4 and A.5 in appendix A.

CHAPTER 5

Discussion and Conclusions

The analysis conducted in this thesis describes the impact of the three URBEM^{DK}-scenarios on the economy of the buildings' space heating and domestic hot water demand and it's grid-bound supply. The scenarios mainly differ in the underlying assumptions regarding the future development of the energy prices and subsidies for thermal refurbishments and the installation of heating technologies in the building stock under the current legislation. These assumptions influence the development of the building stock's space heating and domestic hot water demand up to 2050. The BAU-scenario points out a reduction of the heat demand of 29 %, whereas in the ambitious climate protection-scenario the demand decreases by 44 % up to 2050. The lowest climate mitigation efforts can be seen in the stagnation scenario, where the demand declines by 26 %. All the scenarios consider both the existing building stock and the newly constructed areas. Regarding the impacts on the grid-bound heat supply, two effects are analysed: First, the share of district heating and gas in the total energy demand up to 2050. Second, the levelized distribution costs for district heating and gas. In general, the share of district heating and gas in the total buildings' heat demand is almost the same for all scenarios, but the scenarios differ regarding the levelized distribution costs for district heating and gas. The additional decrease of 21 % in the overall energy demand in the year 2050 in the climate protection-scenario in comparison to the BAU-scenario results in an increase of the specific levelized costs of heat distribution for district heating by 10 % and for gas by 9 %. The stagnation-scenario, which results in 4 % higher final energy demand in the year 2050, shows cost reductions of the specific levelized district heating distribution costs for district heating in amount of 4% and in amount of 1 % for gas.

Concluding, the lower the final energy demand for space heating and domestic hot water is, the higher are the specific heat distribution costs for district heating and gas and vice versa. Especially the case of the stagnation-scenario shows that the economic viability of district heating increases more than the viability of gas. The reason for this effect is that the investment costs in district heating grids are more effective due to the higher heat demand. Although the same effects in the case of gas can be observed, the saving potential for the specific distribution costs for the gas network is limited. The reason is that the yearly decrease of the gas demand based on the building owners investment decisions exceeds the decrease of the district heating demand. Thus, from an economic point of view, considering the economy of the existing gas and district heating infrastructure simultaneously, it makes sense to support the development of district heating areas, where increasing demand is expected due to newly constructed areas as well as extension of the existing grid infrastructure.

Apart from the effects on the heat distribution costs, the assumptions of the three scenarios also affect the total costs for the heat energy system. The cost calculation considers the building stock and the grid-bound supply. These costs include, besides the heat distribution costs, also the annual energy costs and operation and maintenance costs in the building stock for space heating and domestic hot water, the investment costs in the building stock for renovations and the installation of heating systems as well as the public costs. The public costs express the costs for support programmes regarding subsidies for thermal refurbishments and the installation of heating systems. In this sense, the total costs for the climate protection-scenario exceed those of the BAU-scenario by 3 %, the costs in the stagnation-scenario are 2 % lower than in the BAU-scenario. Considering the effect on the CO_2-emissions of the three scenarios, the results show that even in the ambitious climate protection scenario the share of gas is about 25 % in the year 2050 and contradicts the aim of a decarbonisation of our energy system until mid of the century. The reduction of the CO_2-emissions in the three scenarios varies between 56% (stagnation-scenario) and 73 % (climate protection-scenario) from 2015 to 2050.

Concluding, the possible developments analysed for the three scenarios show that, especially in regards to the Paris Agreement, further efforts regarding the decarbonisation are needed and thus fossil fuel consumption should phase out as far as possible. As the reduction of the CO_2-emissions should be achieved at low costs, or even accompanied with economic advantages, the summary above suggests that the costs for double infrastructure should be decreased. A further increase of district heating is only possible if the current legislation in Austria changes: The current legislation doesn't allow gas suppliers to cut the supply of natural gas for consumers, even if another way of heat supply, in the case of this analysis the supply by district heating, would be guaranteed. Thus, the substitution of the gas demand by district heating should be endeavoured.

Therefore, I added another scenario assuming that the modelling approach, where the building owners determine the maximum possible potential for district heating, is adapted. It is assumed that a change of the used grid-bound energy carrier is possible under certain constraints. That means that a substitution of district heating with gas is allowed if it is economically beneficial from a gas and district heating network operator's point of view and if no additional costs for the building owners occur. This is ensured by an annual limitation of the demand possible for substitution not exceeding the annual demand determined by the replacement rate of heating technologies in the building stock. The results show that the specific levelized costs of heat for the adapted version of the climate protection-scenario can be reduced by 17 % in comparison to the climate protection-scenario due to a better utilisation of the existing district heating infrastructure which leads to higher efficiency. Additionally, a reduction of CO_2-emissions by 81 % in the year 2050 in comparison to the base year 2015 is possible.

Concluding, the results point out further economic potential for district heating which would be also beneficial regarding the CO_2-emissions with no additional costs. This approach also leads to the conclusion that the identification of target areas with a high potential for district heating due to a better utilisation of the existing infrastructure is essential for a sustainable dimensioning of the future heating energy system.

A final analysis points out the additional costs to substitute the whole remaining gas demand in the year 2050 by technologies based on renewables. Thus the costs for district heating or decentralized RES-H are compared for each registration district. The results show, depending on the scenario, that the additional potential for district heating varies between 0 % in the adapted version of the climate protection-scenario and 19 % in the BAU-scenario. A spatial distinction, where to extend the existing district heating infrastructure and where to invest in decentralized RES-H, is essential. The additional costs are lower for the climate protection-scenario and even lower for the adapted version of the climate-protection scenario, where the current legislation regarding the obligation of gas distribution operators is neglected. But a comparison of the total costs for space heating and domestic hot water demand in the building stock as well as for heat distribution for all analysed scenario, the BAU-, adapted BAU-, climate protection- and adapted climate protection-scenario, points out the following effects: the savings for the distribution costs can not compensate for the higher total costs for the whole considered heat energy system, as the investment costs in buildings and the annual energy costs in buildings have the highest shares of these costs. Thus, the BAU-scenario remains the scenario with the lowest involved costs. But in the adapted versions of the scenarios, especially for the adapted climate protection-scenario, a reduction of CO_2-emission by 88 % is possible from 2015 until 2050. This is associated by moderate additional costs of 5.7 %. Additionally, it has to be mentioned, that the underlying high energy prices in the climate protection-scenario compared to those in the BAU-scenario lead to substantial higher annual energy costs.

Concluding, considering the mentioned approaches and significant aspects regarding the heating energy system, the results of this thesis show that district heating can contribute to an essential reduction of the space heating and domestic hot water related CO_2-emissions in the building stock up to 88 %. Nevertheless, it has to be ensured that the supply of heat in the district heating grid is possible and the decarbonisation of this supply in an economically optimal way is an aim. However, the heat supply of district heating was not focus of this thesis and is covered in more detail in the PhD-thesis within the URBEM^{DK} in Rab [2017]. From an economic point of view, it can be economically beneficial from a gas and district heating network operator's point of view, especially if there is an already existing infrastructure. A spatial analysis of the future development of the buildings' heat demand and the identification of target areas for district heating then can increase the efficiency of the existing infrastructure and reduce the costs for heat distribution. Therefore, the dismantling of two grid-bound infrastructures is most important.

APPENDIX A

Detailed Results

Table A.4: The share of district heating for the two versions of the BAU-scenario before the reallocation of the remaining gas demand and after. Source: own calculations

	BAU-scenario			adapted BAU-scenario		
reg. district	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]
101	72	92	DH	89	89	dec
102	69	87	DH	83	83	dec
103	89	100	DH	98	98	dec
104	90	98	DH	95	95	dec
105	83	96	DH	93	93	dec
106	92	100	DH	100	100	DH
107	85	97	DH	95	95	dec
201	97	97	dc	100	100	DH
202	71	71	dc	95	95	dec
203	75	100	DH	98	98	dec
204	76	100	DH	100	100	DH
205	73	100	DH	100	100	dec

	BAU			adapted BAU		
reg. district	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]
206	41	41	dc	66	66	dec
207	78	78	dc	100	100	DH
208	33	33	dc	40	40	dec
209	96	100	DH	100	100	DH
210	53	53	dc	56	56	dec
301	42	90	DH	78	92	DH
302	49	49	dc	74	74	dec
303	78	100	DH	100	100	dec
304	12	12	dc	51	51	dec
305	58	99	DH	87	100	DH
306	62	95	DH	89	95	DH
307	57	57	dc	72	72	dec
308	88	88	dc	98	98	dec
309	48	96	DH	87	97	DH
310	69	69	dc	91	91	dec
311	86	86	dc	90	90	dec
401	90	100	DH	100	100	DH
402	51	90	DH	84	91	DH
403	40	84	DH	74	86	DH
404	31	84	DH	68	87	DH
501	48	90	DH	82	91	DH
502	55	91	DH	83	92	DH
503	29	77	DH	66	66	dec
504	30	80	DH	71	83	DH
601	43	89	DH	78	78	dec
602	56	97	DH	88	88	dec
603	48	92	DH	82	82	dec
701	35	86	DH	77	88	DH

	BAU			adapted BAU		
reg. district	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]
702	90	100	DH	100	100	DH
703	66	99	DH	93	99	DH
704	32	83	DH	72	72	dec
705	21	75	DH	63	79	DH
801	60	60	dc	90	90	dec
802	39	86	DH	77	88	DH
803	23	76	DH	62	80	DH
901	67	100	DH	95	100	DH
902	52	98	DH	87	87	dec
903	52	89	DH	79	90	DH
904	34	82	DH	65	65	dec
905	47	86	DH	74	88	DH
906	61	86	DH	80	87	DH
1001	77	77	dc	82	82	dec
1002	87	87	dc	100	100	DH
1003	93	100	DH	100	100	DH
1004	100	100	DH	100	100	DH
1005	76	100	DH	98	98	dec
1006	82	82	dc	100	100	dec
1007	74	99	DH	96	99	DH
1008	85	85	dc	100	100	dec
1009	100	100	DH	100	100	DH
1010	91	91	dc	100	100	DH
1011	77	77	dc	87	87	dec
1012	72	72	dc	75	75	dec
1013	73	73	dc	89	89	dec
1014	71	71	dc	75	75	dec
1015	59	59	dc	74	74	dec

	BAU			adapted BAU		
reg. district	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]
1016	34	34	dc	49	49	dec
1017	34	34	dc	39	39	dec
1018	36	36	dc	43	43	dec
1019	42	82	DH	69	69	dec
1020	100	100	DH	100	100	DH
1021	82	99	DH	97	97	dec
1022	73	73	dc	93	93	dec
1023	76	93	DH	91	92	DH
1101	52	52	dc	57	57	dec
1102	70	70	dc	89	89	dec
1103	53	88	DH	80	80	dec
1104	32	32	dc	48	48	dec
1105	90	90	dc	98	98	dec
1106	0	0	dc	12	12	dec
1107	56	56	dc	73	73	dec
1108	75	75	dc	74	74	dec
1109	100	100	dc	100	100	DH
1110	92	92	dc	100	100	dec
1111	54	54	dc	73	73	dec
1112	34	34	dc	37	37	dec
1113	47	47	dc	65	65	dec
1201	40	40	dc	72	72	dec
1202	60	60	dc	80	80	dec
1203	100	100	DH	100	100	DH
1204	35	77	DH	69	79	DH
1205	47	92	DH	83	94	DH
1206	36	81	DH	72	84	DH
1207	100	100	DH	100	100	DH

	BAU			adapted BAU		
reg. district	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]
1208	48	80	DH	75	75	dec
1209	100	100	DH	100	100	DH
1210	52	52	dc	71	71	dec
1211	41	41	dc	69	69	dec
1301	47	74	DH	71	71	dec
1302	16	16	dc	31	31	dec
1303	7	7	dc	31	31	dec
1304	7	7	dc	9	9	dec
1305	5	5	dc	10	10	dec
1306	7	7	dc	16	16	dec
1307	56	56	dc	70	70	dec
1308	44	44	dc	68	68	dec
1309	46	46	dc	56	56	dec
1310	20	20	dc	20	20	dec
1311	0	0	dc	0	0	dec
1401	40	83	DH	74	85	DH
1402	15	74	DH	52	77	DH
1403	22	22	dc	58	58	dec
1404	52	87	DH	77	77	dec
1405	23	23	dc	35	35	dec
1406	30	30	dc	56	56	dec
1407	0	0	dc	0	0	dec
1408	13	13	dc	33	33	dec
1409	66	79	DH	79	79	DH
1410	20	20	dc	38	38	dec
1411	2	2	dc	4	4	dec
1412	9	9	dc	15	15	dec
1501	46	84	DH	75	85	DH

	BAU			adapted BAU		
reg. district	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]
1502	43	86	DH	77	89	DH
1503	32	80	DH	67	83	DH
1504	71	100	DH	98	98	dec
1505	50	92	DH	84	94	DH
1506	32	80	DH	67	82	DH
1507	47	47	dc	72	72	dec
1601	23	75	DH	63	63	dec
1602	27	27	dc	62	62	dec
1603	63	88	DH	80	88	DH
1604	51	95	DH	86	98	DH
1605	24	74	DH	61	61	dec
1606	84	100	DH	100	100	dec
1607	50	88	DH	80	89	DH
1608	44	44	dc	60	60	dec
1609	8	8	dc	16	16	dec
1610	36	86	DH	76	76	dec
1701	37	84	DH	74	87	DH
1702	35	81	DH	71	71	dec
1703	43	86	DH	76	76	dec
1704	30	30	dc	48	48	dec
1705	5	5	dc	13	13	dec
1706	6	6	dc	19	19	dec
1801	18	18	dc	26	26	dec
1802	18	72	DH	52	52	dec
1803	35	80	DH	69	69	dec
1804	31	31	dc	61	61	dec
1805	10	10	dc	30	30	dec
1901	15	15	dc	36	36	dec

	BAU			adapted BAU		
reg. district	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]
1902	61	87	DH	82	82	dec
1903	26	26	dc	35	35	dec
1904	46	87	DH	77	77	dec
1905	24	24	dc	46	46	dec
1906	11	11	dc	26	26	dec
1907	19	19	dc	36	36	dec
1908	62	100	DH	90	100	DH
1909	37	37	dc	60	60	dec
1910	32	32	dc	43	43	dec
2001	79	79	dc	83	83	dec
2002	62	90	DH	83	83	dec
2003	28	78	DH	67	67	dec
2004	71	99	DH	89	98	DH
2005	31	84	DH	69	69	dec
2006	55	87	DH	80	80	dec
2007	79	96	DH	92	92	dec
2008	32	32	dc	61	61	dec
2101	18	18	dc	18	18	dec
2102	71	71	dc	75	75	dec
2103	100	100	DH	100	100	DH
2104	25	25	dc	36	36	dec
2105	85	85	dc	86	86	dec
2106	17	17	dc	34	34	dec
2107	39	39	dc	55	55	dec
2108	66	66	dc	79	79	dec
2109	100	100	DH	100	100	DH
2110	100	100	DH	100	100	DH
2111	70	70	dc	83	83	dec

	BAU			adapted BAU		
reg. district	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]
2112	80	80	dc	86	86	dec
2113	43	43	dc	51	51	dec
2114	0	0	dc	0	0	dec
2115	30	30	dc	49	49	dec
2116	28	28	dc	28	28	dec
2117	83	96	DH	92	92	dec
2118	83	100	DH	100	100	DH
2119	44	44	dc	63	63	dec
2120	87	87	dc	93	93	dec
2121	53	88	DH	76	76	dec
2122	40	77	DH	69	69	dec
2123	45	87	DH	80	89	DH
2124	27	27	dc	45	45	dec
2125	70	70	dc	79	79	dec
2126	73	99	DH	92	99	DH
2127	0	0	dc	0	0	dec
2128	54	54	dc	62	62	dec
2129	8	65	DH	42	68	DH
2130	0	0	dc	0	0	dec
2201	21	21	dc	25	25	dec
2202	12	12	dc	16	16	dec
2203	3	3	dc	5	5	dec
2204	41	41	dc	44	44	dec
2205	65	65	dc	70	70	dec
2206	94	94	dc	94	94	dec
2207	73	73	dc	75	75	dec
2208	84	84	dc	89	89	dec
2209	100	100	DH	100	100	DH

	BAU			adapted BAU		
reg. district	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]
2210	80	80	dc	86	86	dec
2211	91	100	DH	100	100	DH
2212	40	40	dc	42	42	dec
2213	100	100	DH	100	100	DH
2214	30	30	dc	46	46	dec
2215	100	100	DH	100	100	DH
2216	63	63	dc	75	75	dec
2217	4	4	dc	8	8	dec
2218	100	100	DH	100	100	DH
2219	100	100	DH	100	100	DH
2220	81	81	dc	86	86	dec
2221	23	23	dc	22	22	dec
2222	100	100	DH	100	100	DH
2223	52	52	dc	60	60	dec
2224	61	61	dc	60	60	dec
2225	9	9	dc	11	11	dec
2226	1	1	dc	2	2	dec
2227	32	32	dc	36	36	dec
2228	24	24	dc	47	47	dec
2229	8	8	dc	13	13	dec
2230	10	10	dc	9	9	dec
2231	52	83	DH	81	84	DH
2232	76	76	dc	84	84	dec
2301	39	39	dc	54	54	dec
2302	36	36	dc	47	47	dec
2303	1	1	dc	10	10	dec
2304	48	48	dc	63	63	dec
2305	61	61	dc	79	79	dec

	BAU			adapted BAU		
reg. district	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]
2306	56	56	dc	75	75	dec
2307	88	100	DH	100	100	DH
2308	53	53	dc	56	56	dec
2309	25	25	dc	39	39	dec
2310	50	50	dc	77	77	dec
2311	65	100	DH	90	100	DH
2312	45	45	dc	59	59	dec
2313	7	7	dc	13	13	dec
2314	10	10	dc	21	21	dec
2315	3	3	dc	8	8	dec
2316	23	23	dc	31	31	dec
2317	64	64	dc	73	73	dec
2318	47	47	dc	65	65	dec
2319	95	100	DH	100	100	DH

Table A.5: The share of district heating for the two versions of the climate protection-scenario before the reallocation of the remaining gas demand and after. Source: own calculations

	climate protection-scenario			adapted climate protection-scenario		
reg. district	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]
101	71	86	DH	86	86	dec
102	66	66	dec	78	78	dec
103	87	95	DH	94	94	dec

	BAU			adapted BAU		
reg. district	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]
104	87	96	DH	95	95	dec
105	81	91	DH	89	89	dec
106	94	100	DH	100	100	DH
107	84	93	DH	93	93	dec
201	100	100	DH	100	100	DH
202	74	74	dec	91	91	dec
203	77	94	DH	95	95	dec
204	78	100	DH	100	100	DH
205	74	95	DH	95	95	dec
206	39	39	dec	64	64	dec
207	80	80	dec	97	97	dec
208	37	37	dec	44	44	dec
209	100	100	DH	100	100	DH
210	52	52	dec	55	55	dec
301	43	80	DH	79	79	dec
302	48	48	dec	70	70	dec
303	79	79	dec	99	99	dec
304	13	13	dec	52	52	dec
305	64	94	DH	93	93	dec
306	64	88	DH	88	88	dec
307	59	59	dec	74	74	dec
308	87	87	dec	99	99	dec
309	49	84	DH	85	85	dec
310	71	71	dec	88	88	dec
311	86	86	dec	89	89	dec
401	90	90	dec	100	100	DH
402	49	79	DH	81	81	dec
403	40	73	DH	73	73	dec

	BAU			adapted BAU		
reg. district	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]
404	28	69	DH	68	68	dec
501	49	81	DH	82	82	dec
502	56	83	DH	83	83	dec
503	30	68	DH	68	68	dec
504	28	67	DH	69	69	dec
601	40	40	dec	75	75	dec
602	60	60	dec	90	90	dec
603	50	82	DH	82	82	dec
701	35	72	DH	75	76	DH
702	99	100	DH	100	100	DH
703	67	90	DH	91	92	DH
704	30	68	DH	69	69	dec
705	21	62	DH	64	64	dec
801	61	61	dec	89	89	dec
802	38	73	DH	74	74	dec
803	22	62	DH	60	60	dec
901	70	97	DH	98	98	dec
902	53	53	dec	89	89	dec
903	53	80	DH	80	80	dec
904	33	33	dec	66	66	dec
905	46	76	DH	74	74	dec
906	62	82	DH	82	82	dec
1001	76	76	dec	80	80	dec
1002	89	89	dec	100	100	DH
1003	99	100	DH	100	100	DH
1004	100	100	DH	100	100	DH
1005	79	79	dec	98	98	dec
1006	86	86	dec	100	100	dec

	BAU			adapted BAU		
reg. district	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]
1007	79	96	DH	96	96	dec
1008	90	90	dec	100	100	DH
1009	100	100	DH	100	100	DH
1010	94	94	dec	100	100	DH
1011	80	80	dec	91	91	dec
1012	82	82	dec	82	82	dec
1013	76	76	dec	85	85	dec
1014	72	72	dec	75	75	dec
1015	59	59	dec	76	76	dec
1016	36	36	dec	55	55	dec
1017	35	35	dec	45	45	dec
1018	39	39	dec	45	45	dec
1019	44	79	DH	74	74	dec
1020	100	100	DH	100	100	DH
1021	88	100	DH	100	100	DH
1022	75	75	dec	90	90	dec
1023	82	94	DH	94	94	DH
1101	62	62	dec	67	67	dec
1102	70	70	dec	89	89	dec
1103	54	82	DH	80	80	dec
1104	31	31	dec	52	52	dec
1105	94	94	dec	100	100	DH
1106	0	0	dec	0	0	dec
1107	55	55	dec	75	75	dec
1108	85	85	dec	82	82	dec
1109	100	100	DH	100	100	DH
1110	97	97	dec	100	100	DH
1111	56	56	dec	73	73	dec

	BAU			adapted BAU		
reg. district	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]
1112	36	36	dec	29	29	dec
1113	47	47	dec	70	70	dec
1201	39	39	dec	72	72	dec
1202	63	63	dec	83	83	dec
1203	100	100	DH	100	100	DH
1204	34	69	DH	70	72	DH
1205	51	87	DH	88	88	dec
1206	36	71	DH	74	75	DH
1207	100	100	DH	100	100	DH
1208	46	75	DH	74	74	dec
1209	94	94	dec	100	100	dec
1210	55	55	dec	76	76	dec
1211	40	40	dec	68	68	dec
1301	47	47	dec	67	67	dec
1302	15	15	dec	30	30	dec
1303	6	6	dec	29	29	dec
1304	7	7	dec	11	11	dec
1305	5	5	dec	11	11	dec
1306	8	8	dec	14	14	dec
1307	53	53	dec	71	71	dec
1308	44	44	dec	71	71	dec
1309	45	45	dec	57	57	dec
1310	19	19	dec	19	19	dec
1311	0	0	dec	0	0	dec
1401	40	76	DH	76	76	dec
1402	14	62	DH	47	47	dec
1403	24	24	dec	61	61	dec
1404	53	53	dec	78	78	dec

	BAU			adapted BAU		
reg. district	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]
1405	23	23	dec	37	37	dec
1406	32	32	dec	61	61	dec
1407	0	0	dec	0	0	dec
1408	13	13	dec	31	31	dec
1409	67	76	DH	78	79	DH
1410	19	19	dec	39	39	dec
1411	2	2	dec	6	6	dec
1412	8	8	dec	14	14	dec
1501	49	77	DH	75	79	DH
1502	45	79	DH	77	77	dec
1503	32	70	DH	69	69	dec
1504	77	100	DH	100	100	DH
1505	51	85	DH	87	87	dec
1506	32	70	DH	68	68	dec
1507	49	49	dec	74	74	dec
1601	22	22	dec	65	65	dec
1602	27	27	dec	60	60	dec
1603	66	86	DH	82	82	dec
1604	58	93	DH	94	94	dec
1605	25	25	dec	63	63	dec
1606	88	88	dec	100	100	DH
1607	48	78	DH	78	78	dec
1608	40	40	dec	58	58	dec
1609	8	8	dec	18	18	dec
1610	38	38	dec	79	79	dec
1701	37	75	DH	77	77	dec
1702	35	72	DH	72	72	dec
1703	44	44	dec	78	78	dec

	BAU			adapted BAU		
reg. district	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]
1704	27	27	dec	48	48	dec
1705	5	5	dec	13	13	dec
1706	4	4	dec	19	19	dec
1801	18	18	dec	25	25	dec
1802	19	19	dec	54	54	dec
1803	36	36	dec	69	69	dec
1804	32	32	dec	65	65	dec
1805	9	9	dec	28	28	dec
1901	14	14	dec	35	35	dec
1902	63	83	DH	82	82	dec
1903	25	25	dec	32	32	dec
1904	48	80	DH	78	78	dec
1905	26	26	dec	52	52	dec
1906	10	10	dec	23	23	dec
1907	19	19	dec	32	32	dec
1908	70	100	DH	100	100	DH
1909	43	43	dec	61	61	dec
1910	30	30	dec	42	42	dec
2001	81	81	dec	83	83	dec
2002	65	65	dec	85	85	dec
2003	29	29	dec	68	68	dec
2004	75	95	DH	93	93	dec
2005	30	30	dec	68	68	dec
2006	57	82	DH	79	79	dec
2007	81	81	dec	93	93	dec
2008	29	29	dec	59	59	dec
2101	19	19	dec	20	20	dec
2102	79	79	dec	82	82	dec

	BAU			adapted BAU		
reg. district	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]
2103	100	100	DH	100	100	DH
2104	26	26	dec	39	39	dec
2105	86	86	dec	90	90	dec
2106	17	17	dec	30	30	dec
2107	38	38	dec	54	54	dec
2108	70	70	dec	82	82	dec
2109	100	100	DH	100	100	DH
2110	100	100	DH	100	100	DH
2111	78	78	dec	86	86	dec
2112	81	81	dec	91	91	dec
2113	49	49	dec	57	57	dec
2114	0	0	dec	0	0	dec
2115	29	29	dec	49	49	dec
2116	30	30	dec	31	31	dec
2117	83	96	DH	93	93	dec
2118	89	100	DH	100	100	DH
2119	43	43	dec	62	62	dec
2120	96	96	dec	100	100	DH
2121	54	82	DH	77	77	dec
2122	40	73	DH	71	71	dec
2123	47	81	DH	84	85	DH
2124	27	27	dec	38	38	dec
2125	77	77	dec	85	85	dec
2126	79	99	DH	98	98	dec
2127	0	0	dec	0	0	dec
2128	52	52	dec	62	62	dec
2129	0	50	DH	37	54	DH
2130	0	0	dec	0	0	dec

	BAU			adapted BAU		
reg. district	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]
2201	22	22	dec	25	25	dec
2202	14	14	dec	18	18	dec
2203	3	3	dec	6	6	dec
2204	47	47	dec	52	52	dec
2205	78	78	dec	76	76	dec
2206	95	95	dec	98	98	dec
2207	82	82	dec	84	84	dec
2208	85	85	dec	93	93	dec
2209	100	100	DH	100	100	DH
2210	87	87	dec	93	93	dec
2211	91	100	DH	99	99	dec
2212	39	39	dec	41	41	dec
2213	100	100	DH	100	100	DH
2214	28	28	dec	45	45	dec
2215	100	100	DH	100	100	DH
2216	66	66	dec	79	79	dec
2217	4	4	dec	3	3	dec
2218	100	100	DH	100	100	DH
2219	100	100	DH	100	100	DH
2220	82	82	dec	88	88	dec
2221	28	28	dec	28	28	dec
2222	100	100	DH	100	100	DH
2223	58	58	dec	66	66	dec
2224	66	66	dec	65	65	dec
2225	10	10	dec	12	12	dec
2226	1	1	dec	0	0	dec
2227	37	37	dec	44	44	dec
2228	23	23	dec	48	48	dec

	BAU			adapted BAU		
reg. district	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]	share dh 2050[%]	share dh 2050 after reall. [%]	used technology 2050 for reall. [%]
2229	9	9	dec	16	16	dec
2230	12	12	dec	12	12	dec
2231	51	79	DH	89	89	DH
2232	83	83	dec	90	90	dec
2301	39	39	dec	55	55	dec
2302	41	41	dec	50	50	dec
2303	1	1	dec	6	6	dec
2304	51	51	dec	67	67	dec
2305	61	61	dec	80	80	dec
2306	62	62	dec	75	75	dec
2307	97	100	DH	100	100	DH
2308	57	57	dec	59	59	dec
2309	23	23	dec	38	38	dec
2310	50	50	dec	75	75	dec
2311	71	100	DH	100	100	dec
2312	46	46	dec	56	56	dec
2313	6	6	dec	14	14	dec
2314	7	7	dec	21	21	dec
2315	3	3	dec	9	9	dec
2316	21	21	dec	27	27	dec
2317	71	71	dec	78	78	dec
2318	49	49	dec	68	68	dec
2319	100	100	DH	100	100	DH

Table A.1: Used energy carriers based on building owners investment decision, neglecting the detailed distribution costs for district heating for existing building stock for the BAU-scenario.

	2015	2020	2030	2050
Auxilliary E.	165	177	207	255
Solar thermal E	73	158	347	742
Ambient E.	67	132	194	184
Gas	6907	6322	5116	3069
Oil	438	289	94	0
Coal	15	10	4	0
Wood log	308	284	229	13/
Wood chips	5	17	44	66
Pellets	31	65	181	284
Electricity	1063	840	374	11
Electricity Heatpump Water/Water	3	5	10	10
Electricity Heatpump Air/Water	18	21	22	16
District Heat	5785	5731	5673	4999

Table A.2: Used energy carriers based on building owners investment decision, neglecting the detailed distribution costs for district heating for the whole building stock including newly constructed areas for the BAU-scenario.

	2015	2025	2035	2050
Auxilliary E.	160	186	214	247
Solar thermal E	78	252	447	747
Ambient E.	70	151	192	185
Gas	7112	6201	5219	3780
Oil	434	169	38	0
Coal	15	7	2	0
Wood log	306	260	199	151
Wood chips	16	52	72	102
Pellets	51	203	342	540
Electricity	1056	600	191	10
Electricity Heatpump Water/Water	9	22	28	24
Electricity Heatpump Air/Water	30	59	72	64
District Heat	5889	5819	5740	5253

Table A.3: Renovation rates with impact on thermal performance of building envelope in the different scenarios.

	2015-2019	2020-2024	2025-2029	2030-2034	2035-2039	2040-2044	2045-2049
BAU	0.67	0.97	0.79	0.68	0.65	0.66	0.68
stagnation	0.67	0.96	0.78	0.70	0.67	0.67	0.68
climate protection	1.30	2.04	1.97	1.57	1.65	1.85	2.10

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COP21 2015 United Nations Climate Change Conference

GIS Geographic information system

GisData GIS building data

KliP II „Klimaschutzprogramm II “

MA39 Viennese municipal department 39 [Magistratsabteilung 39 der Stadt Wien]

MA41 Viennese municipal department 41 [Magistratsabteilung 41 der Stadt Wien]

RAP Renewable Action Plan Vienna

RES-H renewable energy sources for heating

SEP „Städtisches Energieeffizienz- Programm “

SPK Vienna solar potential registry [Wiener Solarpotenzialkataster]

STEP Stadtentwicklungsplan 2025

CHP combined heat and power

USCA URBEM smart city application

WSTW Viennese municipal utility [Wiener Stadtwerke]

WWK Vienna Heat registry [Wiener Wärmekataster]

Nomenclature

$\Delta\text{FED}_{b,t}^{\text{both},1}$	change of district heating and gas demand between two simulation periods
$\Delta\text{FED}^{\text{both,neg}}$	negative change of district heating and gas demand between two simulation periods
$\Delta\text{FED}_{b,t}^{\text{DH},1}$	change of district heating demand between two simulation periods
Π	network operators' profit
$\text{age}_{b,t}^{\text{DH}}$	year of connection of building block b
$\text{FED}_{b,t}^{\text{both},1}$	the connected final energy demand for gas and district heating [MWh]
$\text{FED}_{b,t}^{\text{DH},2}$	The connected final energy demand for district heating of building block b at time t [MWh]
$\text{FED}_{b,t}^{\text{gas},2}$	The connected final energy demand for gas of building block b at time t [MWh]
$\text{FED}_{t}^{\text{DH},2}$	The connected final energy demand for district heating for all building blocks b at time t [MWh]
$\text{FED}_{t}^{\text{gas},2}$	The connected final energy demand for gas for all building blocks $b$at time t [MWh]

$\mathrm{GFA}_{b,t}^{\mathrm{DH},2}$	The connected gross floor area for district heating of building block b at time t [m^2]
$\mathrm{GFA}_{b,t}^{\mathrm{gas},2}$	The connected gross floor area for gas of building block b at time t [m^2]
$\mathrm{grid}_t^{\mathrm{length,DH}}$	length of the district heating grid at time t
$\mathrm{grid}_t^{\mathrm{length,gas}}$	length of the gas grid at time t
Per_b	perimeter of building block b [m]
$b \in B^{\mathrm{con,DH}}$	set of building blocks initially connected to district heating
$b \in B^{\mathrm{con,gas}}$	set of building blocks initially connected to gas
B	set of building blocks
b	building block $b \in B$
$c^{\mathrm{g,DH}}$	heat generation costs district heating [€]
$c^{\mathrm{ReInv,DH}}$	re-investment costs for district heating [€]
$c^{\mathrm{ReInv,gas}}$	re-investment costs for gas [€]
$c^{\mathrm{op,DH}}$	operation and maintenance costs district heating [€]
$c^{\mathrm{op,gas}}$	operation and maintenance costs gas [€]
$c_{P_{b,t}}^{\mathrm{GridInv,DH}}$	the costs per meter to connect building block b in period t to the district heating grid [€/m]
$c^{\mathrm{Inv,DH}}$	investment costs for district heating [€]
$c^{\mathrm{Inv,gas}}$	investment costs for gas [€]
$c^{grid,DH}$	costs for maintenance of the district heating network [€]
$c^{grid,DH}$	costs for the expansion of the district heating network [€/MW]
$c^{grid,gas}$	costs for maintenance of the gas network[€]

$c^{grid,gas}$	costs for the expansion of gas network [€/MW]
c_t^{el}	electricity price [€/MWh]
c_t^{tot}	total costs for expansion and extension for district heating and gas networks [€]
DC	distribution costs [€/MWh]
DC^{Inv}	distribution costs for investments [€/MWh]
DC^{op}	distribution costs for operation and maintenance [€/MWh]
DC^{ReInv}	distribution costs for reinvestments [€/MWh]
hc_t	costs for heat production [€/MWh]
hl^{DH}	heat losses [%]
l_b^{DH}	required length to connect building block b to district heating network [m]
M	big number
$nC_{b,t}^{\text{DH}}$	building block b initially connected to district heating network in period t
$p^{\text{base,DH}}$	district heating base price [€/MW]
$p^{\text{dc,DH}}$	district heating demand charge [€/MWh]
$P_{b,1}^{\text{DH,2}}$	The connected load for district heating of building block b at time t [MW]
$P_{b,t}^{\text{gas,2}}$	The connected load for gas of building block b at time t [MW]
$p_t^{\text{netcharge,gas}}$	gas network charge [€/MWh]
r	interest rate [%]
R_t^{tot}	total revenues from heat sales [€]

T	set of timesteps
t	timestep
T_a	amortisation horizon
T_{Inv}	set of investment periods
v	share, which has to be supplied by the same energy carriers as in the previous periods [%]
$x^{\text{con}}_{b,t}$	building block b is either connected to gas and/or district heating or not
$x^{\text{DH}}_{b,t}$	building block b either connected to district heating or not
$x^{\text{gas}}_{b,t}$	building block b either connected to gas or not

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