Dissertation

Economic assessment of district heating grid infrastructure

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Abstract

The European Union has set an ambitious target of achieving climate neutrality by 2050, and decarbonizing the heating sector is a crucial contribution towards this goal. To initiate this, the EU revised the Energy Efficiency Directive in 2023, requiring Member States to mandate municipalities with over 45000 residents to conduct heating and cooling (H&C) planning. H&C planning involves exploring the possibility of using local renewable heating sources, whose integration is often intertwined with district heating (DH) systems. DH is, however, an investment-intensive infrastructure that necessitates thorough analyses before its implementation. This thesis employs techno-economic approaches to assess the potential of DH at various spatial levels, focusing on the costs associated with the grid infrastructure. The implications of the findings at each spatial level are discussed.

Based on the identified gaps in the literature, this thesis answers the following research questions (RQ):

- What is the impact of gradual heat demand reduction and DH market share increase in DH areas on the economic viability and potential of the DH systems on the EU level?
- What is the impact of connection rates in sparse urban and suburban areas on the DH potentials?
- How to identify the economic potential of DH on a national level while considering the spatiotemporal aspect of heat supply and demand under different scenarios, and how can it be used as a guideline for similar studies in other countries?
- What are the main advantages and disadvantages of using a generic DH grid modelling approach based on a regression model for determination of the DH potentials, and to what extent do its results align with those obtained from an optimization-based model? What are the challenges of using each model in the context of DH grid modelling and DH potential?

Accordingly, the core objective of this work is to develop and apply methodologies to estimate the DH potential on the EU, national and local levels, and to elaborate on the technical, economic and policy implications of results at each level.

The core objective of the thesis is covered in 4 parts: In the first part, a comparison of the DH grid modelling based on the effective width concept with a detailed optimization-based modelling approach is provided (Chapter 3). The second part studies the DH potential on a European level (Chapter 4). Here, the focus is put on large DH systems. The study of smaller DH systems (e.g., 5th-generation DH systems) is out of the scope of this thesis. In this chapter, new methodological elements for modelling the impact of connection rates below 100% on heat distribution costs in both dense and sparse areas are introduced. Subsequently, the economic potential of DH under climate neutrality in the case of Austria is studied (Chapter 5). Finally, Chapter 6 provides a summary of findings, strengths and limitations found in previous chapters as well as a review of challenges and barriers in the implementation of heat plans and utilization of DH. The key conclusions from the thesis are as follows:

- The approach adopted in this thesis, which incorporates the effective width concept, offers a reliable and easy-to-implement means of assessing DH potentials in pre-feasibility studies. While it might be simplistic for municipalities that have already established advanced heating and cooling planning procedures, it is particularly well-suited for those in the preliminary planning stages. Moreover, it is suitable for studying DH potentials at a larger scale, such as a province, a state or a country.
- High heat demand densities are considered a favourable condition for implementing DH systems. However, it is important to consider the future heat demand development in studying DH potentials, especially in light of the EU's climate neutrality goals. If heat demand decreases in the future, it can lead to lower DH potentials. Therefore, modelling the impact of gradual heat demand reduction in estimating DH potentials is important.
- To maintain overall efficiency in the system, DH operators often increase the connection rates to avoid over-dimensioned pipes and suppress higher heat losses. Targeting a high DH market share in DH areas is effective in reaching economic viability for the DH system in an area and highly impacts the overall DH grid costs.
- In case of considerable heat demand reduction until 2050, a drastic increase in the DH market share of DH areas can contribute to maintaining the specific grid costs at a competitive level. In spite of the DH market share increase in DH areas, the overall heat supply level does not grow considerably due to overall demand reductions.
- Expanding DH grids requires a significant investment in the grid infrastructure. This can only be triggered with favourable financial and political support schemes like low-interest or long-term loans.
- Analysing the economic potential of DH on a national level is a time and CPU-intensive task. Clustering the potential DH areas with similar characteristics is an efficient approach to tackling this issue. In other words, regions with similar characteristics (DH potential, size of area, availability of heat sources, political conditions, etc.) can follow a similar approach towards implementing DH systems.
- The approach to heating and cooling planning can vary greatly based on the availability of financial resources, access to expert workforces, level of detail, policy framework, and stage of the process. Municipalities tend to delve deeper into the specifics as they revise their plans.
- It's crucial to have sufficient policy support in place for effective heating and cooling planning and its implementation at the municipal level. DH zoning, along with sufficient policy support, is a key enabler for DH systems in dense urban areas with high heat demands.

Kurzfassung

Die Europäische Union hat sich das ambitionierte Ziel gesetzt, bis 2050 Klimaneutralität zu erreichen, und die Dekarbonisierung des Wärmesektors ist ein entscheidender Beitrag zu diesem Ziel. Um dies zu initiieren, hat die EU im Jahr 2023 die Energieeffizienz Richtlinie überarbeitet, die die Mitgliedstaaten verpflichtet, Gemeinden mit über 45.000 Einwohnern dazu zu verpflichten, eine Wärme- und Kälteplanung (WKP) durchzuführen. Die WKP umfasst die Untersuchung der Möglichkeit der Nutzung lokaler erneuerbarer Wärmequellen, deren Integration oft eng mit Fernwärmesystemen (FW) verbunden ist. FW ist jedoch eine investitionsintensive Infrastruktur, die vor ihrer Implementierung gründliche Analysen erfordert. Diese Dissertation verwendet techno-ökonomische Ansätze, um das Potenzial von FW auf verschiedenen räumlichen Ebenen zu bewerten, wobei der Fokus auf den mit der Netz-Infrastruktur verbundenen Kosten liegt. Die Auswirkungen der Ergebnisse auf jeder räumlichen Ebene werden diskutiert.

Basierend auf den identifizierten Lücken in der Literatur beantwortet diese Arbeit die folgenden Forschungsfragen (FQ):

- Wie wirkt sich eine sinkende Wärmenachfrage und ein Anstieg des FW-Marktanteils in FW-Gebieten auf die Wirtschaftlichkeit und das Potenzial der FW-Systeme auf EU-Ebene aus?
- Wie beeinflussen Anschlussgraden in dünn besiedelten Gebieten die FW-Potenziale?
- Wie lässt sich das wirtschaftliche Potenzial von FW auf nationaler Ebene identifizieren, unter Berücksichtigung des räumlich-zeitlichen Aspekts von Wärmeangebot und -nachfrage in verschiedenen Szenarien, und wie kann dies als Leitfaden für ähnliche Studien in anderen Ländern verwendet werden?
- Welche Vor- und Nachteile hat die Verwendung eines generischen FW-Netzmodellierungsansatzes, der auf einem Regressionsmodell zur Bestimmung der FW-Potenziale basiert, und inwieweit stimmen seine Ergebnisse mit denen eines optimierungsbasierten Modells überein? Welche Herausforderungen ergeben sich bei der Verwendung jedes Modells im Kontext der FW-Netzmodellierung und des FW-Potenzials?

Entsprechend besteht das Hauptziel dieser Arbeit darin, Methoden zu entwickeln und anzuwenden, um das Fernwärmepotenzial auf EU-, nationaler und lokaler Ebene zu schätzen und die technischen, wirtschaftlichen und politischen Auswirkungen der Ergebnisse auf jeder Ebene zu erläutern.

Kurzfassung

Das Hauptziel der Arbeit wird in vier Teilen behandelt: Im ersten Teil wird ein Vergleich der FW-Netzmodellierung basierend auf dem Konzept der effektiven Breite mit einem detaillierten optimierungsbasierten Modellierungsansatz vorgenommen (Kapitel 3). Der zweite Teil untersucht das FW-Potenzial auf europäischer Ebene (Kapitel 4), wobei der Schwerpunkt auf großen FW-Systemen liegt. Die Untersuchung kleinerer FW-Systeme (z. B. 5. Generation FW-Systeme) fällt nicht in den Rahmen dieser Dissertation. In diesem Kapitel werden neue methodische Elemente zur Modellierung des Einflusses von Anschlussraten unter 100 % auf die Wärmeverteilungskosten in sowohl dicht- als auch dünnbesiedelten Gebieten eingeführt. Anschließend wird das wirtschaftliche Potenzial von FW unter Klimaneutralität in Österreichs untersucht (Kapitel 5). Schließlich fasst Kapitel 6 die Ergebnisse, Stärken und Schwächen der vorherigen Kapitel zusammen und bietet einen Überblick über Herausforderungen und Hindernisse bei der Umsetzung von Wärmeplänen und der Implementierung der FW. Die wichtigsten Schlussfolgerungen der Dissertation sind wie folgt:

- Der in dieser Dissertation angewandte Ansatz, der das Konzept der effektiven Breite einbezieht, bietet eine zuverlässige und einfach umsetzbare Methode zur Bewertung von FW-Potenzialen in den Vormachbarkeitsstudien. Während er für Gemeinden, die bereits fortgeschrittene Planungsverfahren für Wärme und Kälte etabliert haben, möglicherweise zu einfach ist, eignet er sich besonders gut für solche in den frühen Planungsphasen. Darüber hinaus ist er geeignet für die Untersuchung von FW-Potenzialen in größerem Maßstab, wie einer Provinz, einem Bundesland oder einem Land.
- Hohe Wärmebedarfsdichten gelten als günstige Voraussetzung für die Implementierung von FW-Systemen. Es ist jedoch wichtig, die zukünftige Entwicklung der Wärmenachfrage bei der Untersuchung von FW-Potenzialen zu berücksichtigen, insbesondere im Hinblick auf die Klimaneutralitätsziele der EU. Sinkt die Wärmenachfrage in der Zukunft, kann dies zu geringeren FW-Potenzialen führen. Daher ist die Modellierung des Einflusses einer Senkung der Wärmenachfrage bei der Schätzung von FW-Potenzialen von Bedeutung.
- Um die Gesamteffizienz des Systems aufrechtzuerhalten, erhöhen FW-Betreiber häufig die Anschlussgraden, um überdimensionierte Rohre zu vermeiden, die zu höheren Wärmeverlusten führen können. Ein hoher FW-Marktanteil in FW-Gebieten ist effektiv, um die Wirtschaftlichkeit des FW-Systems in einem Gebiet zu erreichen, und hat erheblichen Einfluss auf die Gesamtkosten des FW-Netzes.
- Im Falle einer erheblichen Verringerung der Wärmenachfrage bis 2050 trägt eine drastische Erhöhung des FW-Marktanteils in FW-Gebieten hauptsächlich dazu bei, die spezifischen Netzkosten auf einem wettbewerbsfähigen Niveau zu halten. Trotz der Erhöhung des FW-Marktanteils in FW-Gebieten wächst das FW-Versorgungsniveau aufgrund der allgemeinen Nachfragerückgänge nicht erheblich.

Kurzfassung

- Der Ausbau von FW-Netzen erfordert erhebliche Investitionen in die Netzinfrastruktur. Dies kann nur durch günstige finanzielle und politische Unterstützungsprogramme wie zinsgünstige, langfristige Kredite oder FW-Zonierungen ausgelöst werden.
- Die Analyse des wirtschaftlichen Potenzials von FW auf nationaler Ebene ist eine zeit- und rechenintensive Aufgabe. Die Clusterung potenzieller FW-Gebiete mit ähnlichen Merkmalen ist ein effizienter Ansatz, um dieses Problem anzugehen. Anders gesagt, Regionen mit ähnlichen Merkmalen (FW-Potenzial, Gebietsgröße, Verfügbarkeit von Wärmequellen, politische Bedingungen usw.) können einen ähnlichen Ansatz zur Implementierung von FW-Systemen verfolgen.
- Der Ansatz zur WKP kann je nach Verfügbarkeit finanzieller Ressourcen, Zugang zu Fachkräften, Detaillierungsgrad, politischem Rahmen und Phase des Prozesses stark variieren. Kommunen neigen dazu, bei der Überarbeitung ihrer Pläne tiefer in die Details einzutauchen.
- Es ist entscheidend, ausreichende politische Unterstützung für eine effektive WKP und deren Umsetzung auf kommunaler Ebene zu haben. FW-Zonierung, zusammen mit ausreichender politischer Unterstützung, ist ein wichtiger Faktor für FW-Systeme in dicht besiedelten städtischen Gebieten mit hoher Wärmenachfrage.
- Die Arbeit zeigt, dass das wirtschaftliche Potenzial von FW-Systemen in Österreich unter günstigen Bedingungen bis 2050 mehr als die Hälfte der gesamten Wärmenachfrage übersteigen kann.

Table of Contents

List of Figures

List of Tables

Abbreviations

Abbreviation	Description
CAPEX	Capital Expenditure
CBA	Cost-Benefit Analysis
CHP	Combined Heat and Power
DH	District Heating
DHC	District Heating and Cooling
EC	European Commission
EED	Energy Efficiency Directive
EU	European Union
GFA	Gross Floor Area
GFAD	Gross Floor Area Density
GFAD	Gross Floor Area Density
GIS	Geographic Information System
H&C	Heating and Cooling
HDD	Heat Demand Density
HDD	Heat Demand Density
HDM	Heat Density Map
JRC	Joint Research Centre
LAU 2	Local Administrative Units Level 2
LCOH	Levelized Cost of Heat
MILP	Mixed Integer Linear Programming
MS	Member States
NUTS	Nomenclature of Territorial Units for Statistics
O&M	Operation and Maintenance
RQ	Research Question
VAT	Value-Added Tax
WEM	Scenario “With Existing Measures”

Nomenclature

Parameter	Description	Unit
A_L	Land area	m2
C_1	Construction costs constant	€/m
C_2	Construction costs coefficient	€/m2
C_d	Levelized cost of heat distribution	€/GJ
d_a	Average pipe diameter	m
D_T	Annual heat demand in year T	GJ
E_t	Energy generated in the t^{th} year	GJ
F_t	Fuel expenditures in the t^{th} year	€
GFA	Gross floor area	m2
I	Heat distribution investments	€
L	Trench length	M
LHD	Linear heat density	GJ/m
m	Number of years required to achieve the target DH market share	-
M_t	Operations and maintenance (O&M) expenditures in the t^{th} year	€
MS_t	DH Market share within DH areas in t^{th} year	M
n	Depreciation time or amortization period	year
pr	Plot ratio	-
q	Useful energy demand covered by DH per unit of heated floor area	GJ/m2
Q_T	Useful energy demand covered by district heating in year T	GJ
r	Discount rate	%
S	Expected accumulated energy saving over a given period	%
T	The base year for the calculation	-
$UED_{DH,t}$	Useful energy demand covered by DH in the t^{th} year	GJ
w	Effective width	M

1 Introduction

One significant challenge on the way of climate neutrality lies in reducing carbon emissions from the heating sector, which has long relied on fossil fuels. In this context, district heating (DH) emerges as a pivotal player, offering a versatile solution that can enhance overall efficiency and provide an eco-friendly heat supply by integrating local renewable heat sources.

This thesis looks into the potential of DH. The chapters present a range of perspectives, from the EU-level DH potential to the assessment of the economic potential of the DH in Austria. The introduction chapter serves as a prologue to these chapters, providing an overarching context and connecting different threads that unfold across the subsequent chapters.

1.1 Motivation

Heating and cooling (H&C) systems account for a significant portion of total energy consumption and have been a major focus for cities and countries worldwide, particularly those with high heating or cooling needs. In Europe, there has been a heightened focus on this issue over the past two decades, particularly after the Paris Agreement. The European Union (EU) has set an ambitious target of achieving climate neutrality by 2050, and decarbonizing the heating sector is a crucial contribution towards this goal.

A key policy instrument for decarbonizing the H&C sector is the Energy Efficiency Directive (EED). Article 14 of the Energy Efficiency Directive, which was adopted in 2012 (Directive (EU) 2012/27, hereon EED I), required member states (MS) of the European Union (EU) to conduct a "comprehensive assessment of the potential for the application of high-efficiency cogeneration and efficient DHC" by the end of 2015 [1].

According to Cornelis and Vingerhoets [2], the national reports submitted in 2015 varied in their methods and level of detail. To address these discrepancies, the Joint Research Centre (JRC) of the European Commission (EC) provided recommendations, which led to an update of Annexes VIII and IX of the EED I and a reporting template to standardize the comprehensive assessments by MS [3]. With the revised Energy Efficiency Directive from 2018 (Directive (EU) 2018/2002, hereon EED II), the requirements of Article 14 and Annex VIII were rephrased to ask for "comprehensive assessments of the potential for efficient heating and cooling."

EED I was adopted before the Paris Agreement [4] and the subsequent adoption of climate neutrality targets in Europe [5, p. 11]. Consequently, the expected outcomes and methodological aspects of the cost-benefit analysis (CBA) in the comprehensive assessment reports under Article 14 of the EED I were refined in EED II (more details in Chapter 5.1). However, the fundamental idea of the CBA remained the same as in EED I.

Continuing the effort towards achieving climate neutrality in Europe, the EC has recently updated the Energy Efficiency Directive (Directive (EU) 2023/1791, hereon EED III). For the purpose of the comprehensive assessments, MS should carry out a CBA covering their territory on the basis of climate conditions, economic feasibility and technical suitability [6]. EED III also requires MS to mandate municipalities with over 45000 residents to conduct H&C planning [7]. The H&C plans should be based on the information and data provided in the national comprehensive assessments.

H&C planning involves exploring the possibility of using local renewable heating sources, whose integration is often intertwined with DH systems. Experts often consider DH infrastructure as an essential means to economically integrate climate-friendly technologies into the energy system due to the possibility it provides for aggregating loads, providing economy of scale and integration of local renewable energy sources. Accordingly, DH is an inevitable part of comprehensive assessments, cost-benefit analyses and also heat plans. DH is, however, an investment-intensive infrastructure that necessitates thorough pre-feasibility analyses before its implementation. This thesis employs techno-economic approaches to assess the potential of DH at various spatial levels, focusing on the costs associated with the grid infrastructure.

The topic of DH potential is covered with remarkable studies that have expanded the knowledge of the economic feasibility of DH and its environmental impact. However, there are still gaps in the existing literature which will be addressed in this thesis. A detailed review of the literature and the identified gaps will be elaborated on in chapters 3, 4 and 5. Here, a summary of the identified gaps is presented.

The first gap is the consideration of future demand developments. Many previous studies, while providing valuable insights into DH potential, have often overlooked the dynamic nature of heat demand. The adoption of new European climate targets and laws, such as the European Green Deal, the Fit-for-55 package and in particular the revised Energy Performance of Buildings Directive (EPBD, Directive (EU) 2024/1275), has introduced new dimensions to the heat demand scenarios that must be considered in the DH potential assessment.

The second gap revolves around the gradual implementation of DH grids. Most studies (e.g. [8], [9], [10], [11]) have considered 100% connection rates in DH areas for economic analyses. In practice, DH grid expansion occurs incrementally, influenced by factors like financial constraints and human resources. The stepwise construction of DH networks introduces a dynamic aspect that has been largely unexplored in previous studies.

The third gap pertains to the methodology used in calculating heat distribution costs in combination with the previously mentioned gaps. Many studies have relied on the concept of effective width, a relationship between land area and DH trench length. This approach, while informative, has its limitations. Recent advancements, such as the one presented by the Horizon 2020 project sEEnergies [12], introduce new dimensions by considering service pipes and adjusting cost components for each EU member state.

The fourth gap addresses DH potential in sparse areas, which has seldom been the central focus of research. Sparse regions present unique challenges and opportunities that need to be explored to gain a more comprehensive understanding of DH potential.

The fifth challenge pertains to the need for a methodology that can effectively identify the economic potential of DH in a very large area, e.g., in a country. This is particularly important for conducting analyses within the Comprehensive Assessment of the Potential for Efficient Heating and Cooling as first outlined in Article 14 of the Energy Efficiency Directive I (Directive 2012/27/EU, hereon EED I) and its revisions [1], [7], [13]. Given the intricacy and computational demands of these analyses, finding an efficient approach to conduct them is needed.

1.2 Research questions and objective

Based on the identified gaps in the literature, this thesis answers the following research questions (RQ):

- **RQ1**: What are the main advantages and disadvantages of using a generic DH grid modelling approach based on a regression model for the determination of the DH potentials, and to what extent do its results align with those obtained from an optimization-based model? What are the challenges of using each model in the context of DH grid modelling and DH potential?
- **RQ2**: What is the impact of connection rates in sparse urban and suburban areas on the DH potentials?
- **RQ3**: What is the impact of gradual heat demand reduction and DH market share increase in DH areas on the economic viability and potential of the DH systems on the EU level?
- **RQ4**: How to identify the economic potential of DH on a national level while considering the spatiotemporal aspect of heat supply and demand under different scenarios, and how can it be used as a guideline for similar studies in other countries?

Accordingly, the core objective of this work is to develop and apply methodologies to estimate the DH potential on the EU, national and local levels, and to elaborate on the technical, economic and policy implications of results at each level.

The contributions in this thesis are based on the following peer-reviewed articles: Impact of Distribution and Transmission Investment Costs of District Heating Systems on District Heating Potential [14], District Heating Distribution Grid Costs: A Comparison of Two Approaches [15], District Heating Potential in the EU-27: Evaluating the Impacts of Heat Demand Reduction And Market Share Growth [16] and The Economic Potential of District Heating Under Climate Neutrality: The Case of Austria [6].

Additional support or foundation for the contents of this thesis can be found in the following co-authored papers: Policy Frameworks For District Heating: A Comprehensive Overview And Analysis Of Regulations And Support Measures Across Europe [17], Spatial Analysis Of Renewable And Excess Heat Potentials For Climate-Neutral District Heating In Europe [18].

The gaps enumerated in Chapter 1.1 and derived research questions should be filled and addressed in a transparent and replicable manner and be consistent with the FAIR (Findable, Accessible, Interoperable, Reusable) principle to facilitate its validation and ensure the possibility of building upon existing results. Therefore, works completed for this thesis have been made available in publicly accessible repositories with open-source licenses.

1.3 Structure of the thesis

This thesis and its constituting peer-reviewed articles address research questions enumerated in Chapter 1.2. The level of contribution of the author of this thesis in each of the peer-reviewed articles is provided in Chapter 7. Although the methodologies used in different chapters have a broad similarity, they have been improved and evolved over time and are slightly different from each other. However, the general idea remains the same. To clarify the overarching idea of this thesis, Chapter 2 briefly explains the methodology used in this thesis.

The research questions of the thesis are covered in 3 parts based on the peer-reviewed articles: In the first part, a comparison of the DH grid modelling based on the effective width concept with a detailed optimization-based modelling approach is provided (Corresponds to RQ1 in Chapter 1.2, is answered in the publications [14], [15] and covered in Chapter 3). The second part studies the DH potential on a European level (Corresponds to RQ2 and RQ3 in Chapter 1.2, is answered in the publication [16] and covered in Chapter 4). Here, the focus is put on large DH systems. The study of smaller DH systems (e.g., 5th-generation DH systems) is out of the scope of this thesis. In this paper, new methodological elements for modelling the impact of connection rates below 100% on heat distribution costs in both dense and sparse areas are introduced. A complementary study is done in Chapter 5, where the economic potential of DH under climate neutrality in the case of Austria is studied (Corresponds to RQ4 in Chapter 1.2 and is answered in the publication [6]).

Chapters 2 to 5 deal with the identification of DH potentials and present methods and approaches to fill the enumerated gaps in Chapter 1.1 and answer the research questions in Chapter 1.2. Chapter 7 draws the main conclusions from the previous chapters, highlighting findings, strengths and limitations. The availability of potential for DH and supporting DH utilization through heat plans does not necessarily lead to its successful implementation. To elaborate on this aspect, challenges and barriers in the implementation of heat plans and utilization of DH are also reviewed in Chapter 7.

2 Method

To answer the research questions raised in Chapter 1.2, different approaches were considered. These approaches have been elaborated in each Chapter separately. However, all these approaches have three things in common:

- Economic calculation for the grid infrastructure costs
- Identification of potential DH areas
- Definition of the economic potential of efficient DH system.

2.1 Economic calculation for the grid infrastructure costs

For the calculation of grid infrastructure costs the levelized cost approach is used. Generally, the Levelized Cost of Energy (LCOE) is calculated as shown in Eq. 2-1:

$$LCOE = \frac{sum\ of\ discounted\ costs\ over\ depreciation\ time}{sum\ of\ discounted\ energy\ produced\ over\ \text{depreciation time}} = \frac{\sum_{t=1}^{n}\frac{I_t+M_t+F_t}{(1+r)^t}}{\sum_{t=1}^{n}\frac{E_t}{(1+r)^t}} \quad \text{(Eq. 2-1)}$$

I_t : investment expenditures in the t^{th} year

M_t : operations and maintenance (O&M) expenditures in the t^{th} year

F_t : fuel expenditures in the t^{th} year

E_t : energy generated in the t^{th} year

r : discount rate

n : depreciation time of the system

Although E is not a direct monetary parameter, it is discounted in LCOE calculations to account for the time value of money and to maintain consistency in present value terms. This approach ensures accurate economic evaluations of energy projects, facilitating decision-making for investors and policymakers.

In this thesis, with regard to the grid infrastructure, it is assumed that the investment decision is made at the beginning of the study horizon. Also, no O&M costs, substation costs or fuel expenditures are considered for calculating the cost of DH grid infrastructure[1]. Additionally, the useful energy demand covered by the DH system is expected to change over the study horizon due to the change in the DH market share inside the DH areas. Only from the end of the study horizon (*m*), when expected DH market shares within DH areas are achieved, until the end of the depreciation time (*n*), a fixed demand coverage by DH is considered. Accordingly, the Eq. 2-1 will be simplified as follows (Eq. 2-2):

$$C_d = \frac{I_0}{\sum_{t=0}^{m} \frac{UED_{DH,t}}{(1+r)^t} + \sum_{t=m}^{n} \frac{UED_{DH,m}}{(1+r)^t}} \quad \text{(Eq. 2-2)}$$

C_d	:	Levelized cost of heat distribution [€/GJ]
m	:	Number of years in study horizon to reach the expected DH market share
$UED_{DH,t}$	:	Useful energy demand covered by DH in the t^{th} year

2.2 Identification of potential district heating areas

The identification of potential DH areas helps in developing new DH systems or extending existing grids. For this purpose, heat planners and researchers use GIS methods for the visualization of the areas and a better understanding of the potentials [19], [20], [21], [22], [23]. Fallahnejad et al. classify GIS methods for the identification of DH potentials into three categories [24]:

- Category I: local focus with an overview of the heat sources and sinks for precise identification of the extension and expansion areas. Starting with large heat consumers like hospitals or hotels, the energy planner looks for possibilities to extend the grids in an economical manner. For instance, Finney et al. identified the existing and potential heat sources and sinks and afterwards, calculated the potential for expansion and extension of the DH grids by looking into the distance of the sinks and sources from the existing grids [25].

[1] More details on limitations and assumptions can be found separately in Chapters 3.3.1, 4.4.6 and 5.4.3. A summary of the strengths and limitations is provided in Chapter 7.2.

This method provides highly accurate and reliable results by focusing on detailed local information about heat sources and sinks, which is useful for making specific investment decisions. However, it is labour-intensive, difficult to replicate in other regions, and not suitable for large-scale analyses.

- Category II: a minimum heat demand threshold is set for considering an area as a potential DH area [21]. This approach was also used by Connolly et al. to determine the suitable technology for heat supply [22].
  This approach can be easily applied to a large region with limited computational effort. However, it may underestimate potential by not considering the economic benefits of interconnecting smaller areas to each other. Also, the risks originating from demand reductions in areas with a heat demand close to the threshold value are not covered.
- Category III: Calculate the heat distribution costs using the concept of effective width, as proposed by Persson and Werner [11], and compare them with other heat supply options. For instance, Nielsen and Möller divided the grid investment into distribution grid and transmission grid investment [26].
  This category offers a more optimistic outlook compared to Category 2. However, it requires careful consideration of the gradual nature of implementing DH systems and the uncertainties related to future heat demand and market conditions.

To tackle the limitations imposed by enumerated approaches, a new method was developed. The heat demand and gross floor area density maps of the residential and service sectors in the form of GIS layers (raster layers with 1-hectare resolution) are the basis for the calculations in this thesis. In this thesis, the terms DH area, market share and potential are defined as follows:

- **DH area**: An area within a region where a DH system partially or fully supplies heat to the buildings. In this Thesis, a DH area can be as small as 1 ha (resolution of input data). Larger DH areas are composed of connected hectare elements.
- **DH market share within a district area (%)**: The share of heat demand in a DH area supplied by the DH system from total heat demand in the same area. In this thesis, “DH market share” or “DH market share in DH areas” are used interchangeably.
- **DH potential (in MWh, GWh, or TWh)**: Shows the amount of energy supplied by the DH system in a specific area. Considering the provided definition for the DH market share, the multiplication of DH market share in a region, like a city or a country, and its total heat demand does not necessarily provide the DH potential.

Given the above definitions, although the DH market shares are inputs of the approach, DH potential cannot be calculated in advance. The calculation of the DH potential is possible once the extent and location of DH areas are identified.

Two conditions should be fulfilled to identify an area as a potential DH area. For the study region, a heat distribution cost ceiling is set exogenously. The first condition ensures that the average heat distribution costs of any potential DH area in the study region may not exceed the pre-defined cost ceiling. **This criterion limits heat distribution costs and is necessary since this chapter does not consider heat generation costs**. The second condition sets a minimum annual DH demand to be reached through the study horizon in order to identify an area as a potential DH area. DH areas are not identified based on administrative borders; therefore, more than one DH area might be identified within a town or city. Also, a DH area can exceed beyond the administrative borders of a city.

The process for identifying DH areas is depicted in Figure 2-1. Initially, all hectare elements with a low annual heat demand are filtered out, using a minimum threshold of 20 MWh/ha/a. Values below this threshold are generally unsuitable for DH, while values above it can be considered. However, setting the threshold too high can result in overlooking DH potential and selectively favouring specific regions.

Next, coherent areas (connected pixels) are extracted. For each coherent area, it is checked if the previously-mentioned two conditions are met:

- If both conditions are met, the coherent area is saved as a potential DH area and its hectare elements are not considered in the next loop.
- If either of the two conditions is not met, the coherent area is not considered a potential DH area.

The analysis continues by increasing the primary threshold by 10 MWh/ha/a, reaching a threshold of 30 MWh/ha/a. The 10 MWh step is a trade-off between accuracy and running time. Smaller steps can be used at the cost of higher computation time. The previous step of identifying coherent areas from remaining pixels is repeated, and the conditions are checked again. Coherent areas that meet both conditions are saved as DH areas, and their hectare elements are removed from the original dataset. The process of increasing the thresholds and identifying potential DH areas continues in a loop until no further pixels or coherent areas remain that meet the two conditions. At that point, the algorithm stops, and the potential DH areas are returned.

To obtain the maximum DH potential, it is advisable to initially set a low demand threshold (20 MWh/ha/a) for eliminating irrelevant pixels. At times, the resulting designated DH area may be extensive, and despite knowing the costs and potentials in each hectare, the user may wish to focus on the most profitable pixels. In these situations, it is recommended to begin with higher thresholds for eliminating irrelevant pixels.

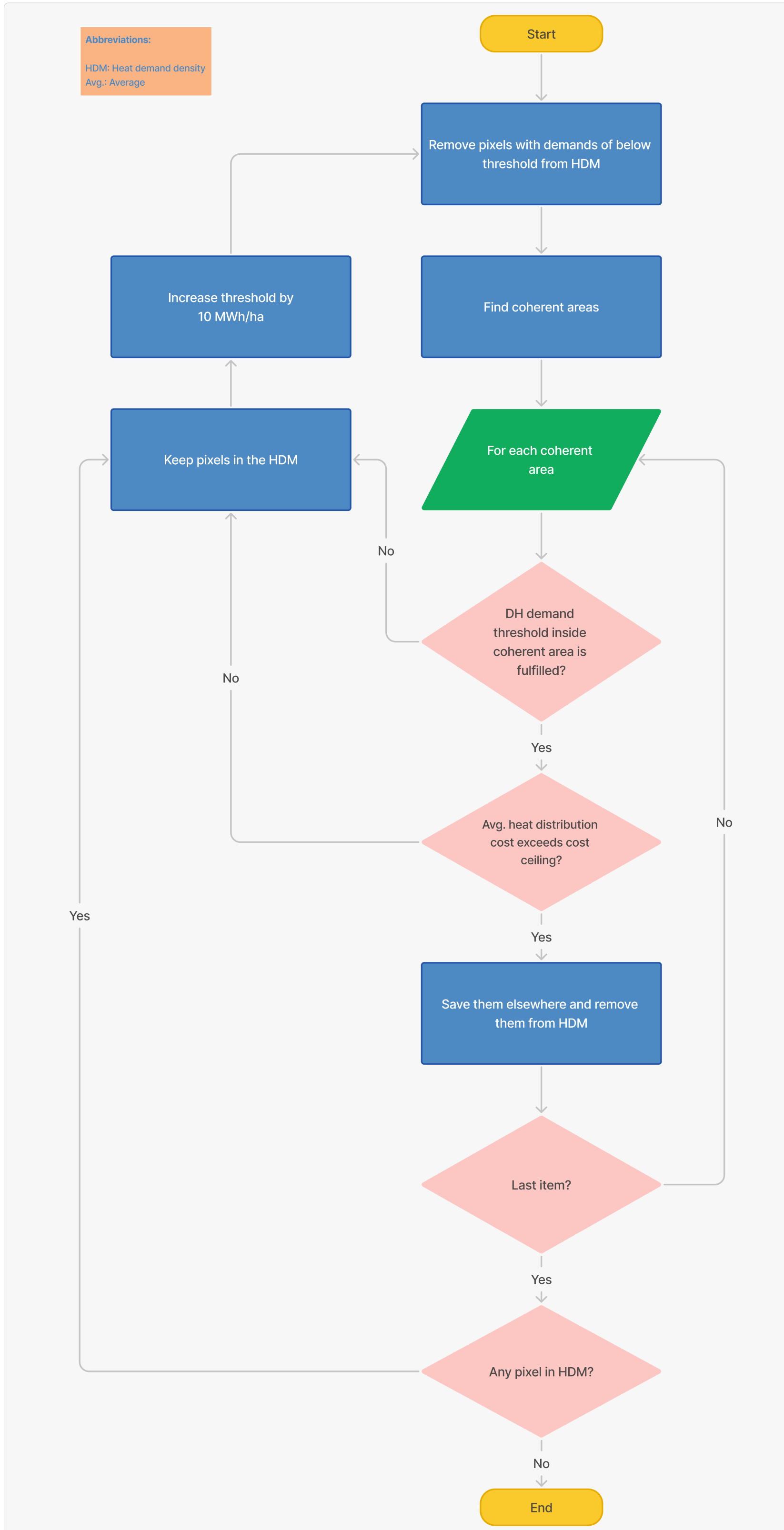


Figure 2-1 Flowchart of identifying potential DH areas

2.3 Definition of the economic potential of efficient district heating system

The definition of an efficient DHC system was revised in the EED III in 2023. The updated definition outlines a path for increasing efficiency and the integration of renewable energy sources in DHC systems. While the Directive does not mandate the transformation of DHC systems, it indirectly renders non-efficient systems ineligible for funding. Additionally, other directives from the EC, such as the Energy Performance of Building Directive (EPBD, Directive (EU) 2024/1275), impose negative consequences for non-efficient DHC systems [27]. For instance, non-efficient DHC systems will not be permitted to provide heating to newly constructed buildings according to Article 11 of EPBD (Directive (EU) 2024/1275) [27]. Figure 2-2 demonstrates the requirements for the efficient DHC system by EED III.

The EED III offers the most recent definition of an efficient DHC system. However, the research conducted in this thesis, particularly in Chapter 5, aligns with the definition of efficient DH as proposed by Jimenez Navarro et al. [28]. According to their proposition, an efficient DHC system by 2030 should incorporate "equal or more renewable energy technologies than fossil-fuelled individual generation energy technologies". By 2050, an efficient DHC system should exclusively rely on a combination of renewable-fuelled heat, including ambient heat, and waste heat sources. To gauge the economic potential of the efficient DH system, a cost-benefit analysis is conducted, and the cost of an efficient DH system within identified potential DH areas is compared with individual supply options.

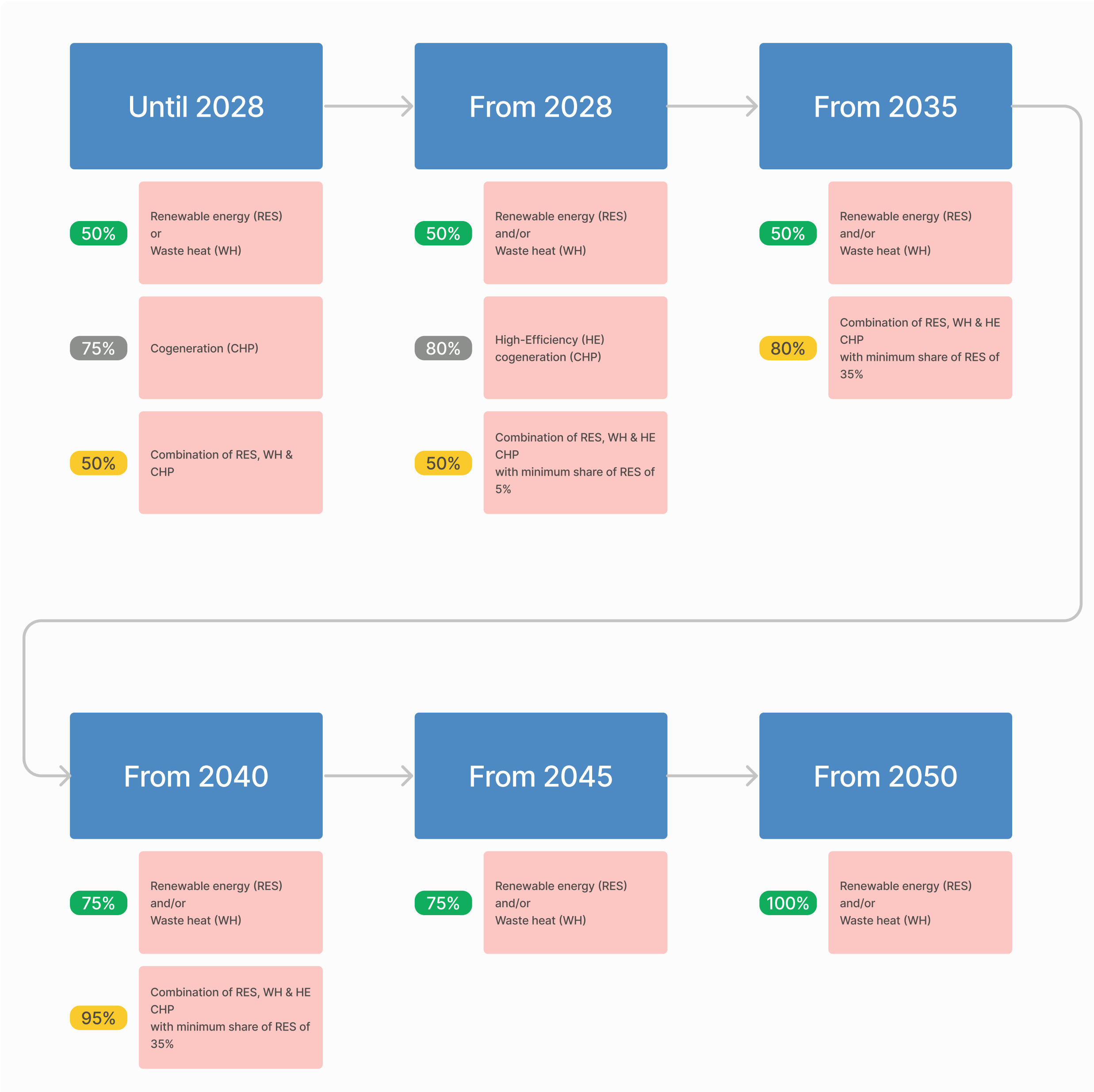


Figure 2-2 Definition of efficient DHC system (Own illustration, contents from EED III [7])

3 The role of GIS in the identification of the district heating potentials

This chapter is mainly based on the following peer-reviewed articles: Impact of Distribution and Transmission Investment Costs of District Heating Systems on District Heating Potential [14] and District Heating Distribution Grid Costs: A Comparison of Two Approaches [15].

Geographic Information Systems (GIS) technology has revolutionized the way we perceive and manage the world around us. GIS can capture, store, analyse, and present spatial data, and its applications extend beyond simple map creation. It is an invaluable asset in fields such as, but not limited to, urban planning, environmental management and disaster response. This chapter highlights the role of GIS in identifying DH potentials using two different methods.

3.1 An overview

The linear heat density is a decisive parameter in the economic viability of implementing a DH system. The concept of effective width was first introduced by Urban Persson and Sven Werner [29] in order to estimate the linear heat densities on the basis of demographic data. Effective width refers to the ratio of a given land area to the length of the DH trench within that area. In contrast to the previous empirical approaches, where the calculation of the trench length and linear heat density was only possible after the implementation of the DH pipelines, the effective width concept allows for the estimation of future linear heat densities in areas where no DH network exists.

The main advantages of the approach are ease of use and low data intensity. The required data by the approach are heat demand densities and plot ratio (*pr*), both of which are today publicly available, especially for EU countries; e.g. from Hotmaps project for EU 27 countries [30], or from heat atlases on a national level such as Danish Heat Atlas [31] or Austrian Heat Map [32]. Furthermore, municipalities across the EU are gradually getting motivated to make a commitment to taking climate protection steps. As a result, heating and cooling planning is practised more frequently across the EU on a municipal level, in many cases leading to further data availability.

The practice of heating and cooling planning is also supported strongly in the revised Energy Efficiency Directive [7], requiring municipalities with a population of more than 45000 to elaborate heating and cooling plans [33]. Considering the fact that district heating and cooling (DHC) is one of the main infrastructures allowing decarbonisation of the heating sector, there is no surprise that the concept of the effective width is being applied extensively for the economic assessment of DH network investments in pre-feasibility stages.

Nielsen and Möller used the effective width concept for estimating DH distribution grid costs in Denmark. The DH distribution grid costs were used together with heat transmission costs and heat production costs to obtain future DH potentials in Denmark [26]. In a similar work, Spirito et al. applied the effective width concept for the estimation of the DH distribution grid cost, which later on was used to calculate the potential diffusion of renewables-based DH for the case study of Milan. For the identification of the most suitable DH areas, they used the DBSCAN clustering algorithm [34].

Fallahnejad et al. proposed an approach based on the effective width concept for the identification of potential DH areas [14]. In their GIS-based approach, areas with low heat demand densities were excluded, and then, coherent areas whose average DH distribution grid costs fall below a pre-defined level were considered as potential DH areas. The distance of potential DH areas from the main heat source and imposed costs of heat transmission are used as criteria for selecting the economical DH areas.

Heat distribution costs obtained from the effective width concept were further used in the Heat Roadmap Europe project – A Horizon 2020 Research and Innovation project [35]. In a paper published by the project, economic suitability for the DH was expressed as annualized network investment cost per unit of delivered heat. Accordingly, the concept of effective width and the definition of economic suitability were used for the study of DH distribution grid costs in EU countries [9]. Dénarié et al. introduced a relation between the effective width and the number of buildings in an area and used it for the estimation of the network length and heat distribution costs. The methodology was validated with existing DH grid data from the city of Milan [36].

Since the introduction of the effective width concept in 2010, the approach has been updated a few times. While the very first version of the approach was based on 100 observations in Sweden, it was broadened to 1703 districts in 83 cities within Germany, France, Belgium and the Netherlands in the next elaboration of the approach in 2011 [11]. Furthermore, separate cost components for the inner-city areas, outer-city areas and park areas were proposed. In 2019, the cost components were merged into one average function covering all three areas and pipe dimensions used in them. Additionally, it was revealed that plot ratio has the highest impact on effective width in sparsely built areas ($pr \leq 0.4$). In contrast to low plot ratio areas, a constant effective width value of 60 m was considered for areas with higher plot ratios.

The efforts in improving the approach and achieving more accurate results for EU countries have been followed further in other studies and projects. The Horizon 2020 project sEEnergies [12], in one of its recent reports, suggested a formula for the calculation of the effective width of service pipes [37]. Furthermore, the formula of effective width for the DH distribution grid was updated. Besides the building data, DH data were obtained from Fjernvarme Fyn (Denmark's 3rd largest DH company) for the city of Odense. The report also pays specific attention to the areas with low plot ratios as well as country-specific construction cost components. The overall approach was elaborated in detail, in a research paper as well [38].

With regards to the DH networks and parallel to the effective width approach, another research stream deals with the detailed planning of DH networks using techno-economic optimization models. Here, the researchers focus on detailed network dimensions, routes, costs and connection of heat sources to the consumers. The temperature is often assumed to be at a steady state, and fluid hydraulics are modelled in a simplified manner as these aspects are rather topics of simulation models. In detailed modelling approaches, the focus is often put on the impact of certain parameters, such as choice of supply technology, use of storage systems or supply temperature, and length, dimension and costs of the network.

Dorfner and Hamacher developed a graph-based optimization model for the determination of the structure and size of large-scale DH networks and applied it to the case study of Munich [39]. The results of the optimization are presented in GIS layers. This model was used as a basis for the development of the open-source model DHMIN [40].

Thermos – a Horizon 2020 project – developed an online, open-source software, where the distribution network as well as the selection of supply technologies are selected in a mixed integer linear programming model [41], [42]. The tool is user-friendly and well-suited for local and district-level studies at building-level resolution. Although the application on larger areas is possible, it is bound with higher data processing and computation time due to its online nature.

Marquant et al. introduced an approach for the study of DH potential at a large scale [43]. The approach divides a given case study into multiple districts according to the result of a density-based clustering algorithm. The potential DH areas are determined in an optimization model. Although the GIS aspects are included in the approach, the DH network is modelled and illustrated in Euclidean distances with estimated heat transfer capacity.

Roeder et al. studied the DH network size and dimension in the presence of thermal storage [44]. The strength of the study is the introduction of a well-structured open-source tool. Their study of 129 DH-connected households showed that by using thermal storage systems, the heat losses and piping costs can be reduced by up to 10% and 14%, respectively. However, the conclusion cannot be generalized as it is project-specific. The authors mentioned that the CPU time for the optimization was ca. 1 hour. Given the low number of buildings in the case study, the CPU time may drastically increase if it is applied to a larger case study.

Designing a DH network and supplying heat with industrial waste heat as a supply source is the focus of the study done by Lumbreras et al. in their recent publication [8]. The approach provides a preliminary economic assessment (private business point of view) of supplying existing buildings with low-temperature heat, in which network dimensions and routes are determined. The authors confirm the need for a backup system for the low-temperature heat supply and suggest using existing decentral heating systems in the buildings for this purpose. However, this aspect was not assessed either from an economic point of view or from an end-user perspective.

Both research streams on effective width and detailed network modelling have their own benefits and limitations. In spite of all the efforts to improve the effective width approach, it is sometimes referred to as a generic approach that is obtained from a region with certain construction economics and without additional details relevant to other areas [45]. These types of arguments are, however, not supported by adequate analyses. In other words, the validation of the approaches is often done based on existing DH networks in case studies, which in general is a creditable approach for the validation but not sufficient for comparing the results of one approach with another. Therefore, it is not clear to which extent DH-related indicators obtained by a detailed modelling approach differ from results obtained by the effective width concept.

This chapter targets filling this gap and highlighting the advantages, disadvantages and challenges of using an effective width approach for the identification of grid costs and lengths in comparison to a detailed modelling approach. Thus, the research questions of this chapter are: (1) For a specific case study, to which extent the results of the generic DH grid modelling approach that is based on the effective width concept comply with the results obtained from a detailed, optimisation-based model? (2) What are advantages and disadvantages of both concepts?

In this chapter, the DHMIN model is used as a detailed modelling approach [40]. Both approaches are applied to the case study of Brasov in Romania.

3.2 Methodology

In this chapter, the steps that should be taken for the comparison of the two approaches are explained. Firstly, potential DH areas are identified. These areas are relevant for the comparison of the two approaches. The results of both approaches depend directly or indirectly on heat demand densities and plot ratios. To understand the differences of results under various heat densities and plot ratios, the identified DH areas are broken into smaller sub-areas. Finally, the DHMIN model is run on all sub-areas.

3.2.1 Identification of potential district heating areas

The effective width concept is a generic approach. In other words, it can be applied to any region for calculating DH metrics such as linear heat density and distribution grid costs. This is true even for regions that are not suitable for implementing DH, e.g., due to very low heat demand densities. Therefore, for comparison of obtained results via the effective width concept with results obtained from the DHMIN model, it is essential to look at suitable areas for DH. In this chapter, suitable areas for implementing DH are referred to as "potential DH areas" or "coherent areas".

Here, for the identification of potential DH areas, a similar approach as proposed by Fallahnejad et al. [14] is followed. Fallahnejad et al. used a heat demand density map and a heated gross floor area density map (for obtaining plot ratios) both with one-hectare resolution as input data. The annual expansion of DH grids was modelled as an evolving market share over the investment period. Additionally, reductions in future heat demands, e.g., due to the thermal retrofitting of buildings, were modelled as an expected accumulated energy saving.

The procedure of calculating DH distribution grid costs in each hectare element of heat demand and heated gross floor area density maps are extracted from reference papers [9], [14] and formulated in equations 3-1 to 3-10. It is assumed that DH market share and accumulated energy saving evolve uniformly in all hectare elements. Plot ratios are not changed throughout the study horizon. For the estimation of effective width and subsequently, distribution gird costs, however, the proposed method by Persson et al. in 2019 [9] was used. Accordingly, the DH distribution grid costs are obtained for each hectare element of the input maps. The corresponding costs of connecting buildings to the distribution grid are not included in the analyses of this chapter. With regards to Eq. 3-5, a pipe diameter of 0.02 m is applied uniformly for all hectare grid cells with linear heat densities of above zero and below 1.5 GJ/m [9].

For the identification of potential DH areas, two conditions should be fulfilled:

- The average distribution grid costs within a potential DH area should be below a pre-defined cost ceiling;
  The average distribution grid cost within a region is obtained by summing the absolute distribution grid costs in Euro divided by the sum of discounted heat demand covered by DH over the depreciation time of the grid. A constant market share and heat supply are considered for the years after the end of the investment period (when the target market share is achieved) until the end of the grid depreciation time.
- The annual heat demand within a potential DH area should be above a given threshold. This condition is relevant for identifying the minimum size of the DH grid system.

$$w = A_L/L = \begin{cases} 137.5 * pr + 5 \quad [m] & 0 < e \leq 0.4 \\ 60 \quad [m] & e > 0.4 \end{cases} \quad \text{(Eq. 3-1)}$$

$$LHD = Q_T/L = pr * q * w = q_T * w \quad [GJ/m] \quad \text{(Eq. 3-2)}$$

$$q = Q_T/GFA \quad [GJ/(m^2)] \quad \text{(Eq. 3-3)}$$

$$q_T = Q_T/A_L \quad [GJ/(m^2)] \quad \text{(Eq. 3-4)}$$

$$d_a = 0.0486 \cdot \ln(Q_T/L) + 0.0007 \quad [m] \quad \text{(Eq. 3-5)}$$

$$D_{T+t} = D_T \cdot \sqrt[m]{(1-S)^t} \quad [GJ] \quad \text{(Eq. 3-6)}$$

$$0 \leq S \leq 1 \quad ; \quad t \in \{0,1,2, \dots, m\} \quad \text{(Eq. 3-7)}$$

$$Q_{T+t} = D_{T+t} \cdot \left[MS_0 + t \cdot \frac{MS_m - MS_0}{m} \right] \quad [GJ] \quad \text{(Eq. 3-8)}$$

$$I/L = C_1 + C_2 * d_a \quad [€/m] \quad \text{(Eq. 3-9)}$$

$$C_d = \frac{C_{1,T} + C_{2,T} \cdot d_a}{\left(\sum_{t=0}^{m} \frac{Q_{T+t}}{(1+r)^t} + Q_{T+m} * \sum_{t=m+1}^{n} \frac{1}{(1+r)^t} \right)/L} \quad [€/GJ] \quad \text{(Eq. 3-10)}$$

w	Effective width [m]
A_L	Land area [m²]
L	Total trench length [m]
Pr	Plot ratio [-]
GFA	Gross floor area [m²]
q	District heating demand per unit of heated floor area in year T [GJ/m²]
q_T	District heating demand per unit of heated land area in year T [GJ/m²]
Q_T	District heating demand in year T [GJ]
D_T	Annual heat demand in year T [GJ]
S	Expected accumulated energy saving over the investment period [%]
m	Number of years required to achieve the target DH market share [-]
n	Depreciation time [year]
d_a	Average pipe diameter [m]
MS_t	DH Market share within DH areas in t^{th} year [m]
I	Heat distribution investments [€]
Q_T / L	Linear heat density [GJ/m]
C_1	Construction costs constant [€/m], here 212 €/m
C_2	Construction costs coefficient [€/m²], here 4464 €/m2
C_d	Levelized cost of heat distribution [€/GJ]
r	Interest rate

The input GIS layers, namely a heat demand density map and a heated gross floor area density map have a resolution of 100x100m. As a result, a potential DH area could be as small as one hectare. There is, however, no upper limit for the size of a coherent area. The above two conditions for the identification of potential DH areas do not lead to uniform characteristics in terms of heat demand densities and plot ratios within cells of a coherent area. Therefore, for a better understanding of the strengths, weaknesses and differences between the results of this approach and the outputs of the DHMIN model, it is necessary to break coherent areas into smaller sub-areas.

3.2.2 Breaking coherent areas into sub-areas

To break coherent areas into sub-areas, a minimum peak load heat demand within each sub-area is set as a criterion. This criterion assures that heat demands in sub-areas are not too low and also are compliant with the existing substations' capacities in the market. Here, a minimum peak load heat demand of 3.5 MW is set for each sub-area. For the determination of sub-areas, an optimization-based clustering approach is used. The optimization model is formulated so that no upper bound for the peak load heat demand is required.

A number of initial seeds within coherent areas are defined. For the calculations in the next step, it is necessary that seeds are located on a street segment. Therefore, it is possible that, in some cases, they lay slightly outside a coherent area. The seeds represent substations, and their initial number should be large enough to fulfil the 3.5 MW criterion. Furthermore, the initial seeds should be distributed across coherent areas (e.g., uniformly with a 200m radius) so that each cell within a coherent area can be allocated to one and only one seed. This is also important for maintaining the cohesion of sub-areas.

The objective function of the optimization model is to minimize the distance of cells in a sub-area from their allocated seed as shown in Eq. 3-11. To minimize the objective function, the model only maintains the most suitable seeds and allocates cells to a limited number of seeds. The mathematical formulation of the optimization model is as follows:

$$\min_{c,s} \sum_{c=1}^{C} \sum_{s=1}^{S} d_{cs} * b_{cs} \qquad \text{(Eq. 3-11)}$$

Where:

$c \in \{1,2,\dots,C\}$ set of cells in the coherent area
$s \in \{1,2,\dots,S\}$ set of initial seeds

Two parameters are defined: d_{cs} shows the distance of cell c from seed s; P_c shows the peak demand in cell c.

Two variables are defined: b_{cs} which is a Boolean that allocates each cell to only one seed; $seed\_b_s$ which is a Boolean showing if the seed should be kept or should be omitted.

The constraints are as follows: one constraint to assure allocation of each cell to only one seed (Eq. 3-12); one constraint to keep seeds that have at least one allocation (Eq. 3-13); one constraint to maintain the minimum heat load demand of 3.5 MW in each cluster (Eq. 3-14).

$$\sum_{s=1}^{S} b_{cs} = 1 \quad \text{(Eq. 3-12)}$$

$$\sum_{c=1}^{C} b_{cs} \geq seed\_b_s \quad \text{(Eq. 3-13)}$$

$$\sum_{s=1}^{S} b_{cs} * P_c \geq 3.5\ MWh \quad \text{(Eq. 3-14)}$$

Once the sub-areas are obtained, the heat demand, DH potential, trench length and specific distribution within sub-areas are calculated.

3.2.3 The DHMIN model

DHMIN is a mixed integer linear programming model, which finds the maximum revenue trade-off for the extension and size of the DH network [40]. The main features of DHMIN are the capability to model peak loads (short duration) and typical loads (long duration), heat source availability (redundancy study), existing DH pipelines, and oblige pipe construction on certain routes to find pipe dimensions and their corresponding heat losses.

In order to use DHMIN, it is necessary to have heat demand data on the building level. Building heat demands are allocated to their closest street segment. To comply with the obtained results from the effective width approach, a connection rate as well as heat saving level are applied to the building heat demands across all street segments. Since the DHMIN model does not support an evolving market share for calculating levelized cost, the highest connection rate through the investment period is taken from the approach based on the effective width and used as input to the DHMIN model. This implies higher heat delivery through the lifetime of the pipelines compared to the effective width approach.

The aggregated peak load demands on street edges are also fed into the model. It is assumed that the substation is capable of supplying the required heat in the sub-area. In contrast to the effective width approach, which was solely based on the demand side, the DHMIN model requires data on the supply side (e.g., heat sale price) as well in order to calculate the revenue. Figure 3-1 depicts the input/output flow of the DHMIN model [40].

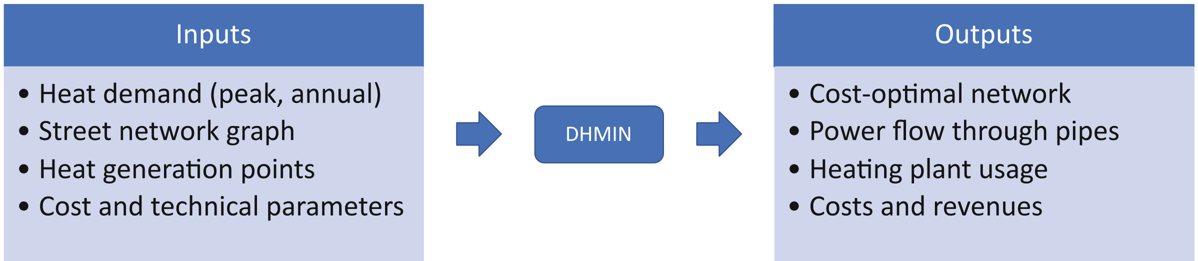


Figure 3-1 Input/output flow chart of model DHMIN (source: [40])

Figure 3-2 illustrates the model input/outputs by an example. In this figure, the street segments are shown in turquoise. In the left figure, the heat loads are shown in red. Higher heat loads are depicted with thicker red lines. The substation is presented by a yellow triangle. In the right-hand-side figure, the optimal heat flow and the extension of distribution grids are shown. Based on the heat flow, suitable pipe dimensions and their associated costs can be calculated. More details on DHMIN model are provided in the reference [40].

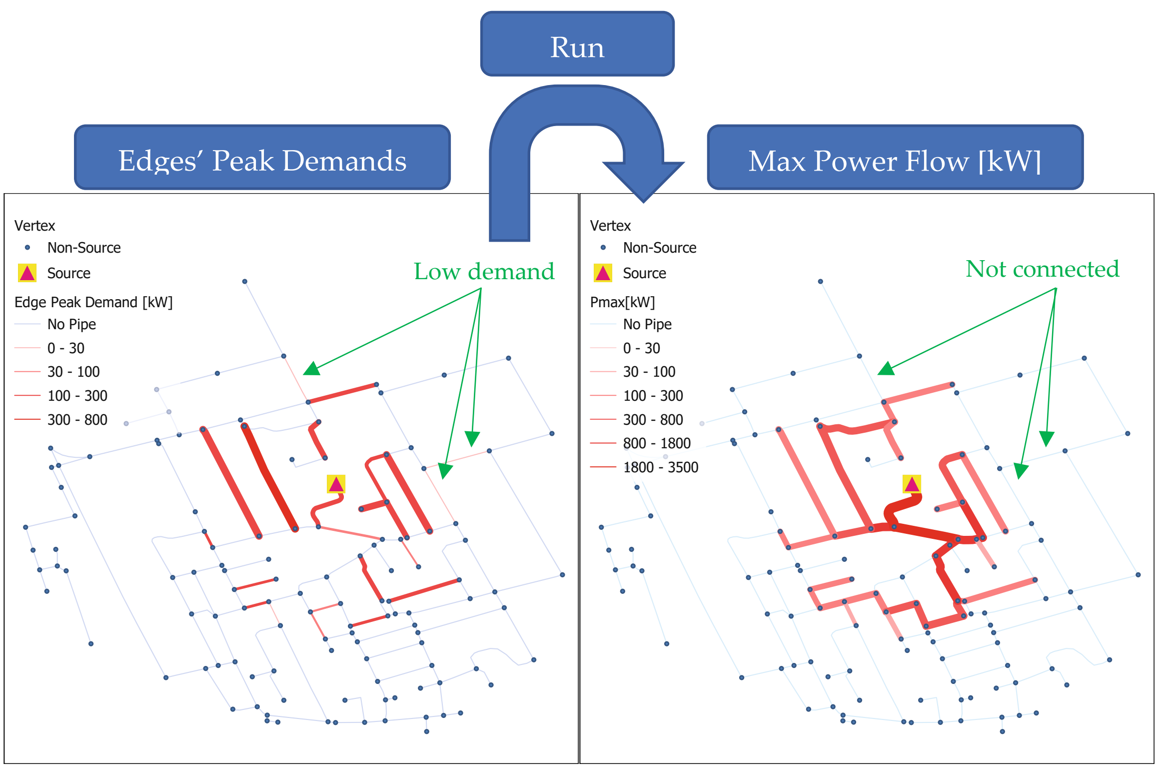


Figure 3-2 Example of input data sets (left) and obtained results (right)

3.3 Case study

The DH system in the city of Brasov was initially designed to supply steam to industry consumers and hot water to residential consumers. By the shutdown of industrial consumers in 1990, the DH system got away from its primary purpose and became ineffective due to oversized pipelines and high heat losses in the grid. The lack of coherent policy in reviving the DH system, as well as the loss of customers, further deteriorated the situation for the DH system in Brasov. In recent years, however, the Local Counsel has established new actions toward the increase of DH efficiency and, consequently, the increase of welfare in Brasov.

In this chapter, the provided policy recommendations for Brasov's DH system by the progRESsHEAT project, a Horizon 2020 project for supporting the market uptake of existing and emerging renewable technologies [46], are used. The policy recommendations aim at increasing the competitiveness of the DH system in Brasov, given the local barriers and drivers for this technology. For the comparison of the results obtained in this chapter with the existing DH grid topology in Brasov [47], the boundary conditions defined in policy recommendations [48] should be considered. In this chapter, however, the main focus is put on the comparison of results of two approaches, which were introduced in Chapter 3.2.

Table 3-1 and Table 3-2 show the input parameters for each model, which are obtained from progRESsHEAT project. As can be seen in the tables, each model requires a different set of input parameters. In the case of the DHMIN model, certain parameters can be provided by the user or can be calculated by the built-in functions in the model. Here, where possible, the built-in function is used. In addition to the input parameters, the input data used by each model are different as well. While the first approach requires only heat demand density map and plot ratio map, the DHMIN model requires shapefile of street segments (obtained from Open Street maps [49]), heat load on each street segment (calculated based on building heat demand from prgRESsHEAT and peak load factor in Table 3-2), max pipeline capacity on each street segment (optional), location of heat source (was set according to the Chapter 3.2.2), etc.

While DH pipes are available in discrete nominal sizes, e.g., DN40 and DN50, DHMIN uses a simplified continuous function for the determination of pipe sizes and costs. DHMIN uses piecewise linearization to keep the problem linear and solve the model with a Mixed Integer Linear Programming (MILP) approach.

Table 3-1 Input parameters for the first approach based on effective width concept (source: [48])

Parameter	Value	Unit	Description
Investment Horizon	16	years	The period in which money flows into the expansion of DH networks
DH market share - Start	16	%	Share of heat demand covered by DH in coherent areas at the start of the investment period
DH market share - End	62	%	Targeted share of heat demand covered by DH in coherent areas at the end of the investment period
Accumulated energy savings (expected)	17.5	%	Achievable heat-saving level by following the policy recommendations at the end of the investment period compared to the start year
Minimum annual heat demand in a potential DH area	1	GWh	The threshold from which an area can be considered a potential DH area
Grid cost ceiling	27	€/MWh	The average DH grid cost within a potential DH area may not exceed this value
Depreciation period	30	years	For the DH network
Discount rate	6	%	-

Table 3-2 Input parameters for the second approach based on the DHMIN model (source: [48])

Parameter	Value	Unit	Description
Investment Horizon	16	years	The period in which money flows into the expansion of DH networks
Heat sale price	89.5	€/MWh	Wholesale heat sale price
Connect quota	62	%	Representing buildings connected to the grid. Here, is considered as a share of the heat demand of buildings along a street segment, which is covered by DH
Pipe costs	built-in function of DHMIN	-	Identifies the cost of the pipeline based on its length and dimension
Thermal losses	built-in function of DHMIN	-	Identifies the heat losses along each pipe segment
Peak load factor	0.000568	-	Used to size pipes
Source vertex capacity	equivalent to the demand in the sub-area	-	Heat load that can be covered by a heat source
Depreciation period	30	years	For the DH network
Discount rate	6	%	-

3.4 Results

First of all, the potential DH areas were identified as explained in chapter 2.1. The obtained coherent areas were divided into sub-areas following the steps in chapter 2.2. In total 15 sub-areas were obtained. Figure 3-3 shows the sub-areas and labels them based on the heat demand in each sub-area. The first three sub-areas belong to the city centre and have higher heat demands compared to the rest of the sub-areas.

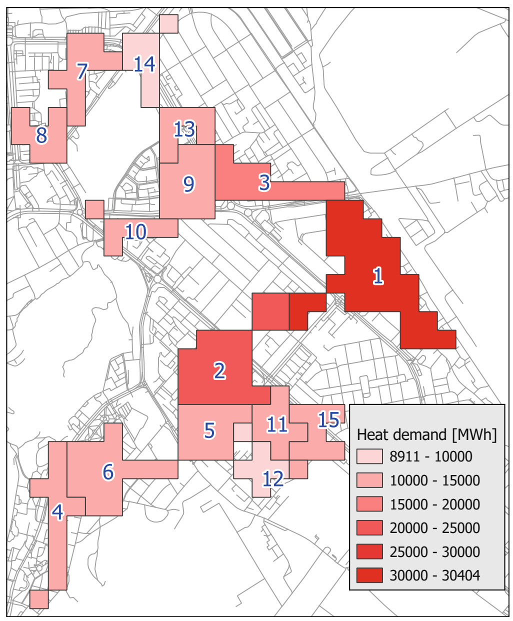


Figure 3-3 District heating sub-areas and their rank based on the heat demand

The indicators for the first approach were calculated for each sub-area, and the DHMIN model was run on each of the 15 sub-areas. Figure 3-4 shows the distribution grid calculated by the DHMIN model in each sub-area. For the comparison of obtained indicators from both approaches, three indicators are investigated.

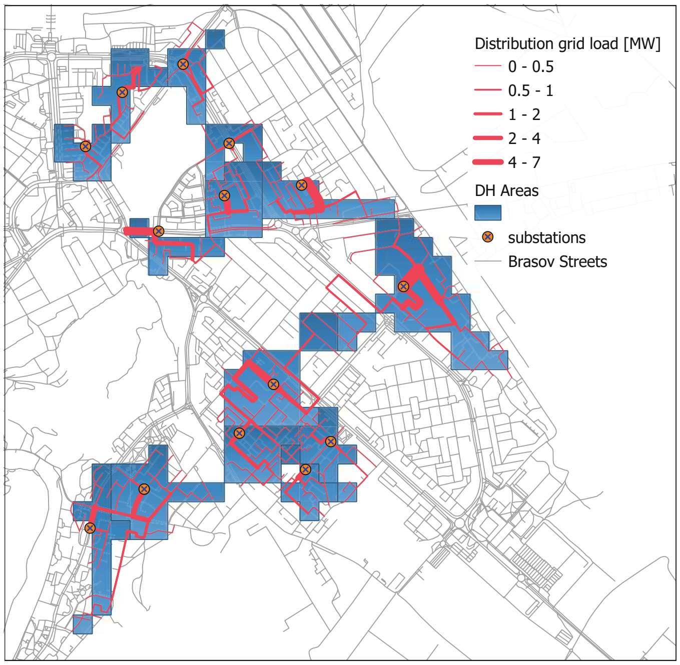


Figure 3-4 Potential district heating areas and distribution grids in sub-areas

Each sub-area is primarily characterised by its annual heat demand and DH potential. Based on the first approach, a DH potential in magnitude of 62% of the total heat demand of the sub-area is achieved deterministically. However, DHMIN covers only a portion of 62% of the heat demand, for which the revenue is maximized. Figure 3-5 shows the heat demand in each sub-area and the achievable DH share obtained from DHMIN. With the exception of sub-area 10, where only 51% market share was achieved, other sub-areas have market shares of close to 62%.

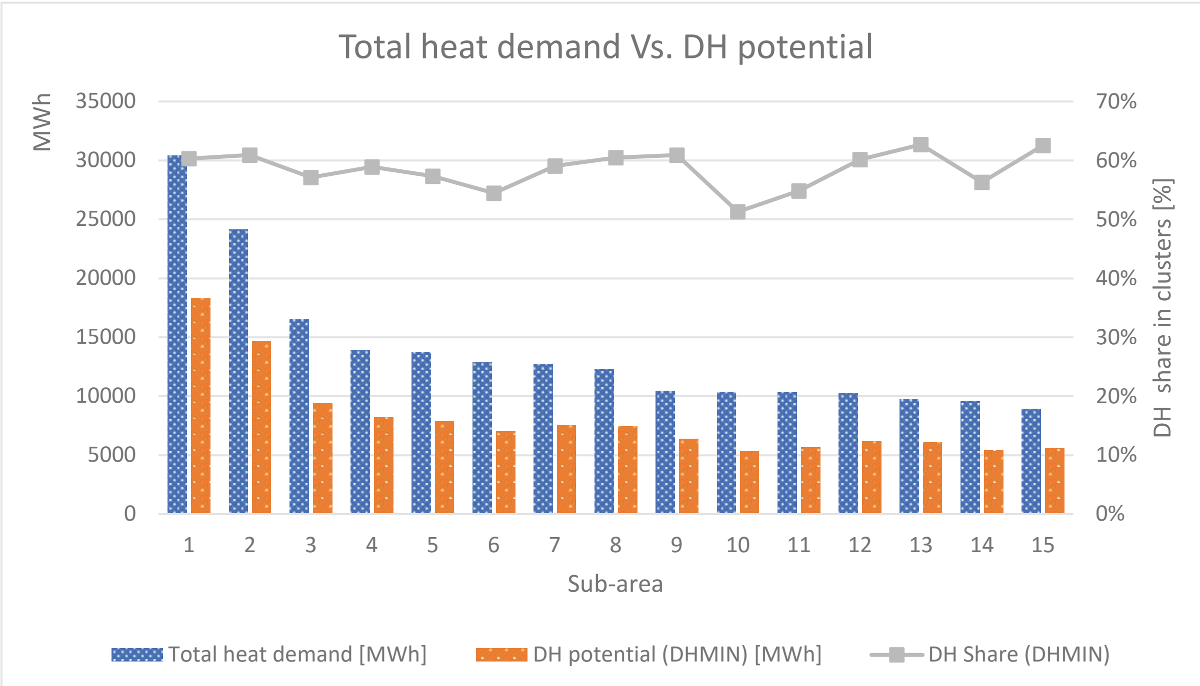


Figure 3-5 Total heat demand Vs. DH potential obtained by DHMIN

Trench length is an important parameter for the cost of distribution grids. Figure 3-6 puts the trench length obtained by both approaches beside each other and also shows their differences in percentage. In contrast to the DH potentials, there is a considerable difference between obtained values from both approaches. This difference is more significant in smaller sub-areas. One reason is the fact that effective width is set to the constant value of 60m for areas with a plot ratio of greater than 0.4, which is basically an average number and might slightly deviate in reality. Another reason is that the DHMIN model uses street segments for estimating trench length, and they might be slightly longer than the required trench length in practice. Despite the differences, the key fact here is that both approaches closely follow the same trench length pattern. In other words, both approaches demonstrate similar peaks and dips.

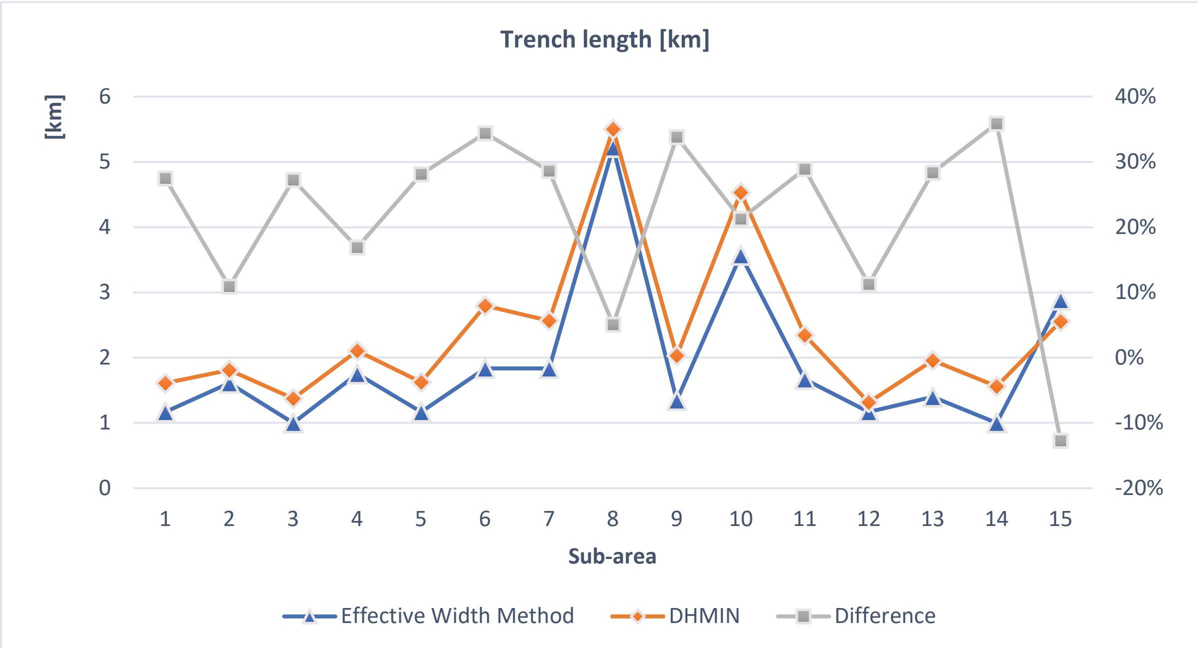


Figure 3-6 Comparison of trench length in sub-areas

The third indicator that is investigated is the specific distribution grid cost in sub-areas. The comparison of specific distribution grid costs is difficult as both approaches have different cost components and model inputs. Figure 3-7 demonstrates the obtained specific distribution grid costs from both approaches. Here, the differences in absolute values (Figure 3-7, left figure) are significant. In all sub-areas, the DHMIN model returns lower distribution grid costs. This is due to the fact that the DHMIN model assumes a constant heat delivery in magnitude of approximately 62% of the heat demand in sub-areas over the lifetime of the distribution grid while the approach based on the effective width considers evolving DH market share starting at 16% of the heat demand in sub-areas.

To facilitate the comparison, the result of each approach is normalized to its average value (Figure 3-7, right figure). As can be seen, both approaches are closely following the same pattern. It can be inferred that the characteristics influencing the specific distribution grid in sub-areas are reflected and followed in both models.

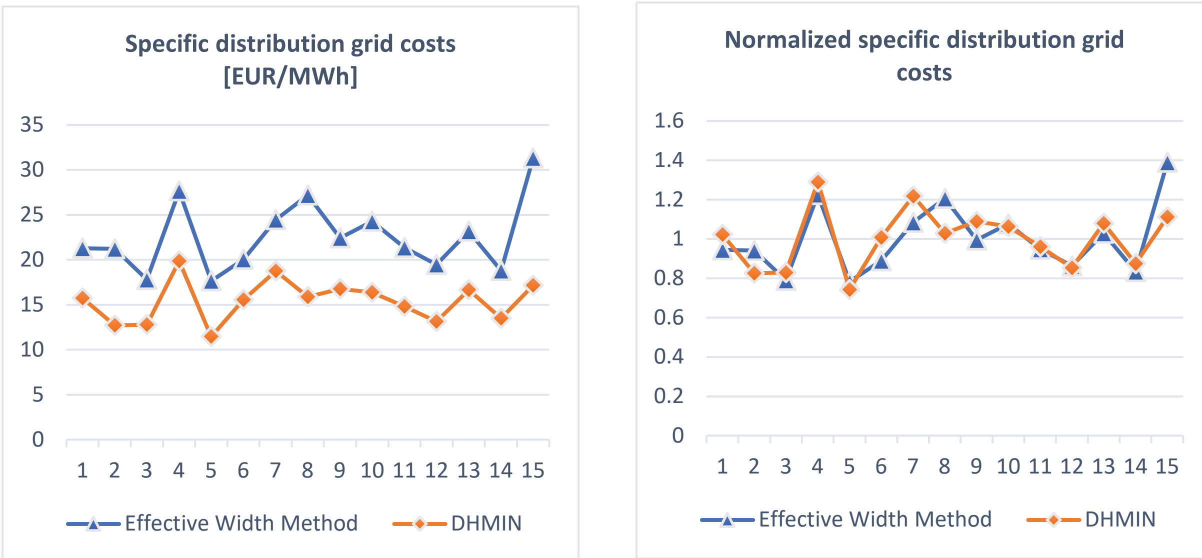


Figure 3-7 Comparison of specific distribution grid costs in sub-areas

3.4.1 Limitations and discussion of results

The limitations of each approach have been mentioned in their reference papers [9], [40] and will be discussed further here. The formula of the effective width has been obtained through an interpolation of the empirical data of the existing DH system [29]. The mixture of the DH generation that was available in the empirical dataset may lead to a better modelling of DH grid costs for a certain DH generation compared to other ones. Moreover, the DH system supply temperature is not addressed directly by the approach as it is encapsulated in the empirical data sets.

The interpolation on the empirical data set gives effective width values that can lead to an overestimation of the DH distribution grid costs in certain cases; while for others might be an underestimation. This aspect has been addressed in the revised version of the approach [37] by putting the effective width line below the values obtained for each sample DH network. Although the obtained costs in this manner lead to a conservative estimation, it can be argued that the obtained potential DH areas based on overestimated costs are highly reliable.

In spite of the limitations, the approach has great benefits. First of all, the methodology is transparent and replicable. It is, therefore, possible to calculate a new formulation of the effective width with another set of DH network data and plot ratios. Once the formulation of effective width is available, no further data on the DH grid is required. Additionally, for the calculation of the DH distribution grid, only two data sets are required: A heat demand density map and a plot ratio map, both of which can be found in open-source data sources. Finally, the low computation time required by the approach can be highlighted as one of its main advantages.

Compared to the effective approach, DHMIN models the DH grid with more details. The additional level of detail is accompanied by the need for additional data, assumptions and simplifications. DHMIN does not model fluid dynamics. Thermal losses are modelled in a simplified manner. The relation between thermal losses, transfer capacity and specific costs of pipes with pipe dimensions are provided in a generic manner within built-in functions. However, if generic functions do not fit a certain case study, they should be revised by the user.

DHMIN considers one supply temperature for the whole DH system. The supply side and temporal aspects are modelled weakly. Although it is possible to do redundancy studies with it, the model is not suitable for unit commitment calculations. Furthermore, inter-temporal optimization for investment decisions is not supported by DHMIN, as it provides an optimal solution for target system configurations. Furthermore, the identification of the ideal technology investment pathways to reach the optimal target configurations is not covered [40]. Due to the optimization nature of the model, solving large-scale problems (>20,000 street segments) requires long CPU time and commercial solvers.

Despite the limitations, DHMIN has great advantages. The model is written in Python and has an open-source license (GNU GPLv3), giving permission for redistribution and modification. Spatial aspects are modelled with great details, which was also relevant for the comparison purposes done in this chapter. The libraries used in the model, allow integrating various open-source and commercial optimization solvers. The numerous components of the model and built-in functions give the possibility to improve the model where additional data is available. Furthermore, DHMIN allows the modelling of existing DH pipelines or imposing pipe construction at certain routes.

Regardless of the approach, to get reliable results on DH potential and costs for a given case study, the input parameters and cost components should be tuned anyway to that case study. The evolution of the gross floor areas should also be a focus of future studies. The identification of potential DH areas can be done with low CPU time using the effective width concept as well as constraints named in Chapter 3.2.1. This could be very useful for large-scale case studies. DHMIN, on the other hand, provides higher spatial details and additional outputs at the cost of higher CPU time. Besides the CPU time, the availability of input data could be decisive. The approach based on the effective width concept is less data intensive and might be preferred in case of data availability. The data preparation and model setup for running the DHMIN model require more effort.

Depending on the use case and required level of detail, one approach might be preferred to the other one. It is also possible to combine both approaches, where the potential DH areas are obtained based on the suggested approach in Chapter 3.2.1 and detailed spatial analyses within coherent areas are done using DHMIN. In this case, more data is required, and preparatory steps are bound with more effort compared to applying only one of the approaches.

Considering the limitations, it should be noted that both approaches are suitable for the pre-feasibility studies. To compare the behaviour of approaches, it was necessary to look at different heat demand levels and sizes of coherent areas. This was done by comparing results in the sub-areas. In the case of DH potential and trench length, both approaches follow similar patterns. With regard to the differences between both methods, it can be concluded that both methods confirm the results of each other with an acceptable approximation.

3.5 Conclusions

In this chapter, two approaches for the calculation of DH distribution grid costs were compared with each other. The first approach was based on the effective width concept. The second approach, on the other hand, was based on a detailed, optimization model. It should be emphasised that the goal of comparisons was not to identify the better approach; but rather to understand the challenges of using each of the two approaches, their strengths and weaknesses. For the comparison, three indicators were investigated: achieved DH potential, trench length and specific distribution grid costs.

Although both approaches provide different values for studied indicators in absolute terms, the comparisons revealed that they demonstrate and follow similar patterns in different sub-areas. Regardless of the approach, to get reliable results for a given case study, the input parameters and cost components should be tuned anyway to that case study.

Depending on the availability of data, one may prefer one approach to the other one. The approach based on the effective width concept is more suitable for cases with limited data availability and might be preferred for calculation on a large area as it does not need any optimization or complex calculation. It is also possible to model an evolving market share through the investment period. To obtain reliable results from the approach based on the effective width concept, besides tuning the cost components for a case study, it is also important to perform some sort of filtration of the potential DH area. Where detailed data is available, the DHMIN model is capable of providing relatively detailed results. The DHMIN model requires no filtration of areas. Running the DHMIN model for a large area, however, requires additional effort for data preparation and model setup. The CPU time for solving the optimization problem could also increase as the case study becomes larger.

4 District heating potential at the EU level

This chapter is mainly based on the peer-reviewed article: District Heating Potential in the EU-27: Evaluating the Impacts of Heat Demand Reduction And Market Share Growth [16].

This chapter presents a novel approach to modelling the gradual reduction in heat demand and the evolving expansion of DH grids for assessing the DH potential in EU member states (MS). It introduces new methodological elements for modelling the impact of connection rates below 100% on heat distribution costs in both dense and sparse areas. The projected heat demand in 2050 is derived from a decarbonization scenario published by the EU, which would lead to a reduction in demand from 3128 TWh in 2020 to 1709 TWh by 2050. The proposed approach yields information on economic DH areas, DH potential, and average heat distribution costs. The results confirm the need to expand DH grids to maintain supply levels in view of decreasing heat demand. The proportion of DH potential from the total demand in the EU-27 rises from 15% in 2020 to 31% in 2050. The analysis of DH areas shows that 39% of the DH potential is in areas with heat distribution costs above 35 EUR/MWh, but most MS have average heat distribution costs between 28 and 32 EUR/MWh. The study reveals that over 40% of the EU’s heat demand is in regions with high potential for implementing DH.

4.1 State of the art

The European Union (EU) has set ambitious climate targets to become climate-neutral by 2050. Decarbonizing the heating sector is one of the key challenges if this target is to be achieved. DH is a technology with both the economic and environmental potential to contribute to the decarbonization of the heating sector in Europe [50] and has, therefore, been studied from different perspectives.

Sven Werner provides an overview of the district heating and cooling in the world [51]. He identifies the disconnection of customers from DH in Eastern Europe and simultaneous DH expansions in other European countries as the main reason for the stagnation of DH supply in Europe at 2.5 EJ/year from 1990 to 2014, referring to the potential of DH systems as a viable heat supply option in the future. Werner emphasizes, however, the need for additional effort in identifying, assessing, and implementing DH potential.

The Heat Roadmap Europe (HRE) [35] can be considered one of the front-runners for identifying and assessing DH potential in Europe. The project is focused on developing low-carbon heating and cooling strategies. HRE foresees an upward potential for DH supply from its current 10% share to 50% by 2050 [52].

Estimating the DH potential through GIS and heat mapping has been practised on different geographical levels. Novosel et al. applied heat mapping to the case study of Zagreb [53]. They calculate the DH potential at different cost levels. Patureau et al. used GIS to categorize regions in France based on their suitability for the low-temperature DH systems and report France's potential for low-temperature district heating and cooling. In a GIS-based approach, Leurent calculates the linear heat density and DH potential using a heat density map of France [54].

The estimation of the DH potential based on heat distribution costs has been addressed in several papers. Möller et al. present the share of annual final heat demand that can be covered under different average annualized investment costs of DH for 14 European countries [55]. Fallahnejad et al. analyse the impact of transmission and distribution grid costs on DH potential for the case study of Vienna [24]. They conclude that policy interventions for implementing DH priority areas are required to achieve the full potential of the DH in Vienna. Dénarié et al. propose a method to assess the network length and heat distribution costs of potential DH systems in Italy [36].

The potential of RES-based DH systems has also been the focus of research work. GIS is often used as a means for calculating the potential. Soltero et al. studied the potential of biomass DH systems in 499 rural areas in Spain [56]. They identify 188 potential areas for implementing the biomass-based DH system, of which 185 rural areas are economically viable.

Matching of source and sinks is another approach for estimating DH potential. Nielsen and Möller performed a GIS-based analysis of future DH potential in Denmark [26]. They demonstrate the potential for DH expansion in many areas of Denmark. High production costs and heat losses are enumerated as barriers to expanding the DH in other regions. Persson et al. analyse the excess heat volumes from fuel combustion activities in the power and industry sectors and identify synergy regions for utilizing the excess heat on the EU-27 level. Pampuri et al. developed a heat demand density map for the Ticino Canton in Switzerland and set a demand threshold to identify suitable areas for DH. Subsequently, the availability of renewable sources for heat supply in the areas identified was investigated. Fallahnejad et al. studied the economic potential of DH under climate neutrality for the case of Austria [6] and in line with Article 14 and Annex VIII of the revised Energy Efficiency Directive [1]. Having identified potential DH areas and nearby RES, they calculate the economic potential of DH by dispatch of available renewable energy sources, and compare the DH costs with decentral supply options.

There are studies in the literature that estimate the potential of DH considering future heat demand and supply systems. Connolly et al. analyse a strategy focusing on the expansion of DH along with the utilization of waste heat, consideration of heat savings and integration of renewable energy sources [57]. They conclude that a heat supply strategy based on DH systems could lead to cost reduction. Champers et al. mapped the DH potential under evolving heat demand scenarios and technologies for the case of Switzerland [58]. They conclude that the DH potential from high-temperature grids would decrease considerably while the DH potential from low-temperature grids would significantly increase.

There is a range of studies that deal with detailed DH grid modelling for the calculation of the economic DH potential. These studies often use optimization or computational-intensive models and focus on a small area. Examples of these studies can be found in [8], [43], [44], [59], [60], [61]. Due to the intensity of the calculation and the high granularity of the required data, these approaches are not suitable for large geographical areas like the EU or national level.

4.2 Core objectives

Five gaps were identified in the literature, which will be addressed in here:

- All studies mentioned above provide great insights into the DH potential in their focus areas. However, many of the studies have not considered future demand developments. Furthermore, the new European climate targets and laws, such as the European Green Deal or Fit-for-55 package, have not been considered in the heat demand scenarios of these studies.
- The studies on the DH potential often consider 100% connection rates in DH areas for their economic analyses. However, implementing the DH grids is realized gradually due to various limitations, such as financial or human resource limitations. The gradual construction and implementation of DH networks affect the economics of DH systems. This gradual implementation has not been addressed in previous studies on the EU level.
- Many of the studies use the concept of the effective width (the relationship between a given land area and the DH trench length within this area) as proposed in [11] or [9] to calculate heat distribution costs. At the same time, the Horizon 2020 project sEEnergies [12] has recently published an updated, validated approach, introducing service pipes in addition to distribution pipes and adapting cost components for each EU member state [37]. The updated approach improves the estimation of the heat distribution costs. The combination of the recent approach with the previously mentioned gaps can provide a more recent and accurate insight into the DH potential.
- DH potential and its economic viability in sparse areas have been addressed in Swedish case studies [62], [63]. However, due to limited DH potential in sparse areas, these regions have not been the mainstream focus of research studies on the EU level. In this chapter, sparse regions and their DH potential will be addressed as well.
- The whole approach is implemented in Python with an open-source license to facilitate the replicability of the results and the possibility of conducting further analyses under

various heat demand scenarios. Furthermore, the outputs of the analyses follow the FAIR principle [64]. This provides an open, reusable, standardised approach for estimating the DH potential, which did not exist beforehand.

Accordingly, the main objectives of this chapter are: (1) to study the impact of ambitious heat demand reductions on DH potential and consider the dynamic aspect of heat demand development in the calculation of heat distribution costs; (2) to consider the evolving DH market shares over time for the economic assessment of the DH grid; (3) to add methodological elements and steps for more accurate modelling of the sparse area and network lengths at DH market shares of below 100%. (4) to synthesize the heat distribution costs and DH potential and the economic implications for future DH expansions.

4.3 Data preparation

The useful heat demand and gross floor area densities of the residential and service sectors for the years 2020 and 2050 in the form of GIS layers are the basis for the calculations in this chapter. These layers were obtained from a report on "renewable space heating under the revised Renewable Energy Directive" published by the European Commission [65]. In this report, the Eurostat energy balances were used as the main source for the final energy demand on a national level in 2020. The future development of the gross floor area is defined exogenously. The demolition of buildings is based on the Weibull distribution and the average lifetime of the buildings. For the year 2050, an optimization model was used to obtain the final energy demands on a country level. The useful energy demands of each country are calculated accordingly. Finally, both useful energy demands and heated gross floor areas are broken down to the hectare level based on the method developed by Müller et al. [66].

The EC report introduces five scenarios besides the baseline scenario, focusing on direct RES heating, electrification, e-fuels, hydrogen and DH [65]. The scenarios were compared quantitatively and qualitatively. Subsequently, a best-case scenario was developed by combining the feasible ways of decarbonising the building stock in the EU-27 countries. The heat demand and gross floor area densities presented in this chapter are based mainly on the best-case scenario.

Figure 4-1 shows the heat demand levels in 2020 and 2050 in the EU member states and the changes in this period according to the Best-Case scenario. Based on the best-case scenario, the useful heat demand of the residential and service sectors in EU-27 countries dramatically decreases from 3,128.8 TWh in 2020 to 1,709.1 TWh in 2050. The dramatic demand reductions can affect the DH potential. To understand the impact of the demand reductions on DH potential, a further heat demand density layer with a less intense demand reduction for 2050 is used. For this purpose, the baseline scenario (BL2050) from the sEEnergies project is employed [67], [68]. The BL2050 scenario is an adapted version of the PRIMES scenario for 2050 [69], [70]. Based on this scenario, the heat demand in EU-27 countries should be reduced to 2088.7 TWh, 379.6 TWh higher than the best-case scenario.

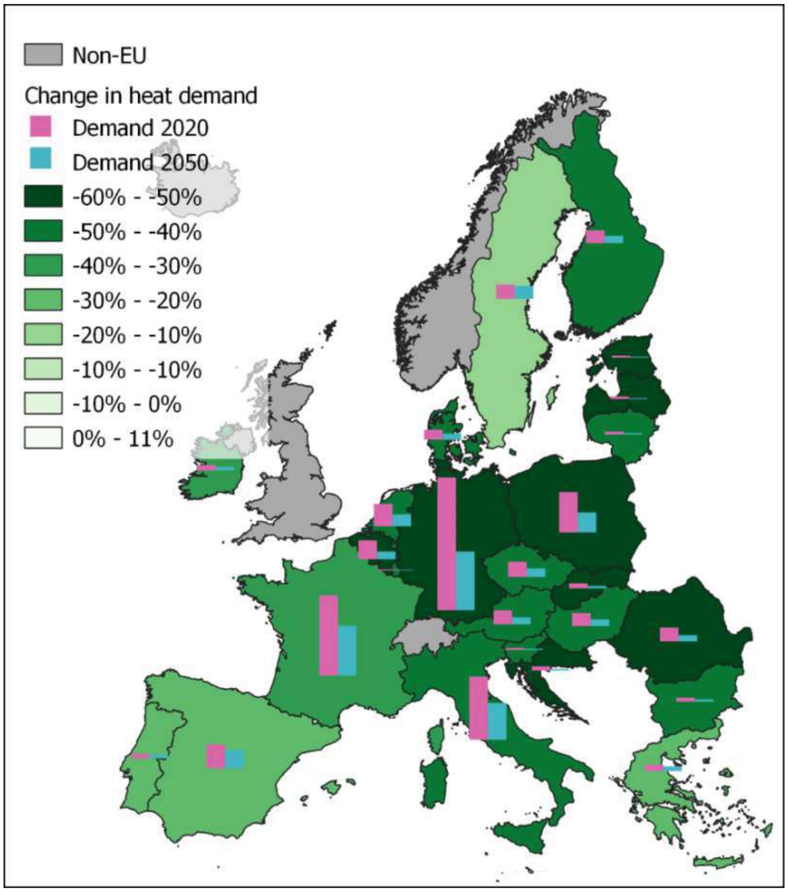


Figure 4-1 Heat demand levels in 2020 and 2050, and the relative changes in residential and tertiary sectors based on the best-case scenario

DH market shares within DH areas are inputs for identifying the DH areas. Considering the decreasing heat demand levels, DH should be expanded further in many regions to maintain the supply level. Therefore, it is expected that DH systems should either maintain high market shares in DH areas or expand significantly till 2050. The impact of the DH market shares on the DH potential is studied in this regard. The values of DH market shares within DH areas in 2020 and 2050 are set so that:

- The obtained DH potentials in 2020 comply with energy balances,
- Considering 2020's DH market shares within DH areas and with regard to the network construction costs in each country, a high DH market share of between 70% and 90% within DH areas is achieved or maintained in 2050.

These values are presented in Figure 4-2.

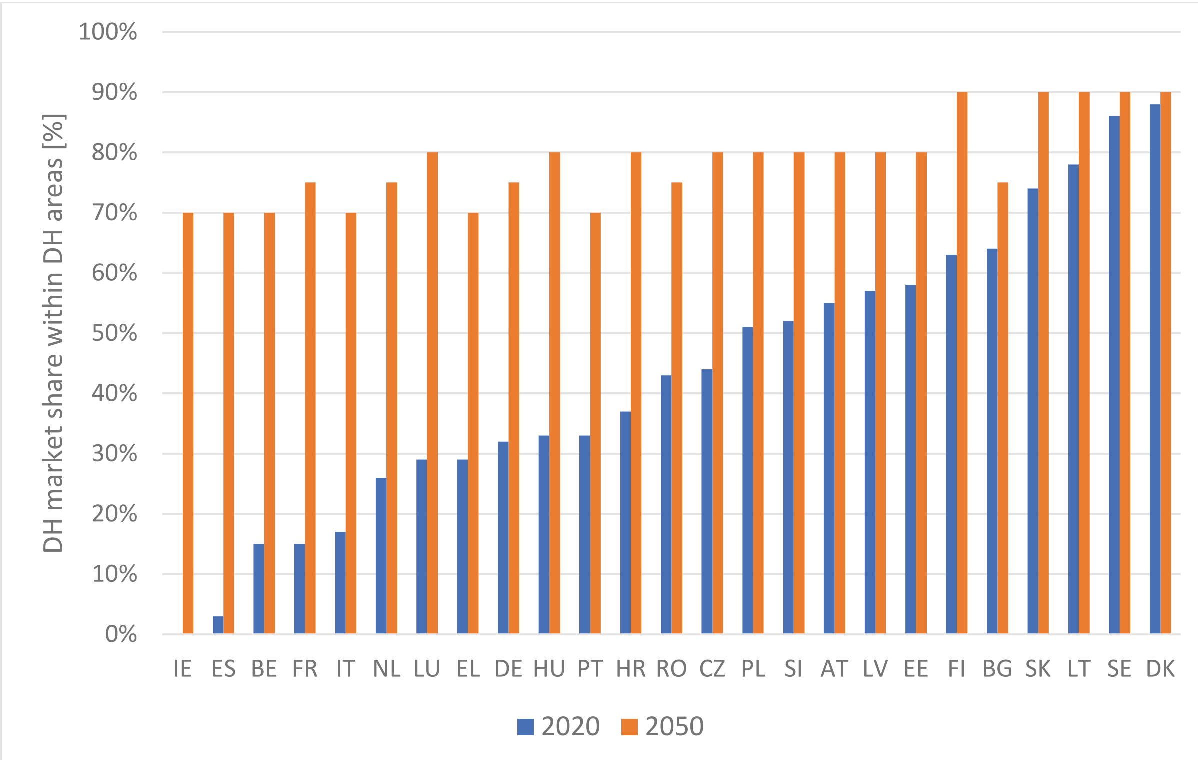


Figure 4-2 DH market shares within DH areas used as inputs for the base year (2020) and target year (2050)

4.4 Methodology

This chapter explains the required steps for calculating the DH distribution and service pipe costs and the required investment for the grids based on the achieved DH market share within identified DH areas. In the context of this chapter, the terms DH area, market share and potential are defined as follows:

- **DH area**: An area within a region where a DH system partially or fully supplies heat to the buildings. In this chapter, a DH area can be as small as 1 ha (resolution of input data). Larger DH areas are composed of several coherent and connected hectare elements. For example, a city can have no, one, two or more DH areas.
- **DH market share within a district area (%)**: The share of heat demand in a DH area supplied by the DH system from total heat demand in the same area. In this thesis, "DH market share" and "DH market share in DH areas" are used interchangeably. DH market shares are defined for each country separately and are model inputs.

- **DH potential (in MWh or GWh, or TWh)**: Shows the amount of energy supplied by the DH system. Considering the provided definition for the DH market share, the multiplication of DH market share in a country and its total heat demand does not provide the DH potential.

Given the above definitions, although the DH market shares are inputs to the model, DH potential cannot be calculated in advance. The calculation of the DH potential is possible once the extent and location of DH areas are identified. The algorithm used for this intention was presented in detail in Chapter 2.2 and will also be elaborated in Chapter 4.4.3.

4.4.1 Heat distribution costs under 100% of market share in district heating areas

In this chapter, a model for assessing the capital cost of DH networks in a national context and identifying the potential DH areas accordingly is introduced.

Persson et al. introduced a methodology to estimate the DH heat distribution costs [9], [11]. Their methodology uses several independent input data, such as pipe diameter, construction costs, interest rate, and demographic data. Figure 4-3 shows the schematic overview of the procedure to calculate DH distribution grid capital costs.

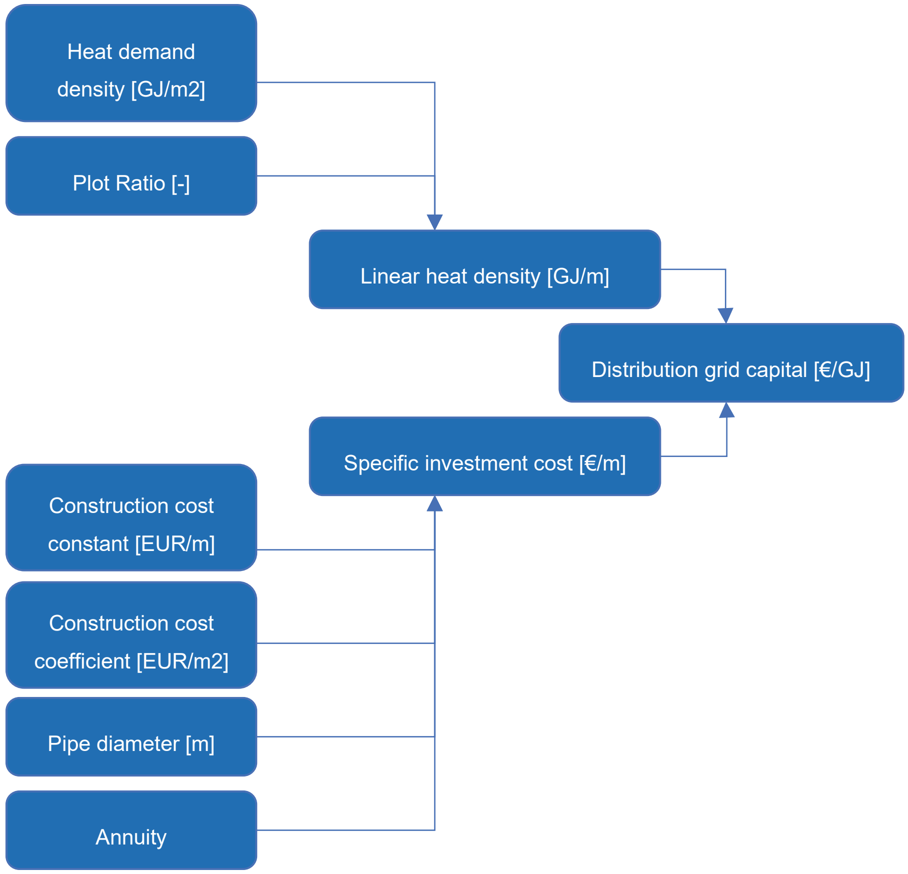


Figure 4-3 Schematic overview of the procedure to calculate DH distribution grid capital costs

Uniform data on heat demand and gross floor area densities, introduced in the previous chapter, are used to apply this method uniformly to a large area. From the gross floor area densities, the plot ratio can be acquired. The following formulas can be applied to each hectare element of the heat demand and gross floor area density maps.

One key concept when assessing DH network investment cost is the linear heat density (*LHD*), defined as the ratio of delivered heat by the DH system (Q_T) in a year to the total DH trench length (*L*), as shown in Eq. 4-1.

$$LHD = Q_T/L \quad [GJ/(m.a)] \qquad \text{(Eq. 4-1)}$$

Persson and Werner use demographic data to calculate the linear heat density analytically. The calculation procedure is shown in equations 4-2 to 4-4. They introduced the concept of effective width (w), which describes the relationship between a given land area (or plot ratio, pr) and the DH trench length within this area [29]. The approach has been used widely and updated a few times with the grid data of different cities. The sEEnergies project addresses one of the most recent updates [12] and provides formulations for the distribution and service pipes. The proposed update is the basis for the calculations performed in this chapter. The effective width of the DH distribution grid can be obtained using Eq. 4-5. As Eq. 4-5 shows, the effective width is assumed to be constant in areas with plot ratios above 0.1353 (hereon, "high plot ratio areas").

$$q = Q_T/GFA \qquad [GJ/(m^2.a)] \qquad \text{(Eq. 4-2)}$$

$$q_T = Q_T/A_L \qquad [GJ/(m^2.a)] \qquad \text{(Eq. 4-3)}$$

$$LHD = \frac{Q_T}{L} = pr * q * w = q_T * w \qquad [GJ/(m.a)] \qquad \text{(Eq. 4-4)}$$

$$w_{DistributionPipe} = A_L/L = \begin{cases} e^2/pr & [m] \quad 0 < pr \leq 0.1353 \\ e^4 & [m] \quad pr > 0.1353 \end{cases} \qquad \text{(Eq. 4-5)}$$

The average distribution pipe diameter ($d_{a,DistributionPipe}$) in meters is calculated using the linear heat density and effective width. In areas with an annual heat demand below 1.5 GJ, the average distribution pipe diameter is set to 20mm.

$$d_{a,DistributionPipe} = \begin{cases} 0.02, & Q_T < 1.5\ GJ \\ 0.0486 \cdot ln(Q_T/L) + 0.0007, & Q_T \geq 1.5\ GJ \end{cases} \qquad [m] \qquad \text{(Eq. 4-6)}$$

Service pipes are referred to as pipes that connect the buildings to the distribution pipes. The effective width of the service pipes ($d_{a,ServicePipe}$) is calculated using Eq. 4-7. An average diameter of 30mm is considered for all service pipes. Only in areas with an annual heat demand below 1.5 GJ, the average service pipe diameter is set to 20mm.

$$w_{ServicePipe} = A_L/L = \begin{cases} e^2/pr & [m] \quad 0 < pr \leq 0.1353 \\ e^{\frac{ln(pr)+3.5}{0.7737+0.18559 \cdot ln\,(pr)}} & [m] \quad pr > 0.1353 \end{cases} \qquad \text{(Eq. 4-7)}$$

$$d_{a,ServicePipe} = \begin{cases} 0.02, & Q_T < 1.5\ GJ \\ 0.03, & Q_T \geq 1.5\ GJ \end{cases} \qquad [m] \qquad \text{(Eq. 4-8)}$$

The specific grid investment cost (I/L) of both distribution and service pipes can be derived using Eq. 4-9. The slope and the intercept of the linear formula are referred to as construction cost constant (C_1) in EUR/m and construction cost coefficient (C_2) in EUR/m², respectively. The parameters C_1 and C_2 are obtained empirically based on the existing networks. Persson et al. calculate these factors for each EU member state [37]. These values are provided in the Appendix of this thesis in Table A.1.

$$\frac{I}{L} = C_1 + C_2 * d_a \qquad [\frac{€}{m}] \qquad \text{(Eq. 4-9)}$$

The levelized cost of heat distribution (C_d) for each unit of delivered heat can be obtained from Eq. 4-10. The annuity factor is obtained based on the discount rate (r) and the depreciation time (n) in years.

$$C_d = \frac{a.I}{Q_s} = \frac{a.(\frac{I}{L})}{(\frac{Q_S}{L})} = \frac{a}{q_{s,T}} \cdot \left(\frac{C_1+C_2 \cdot d_{a,DistributionPipe}}{w_{DistributionPipe}} + \frac{C_1+C_2 \cdot d_{a,ServicePipe}}{w_{ServicePipe}} \right) \quad [\frac{€}{GJ}] \qquad \text{(Eq. 4-10)}$$

$$a = \frac{r*(1+r)^n}{(1+r)^n-1} \qquad \text{(Eq. 4-11)}$$

4.4.2 Heat distribution costs under evolving district heating market share and heat demand

The expansion of DH and connecting new customers is a gradual process. Over time, retrofitting the building stock lowers heat consumption. The economic viability of the DH is affected by both DH heat supply over time and grid expansion. Here, the equations provided in Chapter 4.4.1 are adapted to reflect the impact of the evolving DH market share and heat demand.

The DH market share in a potential DH area shows the portion of heat demand that DH supplies in that area. Considering a time horizon of m years, the annual heat demand changes from its initial value (D_0) to its final value (D_m). It is assumed that the annual heat demands between the base year and target year follow the interpolation in Eq. 4-12. This equation leads to slightly higher heat demand reductions at the beginning of the study horizon and lower reductions near the end.

$$D_t = D_0 \cdot \sqrt[m]{(D_m/D_0)^t} \qquad \text{(Eq. 4-12)}$$

$$t \in T = \{0, 1, 2, \ldots, m\} \qquad \text{(Eq. 4-13)}$$

The DH market share in the base year (MS_0) increases gradually to reach its value in the target year (MS_m). Accordingly, for each hectare element of the map, it is assumed that the delivered heat by DH in t^{th} year (Q_t) follows Eq. 4-14.

$$Q_t = D_t \cdot \left[MS_0 + t \cdot \frac{MS_m - MS_0}{m} \right] \qquad \text{(Eq. 4-14)}$$

The formulation of the effective width in Eq. 4-5 and Eq. 4-7 should be adapted to include the impact of DH market shares of below 100% in DH areas. The effective width has an inverse relation with trench length and is a function of the plot ratio. For high plot ratios ($pr > 0.1353$), the effective width of distribution pipes is independent of the plot ratio. Therefore, the focus is put here on the effective width in low plot ratio areas to find its relation with the DH market share in DH areas.

Chambers et al. show that DH pipeline length is mostly affected by the number of buildings in an area [58]. They provided an empirical formula for calculating the length of supply and return pipes. The trench length can be derived accordingly, as shown in Eq. 4-15.

$$L = l/2 = 65.3 \cdot \ln(N_{buildings}) - 42.25 \quad \text{(Eq. 4-15)}$$

Since the impact of the market share on effective width is only valid in sparse areas with a low plot ratio, it is assumed that a building is either fully supplied by DH or is not connected to the DH at all. In other words, a partial supply of a building with a DH system is not considered here. Therefore, Eq. 4-15 is reformulated and the DH market share is included in its definition. In addition, an adjustment factor is added to the original formula of the effective width (Eq. 4-5) for low plot ratio areas to reflect the impact of the DH market share, as shown in Eq. 4-17.

$$L = 65.3 \cdot \ln(MS \cdot N_{buildings}) - 42.25 \quad \text{(Eq. 4-16)}$$

$$L = A_L \cdot pr \cdot AdjFactor/e^2 \quad \text{(Eq. 4-17)}$$

$$AdjFactor = f(MS) \quad \text{(Eq. 4-18)}$$

$$0 < AdjFactor \leq 1 \quad \text{(Eq. 4-19)}$$

The adjustment factor is defined as a function of the DH market share in DH areas. It can be derived by considering a market share of α%, as shown in Eq. 4-20.

$$\frac{L_{\alpha\%}}{L_{100\%}} = \frac{AdjFactor \cdot pr}{pr} = AdjFactor \quad \text{(Eq. 4-20)}$$

From Eq. 4-5, a plot ratio of 0.1353 leads to a trench length of ca. 183.1m in each hectare, equivalent to connecting 31 buildings based on Eq. 4-15.

Figure 4-4 shows the adjustment factors as a function of the DH market share for different numbers of buildings in a hectare.

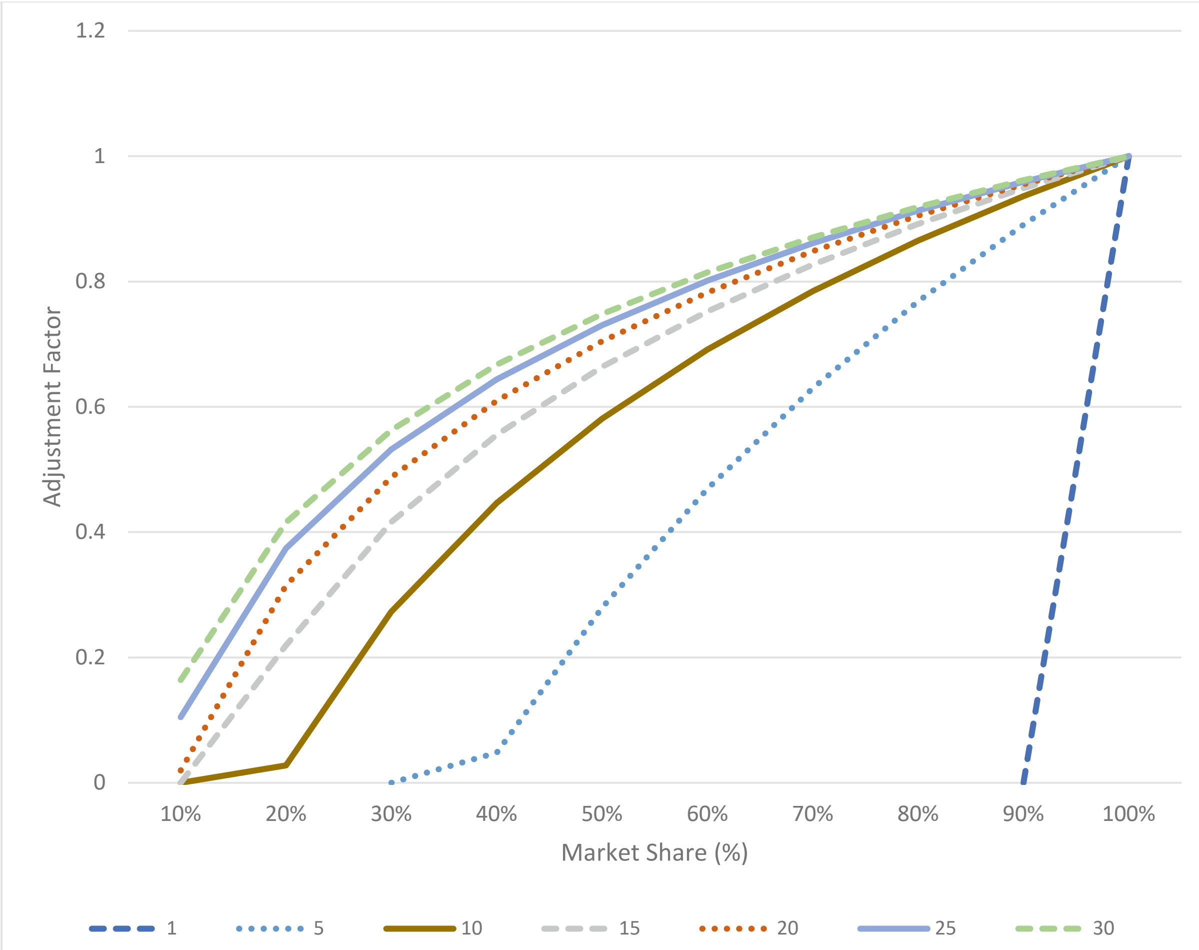


Figure 4-4 Adjustment factors as a function of DH market shares for different numbers of buildings in a hectare

The number of buildings within each hectare of EU-27 countries cannot be obtained easily. However, there are normally few buildings within a hectare in sparse areas with low plot ratios. To simplify the calculation for the adjustment factor, the adjustment factor for ten buildings is used for all areas with a low plot ratio. Here, a minimum adjustment factor of 0.0279 for market shares below 20% is considered. The fitted logarithmic trendline is provided in Eq. 4-21.

$$AdjFactor = \begin{cases} 0.0279, & MS < 20\% \\ 0.604\ln(MS) - 1.7815, & MS \geq 20\% \end{cases} \quad \text{(Eq. 4-21)}$$

The adjustment factor is used to reformulate the effective width for both distribution and service pipes. In the original formulation of the effective width for the service pipes, under higher plot ratios, the effective width rises as the plot ratio rises. This behaviour implies that connecting additional buildings in an area requires longer service pipes. Therefore, lower DH market shares should lead to lower effective width. However, a lower limit of 0.1353 is maintained for the multiplication of the plot ratio and adjustment factor, leading to an effective width of 41.53m. The effective width formulations of distribution and service pipes are provided in Eq. 4-22 and Eq. 4-23, respectively.

$$w_{DistributionPipe} = A_L/L = \begin{cases} e^2/(AdjFactor \cdot pr) & [m] \quad 0 < pr \leq 0.1353 \\ e^4 & [m] \quad pr > 0.1353 \end{cases} \qquad \text{(Eq. 4-22)}$$

$$w_{ServicePipe} = A_L/L = \begin{cases} e^2/(AdjFactor \cdot pr) & [m] \quad 0 < pr \leq 0.1353 \\ e^{\frac{\ln(AdjFactor \cdot pr)+3.5}{0.7737+0.18559 \cdot \ln(AdjFactor \cdot pr)}} & [m] \quad (pr > 0.1353) \ \wedge \ (pr \cdot AdjFactor > 0.1353) \\ 41.53 & [m] \quad else \end{cases}$$

(Eq. 4-23)

Considering the annual evolution of both heat demand and DH market share, the levelized cost of heat distribution (C_d) is obtained by Eq. 4-24. It is assumed that after the target year (m), the heat demand and supplied heat by DH remain constant.

$$C_d = \frac{1}{\sum_{t=0}^{m} q_{T,t} \cdot (1+r)^{-t} + \sum_{t=m}^{n} q_{T,m} \cdot (1+r)^{-t}} \cdot \left(\frac{C_1 + C_2 \cdot d_{a,DistributionPipe}}{w_{DistributionPipe}} + \frac{C_1 + C_2 \cdot d_{a,ServicePipe}}{w_{ServicePipe}} \right) \quad [\frac{€}{GJ}]$$

(Eq. 4-24)

The impact of the adjustment factor will be presented in Chapter 4.5.1.

4.4.3 Identification of district heating areas

For the identification of potential DH areas, the proposed approach by Fallahnejad et al. is used [15]. Two conditions should be fulfilled to identify an area as a potential DH area. For each country, a heat distribution cost ceiling is set exogenously. The first condition ensures that the average distribution grid costs of any potential DH area in a country may not exceed the pre-defined cost ceiling for that country. This criterion limits heat distribution costs and is necessary since this study does not consider heat generation costs. The second condition sets a minimum annual DH demand of 5 GWh to be reached through the study horizon in order to identify an area as a potential DH area. DH areas are not identified based on administrative borders; therefore, more than one DH area might be identified within a town or city. Also, it is possible that the extension of a potential DH area goes beyond the borders of a city.

Both the above conditions, directly and indirectly, are related to the heat demand. The best-case scenario from [65] includes a dramatic heat demand reduction. Therefore, the approach is also applied to the baseline scenario obtained from [68]. Finally, the DH potentials obtained from each scenario are compared.

The method explained in this chapter has been fully implemented in Python and published with an open-source license [71].

4.5 Results

The results chapter is composed of three sub-chapters, in which the impact of the adjustment factor is discussed first. Following this, the obtained DH potential and relevant indicators for the DH are presented.

4.5.1 The impact of the adjustment factor

This chapter looks into the impact of the adjustment factor and corresponding assumptions on the effective width, linear heat density, average pipe diameter, and heat distribution costs for different plot ratios. The parameters used for the calculation are listed in Table 4-1. Heat density levels of 100 and 500 MWh/ha for a low plot ratio case ($pr < 0.1353$), and a high plot ratio case are considered, respectively. A market share of 40% would mean that 40 MWh and 200 MWh of heat demands are covered by DH for each case, respectively.

Table 4-1 Input parameters for the study of the impact of the adjustment factor

Parameter	Value	Unit
Heat density in the DH area	100 (for 4.5.1.1) & 500 (for 4.5.1.2)	MWh/ha
Construction cost constant (C1)	212	EUR/m
Construction cost coefficient (C2)	4464	EUR/m²
Depreciation time	40	Year(s)
Interest rate	2	%

4.5.1.1 Distribution pipes and low plot ratio area

In low plot ratio areas, distribution pipes have a higher impact on the DH grid costs than the service pipes. In this chapter, the impact of the plot ratio and DH market share on effective width, average pipe diameter, linear heat density, and heat distribution cost is presented. The behaviour of the effective width can be extended to the service pipes. However, considering the constant average pipe diameter for the service pipes, the other three parameters have slightly different behaviour.

Figure 4-5 shows the effective width as a function of the plot ratio for different DH market shares in a DH area. The following aspects can be identified in the figure:

- Generally, with the increase of the plot ratio, effective width decreases;
- A decrease in DH market share in the DH areas leads to an increase in the effective width.
- The impact of the DH market share in the DH areas declines as the plot ratio increases.

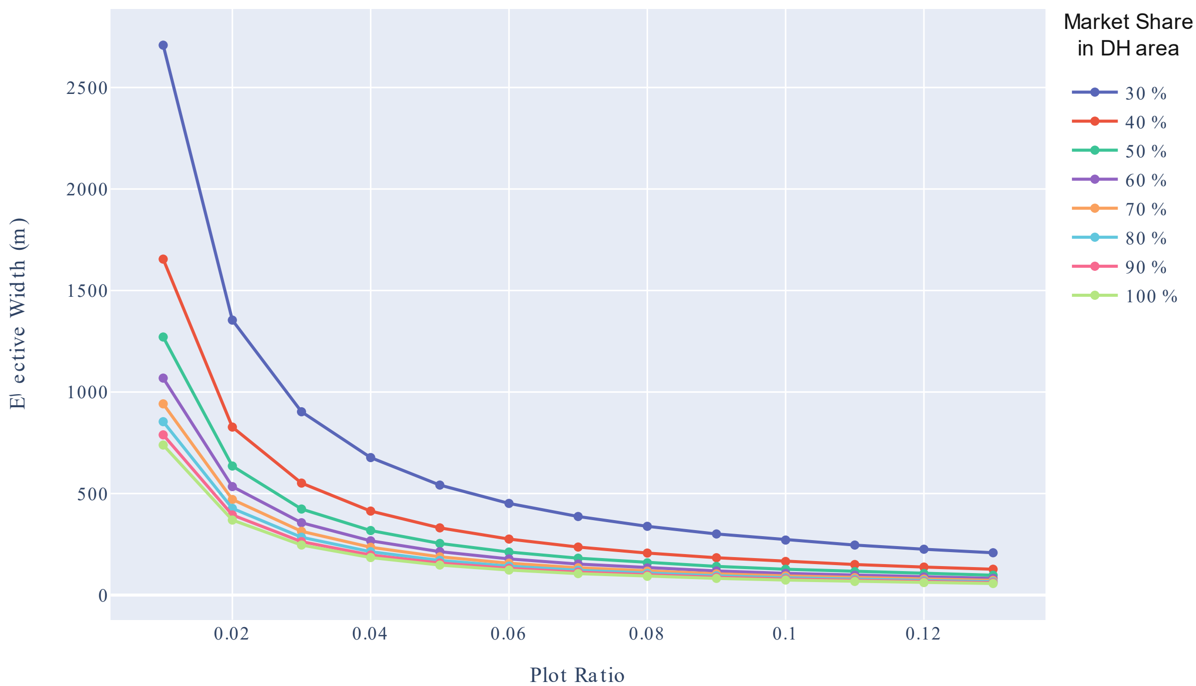


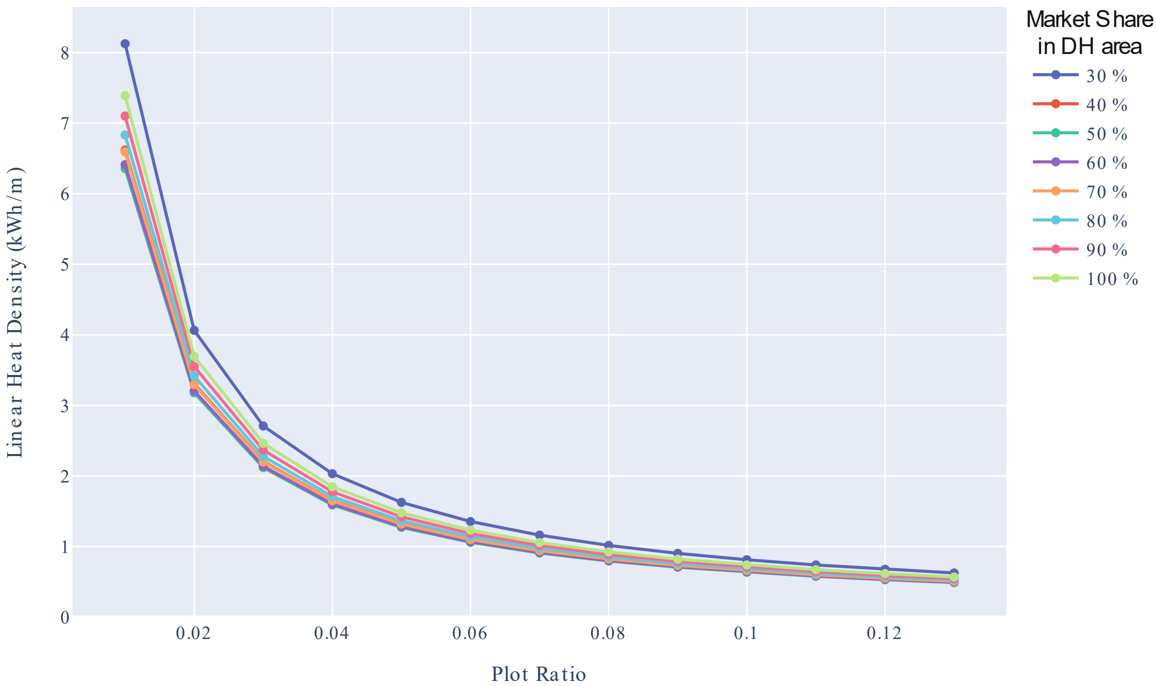
Figure 4-5 Effective width of distribution pipes versus plot ratio for different DH market shares

Linear heat density and the average pipe diameter have similar behaviour, as shown in Figure 4-6. It can be observed that:

- The linear heat density decreases as the plot ratio increases.
- Depending on the gradient (∇) of heat demand coverage at different DH market shares and the gradient of the trench length (or effective width), with the decrease of the DH market share, the average pipe diameter may decrease or increase. This effect can also be seen in the average pipe diameter.

∇ (demand covered by DH) > ∇ (trench length)	→	decrease of the DH market leads to a decrease in the linear heat density
∇ (demand covered by DH) < ∇ (trench length)	→	decrease of the DH market leads to an increase in the linear heat density

- The impact of the DH market share in the DH areas declines as the plot ratio increases.



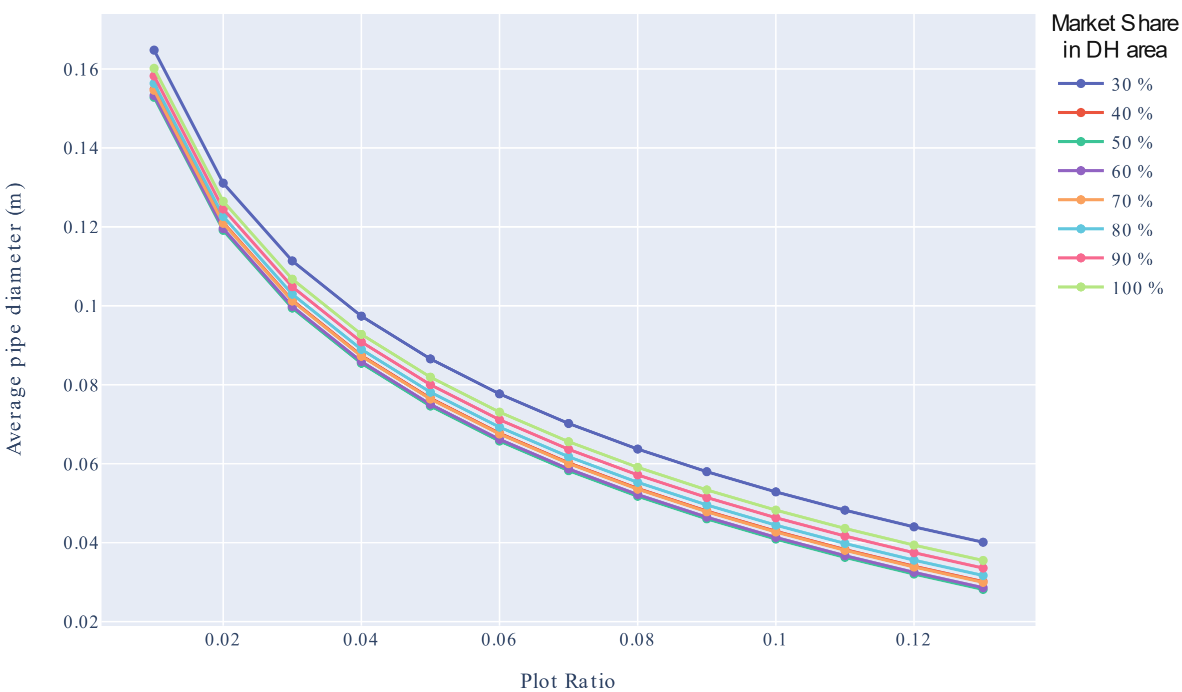


Figure 4-6 Linear heat density (top) and average pipe diameter (bottom) of DH distribution pipes versus plot ratio for different DH market shares

Figure 4-7 demonstrates the relation between the specific investment costs of the DH distribution pipes and the plot ratio. Considering the specific DH distribution grid costs, the following conclusions can be drawn:

- Under a given DH market share, the specific heat distribution costs increase as the plot ratio increases.
- For a given plot ratio and a market share above 40%, the specific investment costs decrease with the increase of the DH market share.
- It has been noted that with a 30% market share, the investment cost is lower than with a 100% market share. This is due to the adjustment factor and is influenced by the distribution of buildings on the land. Providing 30 MWh to 3 buildings could potentially result in a higher linear heat density compared to providing 100 MWh to 10 buildings.
- Although the lower market shares (below 40%) demonstrate low grid investment costs, they might not be attractive. This is because under low DH market shares, DH can be implemented in fewer areas, and the heat sale volume is smaller than in the cases with high market shares. Furthermore, considering other cost components of the DH, such as heat generation costs, the overall specific costs may increase significantly.

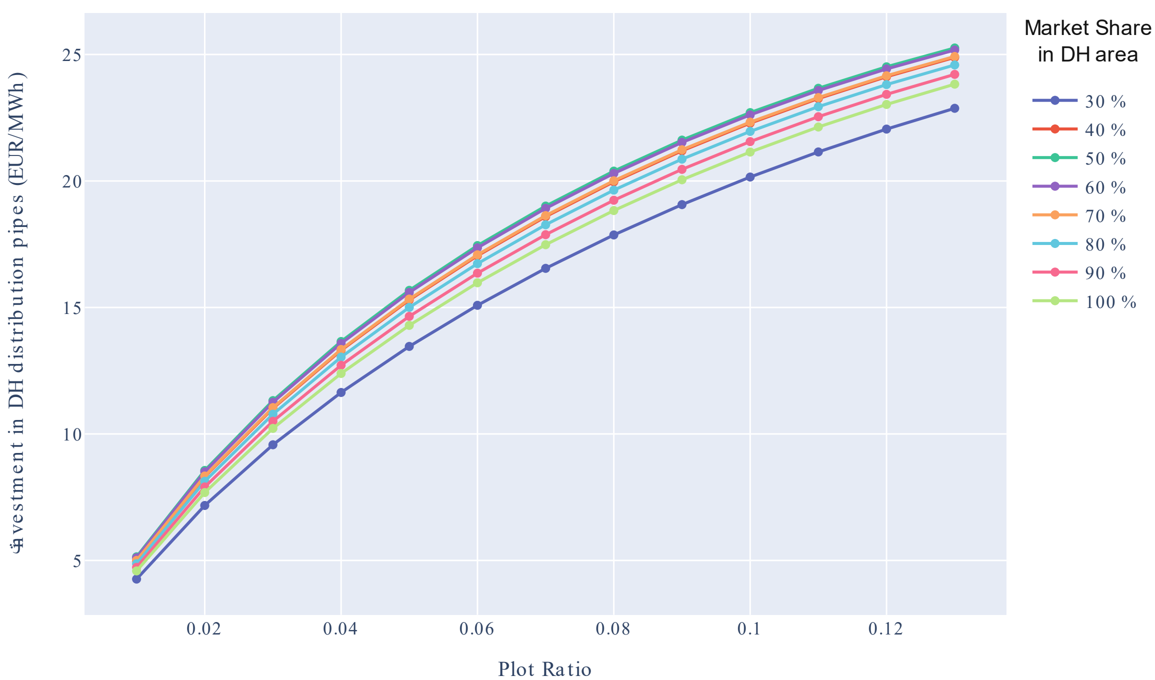


Figure 4-7 Specific investment costs of the DH distribution pipes versus plot ratio for different DH market shares

4.5.1.2 Service pipes and high plot ratio area

Based on Eq. 4-21, a minimum adjustment factor of 0.0279 for market shares below 20% was considered. As can be seen in Figure 4-8, Figure 4-9 and Figure 4-10, by increasing the plot ratio under a given market share, the effective width and the linear heat density increase; however, the specific investment cost decreases. At the same time, increasing the market share for a given plot ratio will increase the effective width and linear heat density and decrease the specific investment costs. However, the jumps become smaller as the market share exceeds 50%.

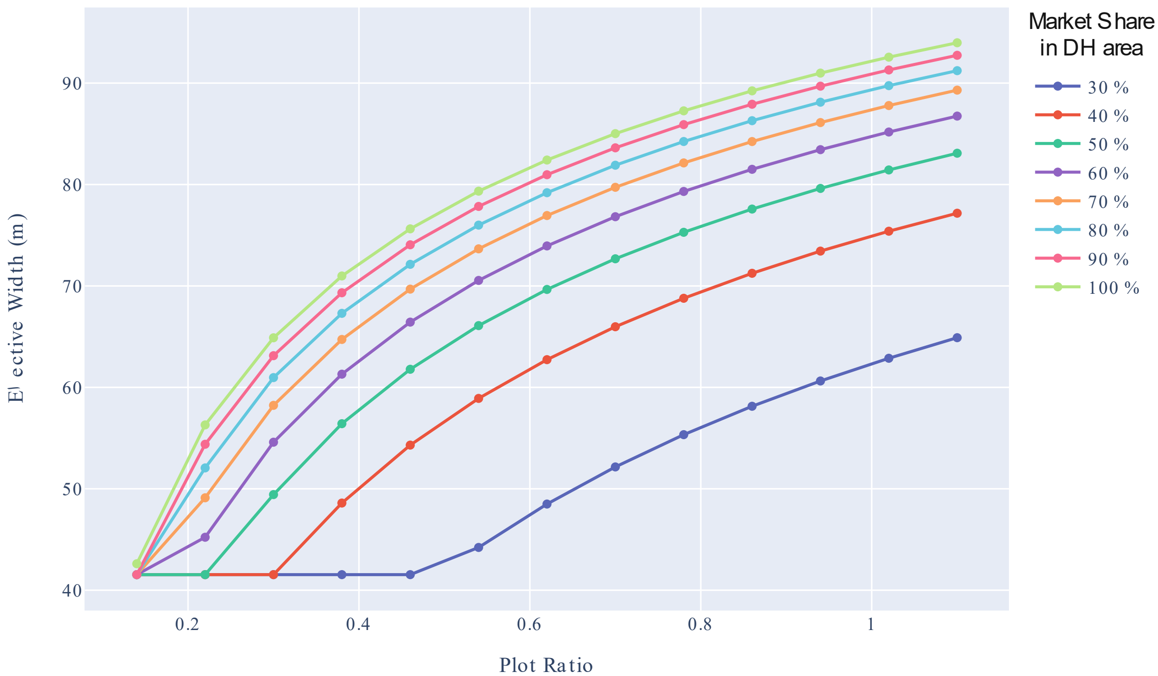


Figure 4-8 Effective width of service pipes versus plot ratio for different DH market shares

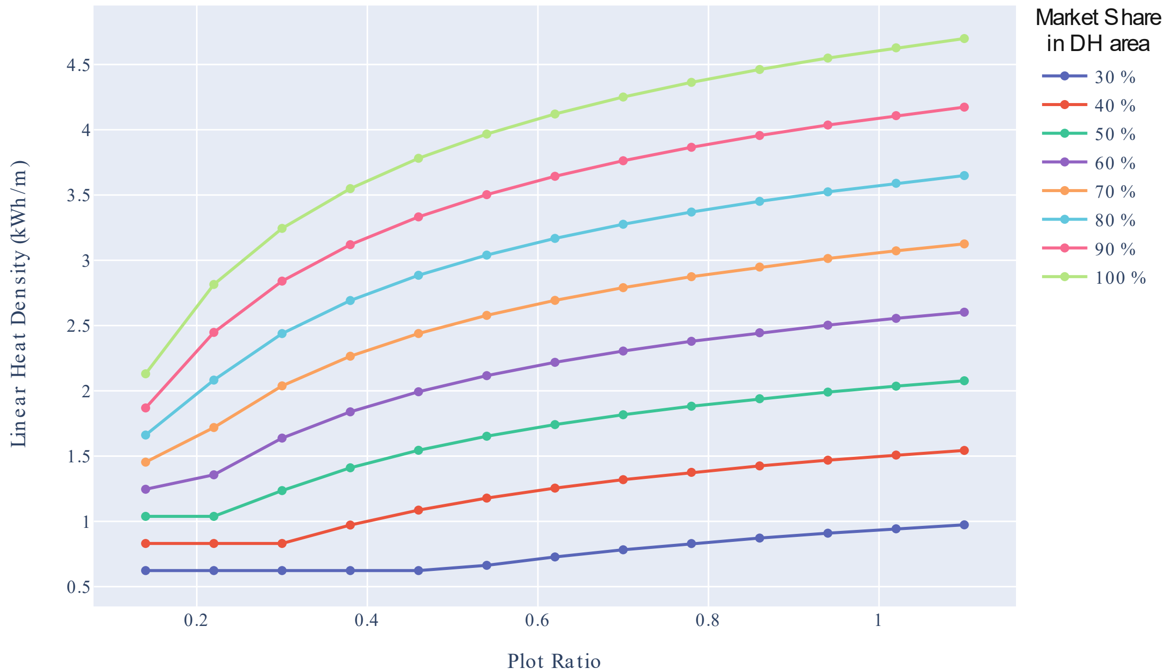


Figure 4-9 Linear heat density of DH service pipes versus plot ratio for different DH market shares

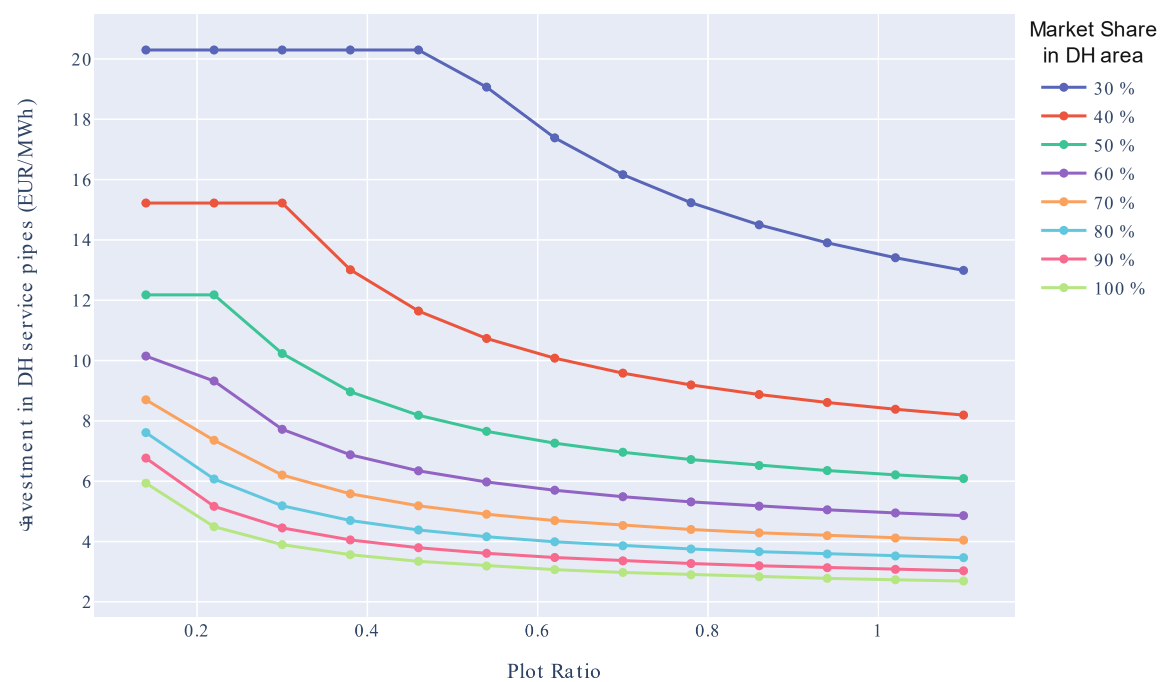


Figure 4-10 Specific investment costs of the DH service pipes versus plot ratio for different DH market shares

4.5.2 District heating potential in EU-27 countries

The calculation for the identification of potential DH areas is conducted with a discount rate of 2% and a depreciation time of 40 years. Input parameters and obtained calculation results for the EU-27 countries are summarized in Table A-2 in the appendix of this thesis. Based on the best-case scenario, the heat demand in the residential and tertiary sectors is expected to decrease by 45%, from ca. 3130 TWh in 2020 to 1710 TWh in 2050.

In 2018, EU-27 countries had a total residential area of 117,924 km2. The identified DH areas in this chapter cover 24.5% of the residential areas (=28911.4 km2) in the EU-27. The heat demand in the identified potential DH areas accounts for 43% and 40% of the total demand in 2020 and 2050, respectively, revealing that a large portion of heat demand in EU-27 countries belongs to the areas with high DH potential. With the increase in DH market shares, the DH potential rises from ca. 477 TWh in 2020 to ca. 531 TWh in 2050. This is equivalent to 15% and 31% of the total heat demand in the EU-27 in 2020 and 2050. Within the identified potential DH areas, up to 77% of the heat demand can be covered by DH. These results show that achieving even higher DH market shares will be possible under favourable financial and political schemes.

The total heat demand and the heat densities are relatively low in Cyprus and Malta. Implementing large DH systems in Cyprus and Malta is economically less attractive. Inside the identified DH areas in other countries, only 34.1 TWh out of 687 TWh in 2050's heat demand exists in the low plot ratio areas ($pr < 0.1353$). In terms of DH potential, it accounts for 28 TWh out of 531 TWh. Such areas are mostly in Sweden, Finland, France, Germany, Poland and the Czech Republic.

Figure 4-11 illustrates the average heat densities within the identified DH areas. These values are obtained by dividing the total heat demand of the identified DH areas by the sum of their areas. These numbers can be used indicatively to find coherent areas with economic potential for implementing DH. In Northern EU counties, the average heat demand density is relatively high. Therefore, even a relatively low threshold for the heat demand density in a region can be largely fulfilled and will lead to an annual heat demand favourable for the economic viability of the DH. In contrast, only high thresholds for the heat demand densities justify having a DH system in Southern EU countries, as the average heat demand densities in these countries are relatively low.

As illustrated in Figure 4-11, in most member states, the average heat density is between 200 and 300 MWh/ha. Prominent exceptions are Estonia, Latvia and Lithuania, which have an average heat density below 130 MWh/ha, and Greece, Spain and Ireland, which have an average heat density of 400 MWh/ha. These values demonstrate the threshold that generally needs to be exceeded in an area of a country in order to be considered a potential DH area. For example, an average heat demand density of 215 MWh/ha in an area within Austria is generally a necessary condition to fulfil other mentioned constraints in this chapter for identifying potential DH areas.

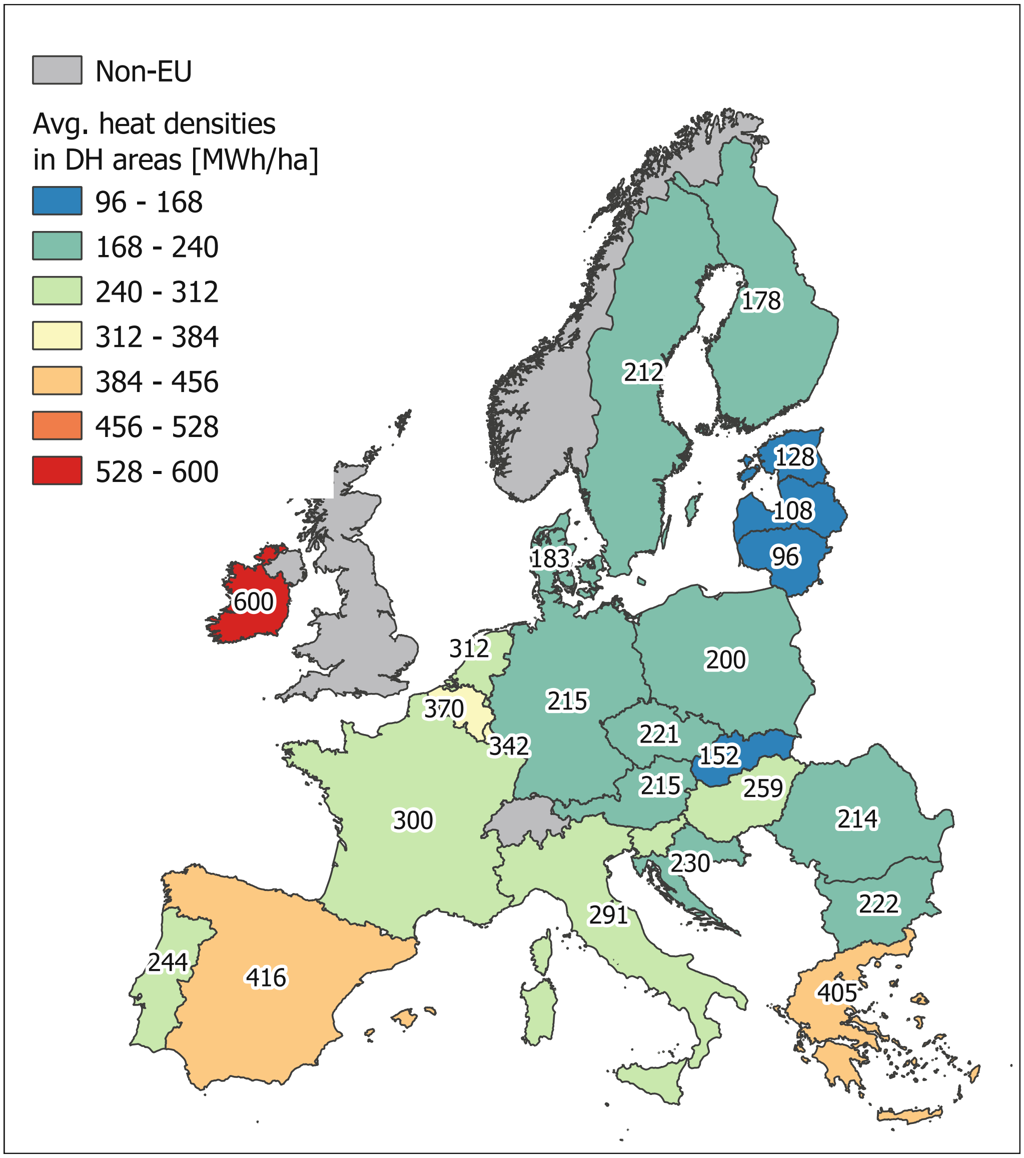


Figure 4-11 Average heat densities in identified DH areas based on Best-Case scenario

4.5.3 District heating grid costs

The calculations performed in this chapter result in an annual investment of EUR_{2020} 11.7 billion for DH grids in EU-27 countries, of which ca. 60% should flow into distribution pipes and ca. 40% into service pipes. Table 4-2 summarizes the required investments in each country. If the market shares of 2050 are maintained, similar figures can be considered for the years beyond 2050.

Table 4-2 Yearly cashflow for investment in DH distribution and service pipes

Country	2020 DH market share in DH areas	2050 DH market share in DH areas	Cash flow [MEUR 2020] for distribution & service pipes
AT	55%	80%	329.9
BE	15%	70%	130.8
BG	64%	75%	114.0
CY	0%	0%	0.0
CZ	44%	80%	443.2
DE	32%	75%	2,675.4
DK	88%	90%	482.2
EE	58%	80%	42.7
EL	29%	70%	106.7
ES	3%	70%	471.2
FI	63%	90%	675.4
FR	15%	75%	1,461.0
HR	37%	80%	57.1
HU	33%	80%	248.7
IE	0%	70%	9.9
IT	17%	70%	1,215.6
LT	78%	90%	78.1
LU	29%	80%	37.5
LV	57%	80%	55.6
MT	0%	0%	0.0
NL	26%	75%	384.2
PL	51%	80%	1,116.6
PT	33%	70%	59.8
RO	43%	75%	234.5
SE	86%	90%	1,129.0
SI	52%	80%	29.1
SK	74%	90%	146.2

TOTAL yearly cashflow on EU-27 level: 11,734 MEUR

Given a significant decrease in heat demand till 2050, expanding DH via achieving higher DH market shares is crucial for maintaining DH competitiveness. Despite the high market shares considered for 2050, as shown in Table A-2, most member states will supply less heat via DH in 2050 compared to 2020. The average specific DH grid costs are obtained by dividing the total grid costs of identified DH areas by the total delivered heat by DH from 2020 to 2050, as per Eq. 4-24. Accordingly, higher starting market shares lead to lower average specific DH grid costs.

Considering the inputs for the DH market shares, the average specific DH grid cost in EU-27 countries would be 31.78 EUR/MWh.

The yearly cashflows in each member state should be looked at along with the supplied heat. In that sense, specific costs provide a better picture of each member state. While average specific DH grid costs in most member states range between 28 to 32 EUR/MWh, a few countries, e.g., Estonia, Lithuania and Latvia, demonstrate lower costs due to high starting DH market shares and heat densities in DH areas. In contrast, in countries with low starting DH market shares, e.g., the Netherlands, Spain and Italy, the average specific DH grid cost exceeds 34 EUR/MWh. An overview of the average specific DH grid costs is provided in Figure 4-12.

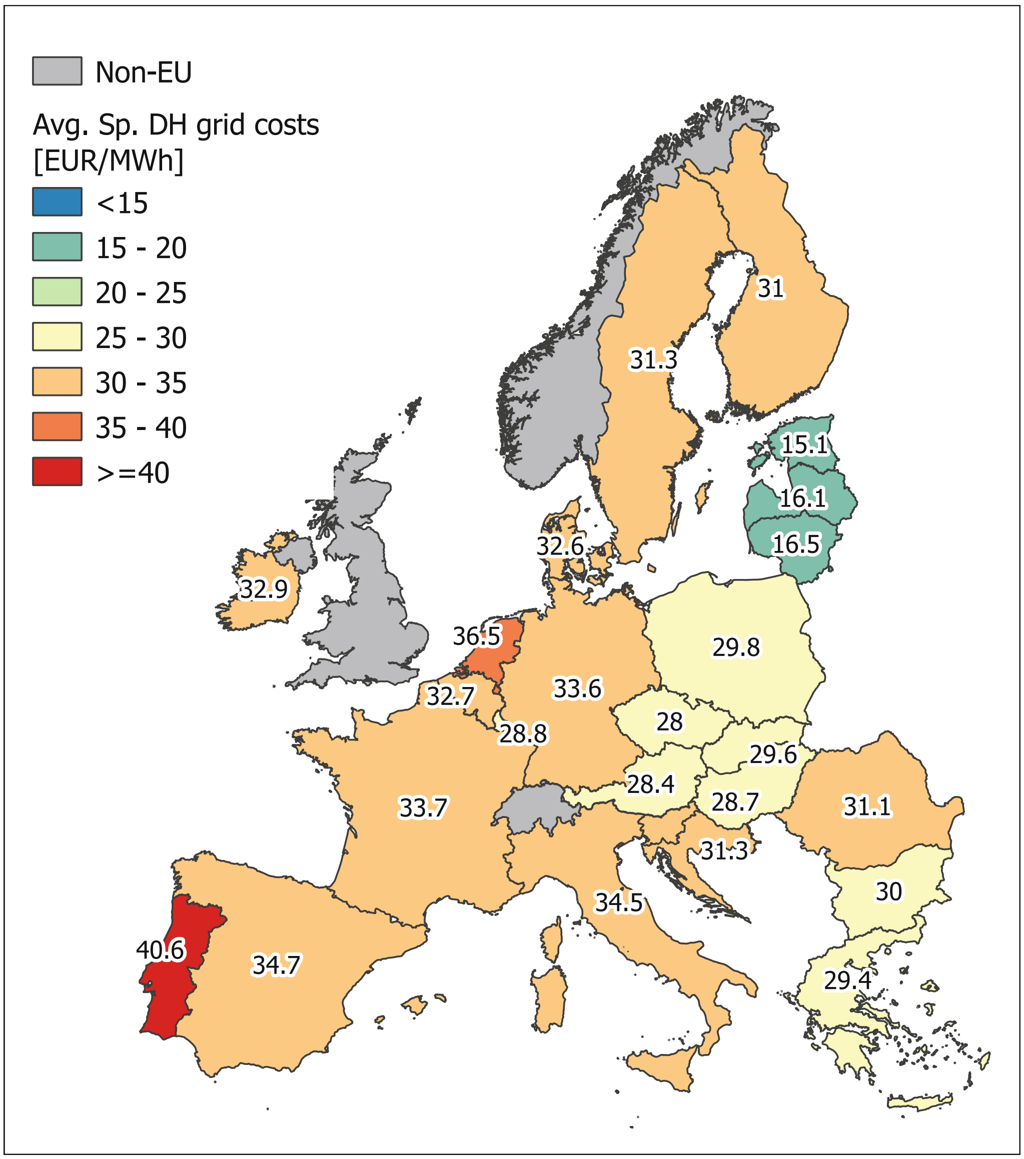


Figure 4-12 Average specific DH grid costs based on Best-Case scenario

4.5.4 Synthesis of district heating potentials and grid costs

To better understand the results, four categories of average specific DH grid costs are defined, and further analyses are conducted based on these categories.

- 0-20 EUR/MWh
- 20-30 EUR/MWh
- 30-35 EUR/MWh
- ≥ 35 EUR/MWh

Figure 4-13 shows the share of absolute DH grid investments (EUR_{2020} 11.7 billion) and the share of 2050's DH potential (530.6 TWh/year) corresponding to each average specific DH grid cost category in the EU-27. The investment in DH areas with an average specific DH grid cost of below 30 EUR/MWh requires 25.2% of the annual investment but constitutes 31.1% of the overall DH potential in 2050. Higher average specific DH grid costs result from low starting market shares or high construction costs (see Appendix A.2) or low heat densities and plot ratios. It can also be seen that reaching the defined market shares at the EU level requires significant investment in areas with average specific DH grid costs above 35 EUR/MWh.

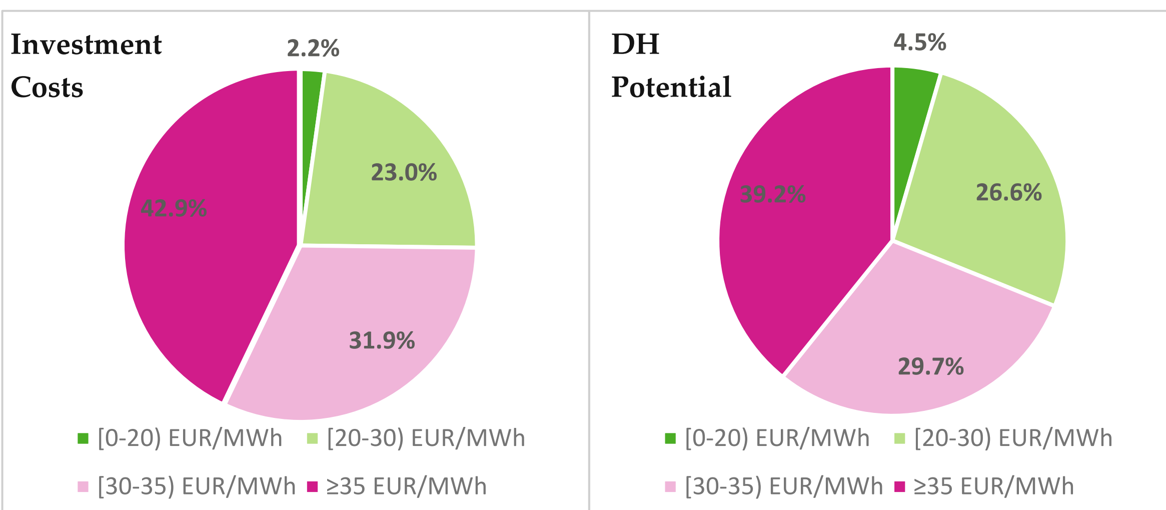


Figure 4-13 Share of investment costs (left figure) and share of DH potentials (right figures) corresponding to each average specific DH grid cost category (EU-27)

Figure 4-14 shows the cumulative DH potential in each average specific DH grid cost category. In this figure, DH areas are sorted in ascending order based on their potential. Therefore, the slope of each curve at each point shows the amplitude of DH potential added by a region. Although a major portion of the DH potential belongs to large DH areas, especially in dense urban areas, numerous DH areas with small DH potential constitute a considerable share of the total DH potential cumulatively. All four cost categories comprise DH areas ranging from small to large DH potential. It can, therefore, be concluded that DH planning should not only be sought within dense urban areas but also within small areas with lower DH potential.

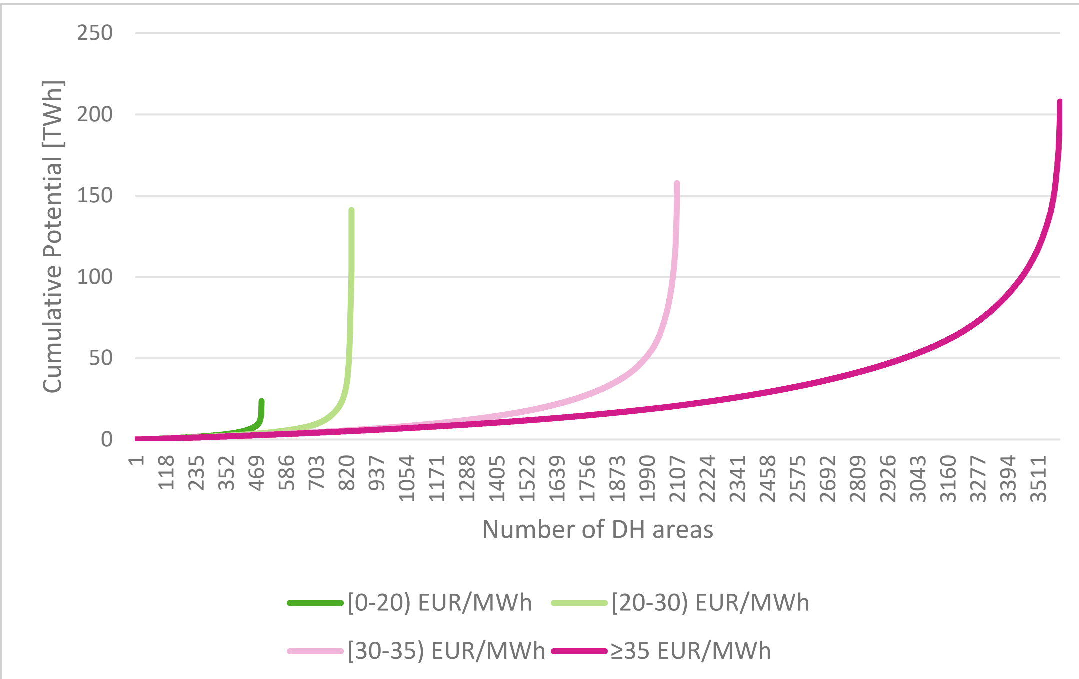


Figure 4-14 Cumulative DH potential of each average specific DH grid cost category (EU-27)

The distribution of DH potential between different cost categories is not uniform in the member states. Figure 4-15 illustrates the share of DH potentials corresponding to average specific DH grid cost categories in the EU member states in pie charts, putting them on top of the average specific DH grid costs provided in Figure 4-12. The impact of low starting market shares, high construction costs, low heat densities, and low plot ratios can be traced in each member state.

The synthesis of the average costs depicts a favourable condition for DH expansion in Baltic and Eastern European countries. Favourable DH grid costs can also be observed in Greece and Bulgaria; however, the DH potential is relatively low in these two countries. In Denmark, Sweden and Finland, higher construction costs and market shares, besides lower heat densities, could be enumerated for average DH grid costs above 35 EUR/MWh. Low starting DH market share in identified potential DH areas is the main reason for costs above 35 EUR/MWh in France, Italy, and Spain. In France, however, more than 45% of the DH potential falls in the cost category of below 30 EUR/MWh. Other member states show a mixed combination of low and high specific DH grid costs.

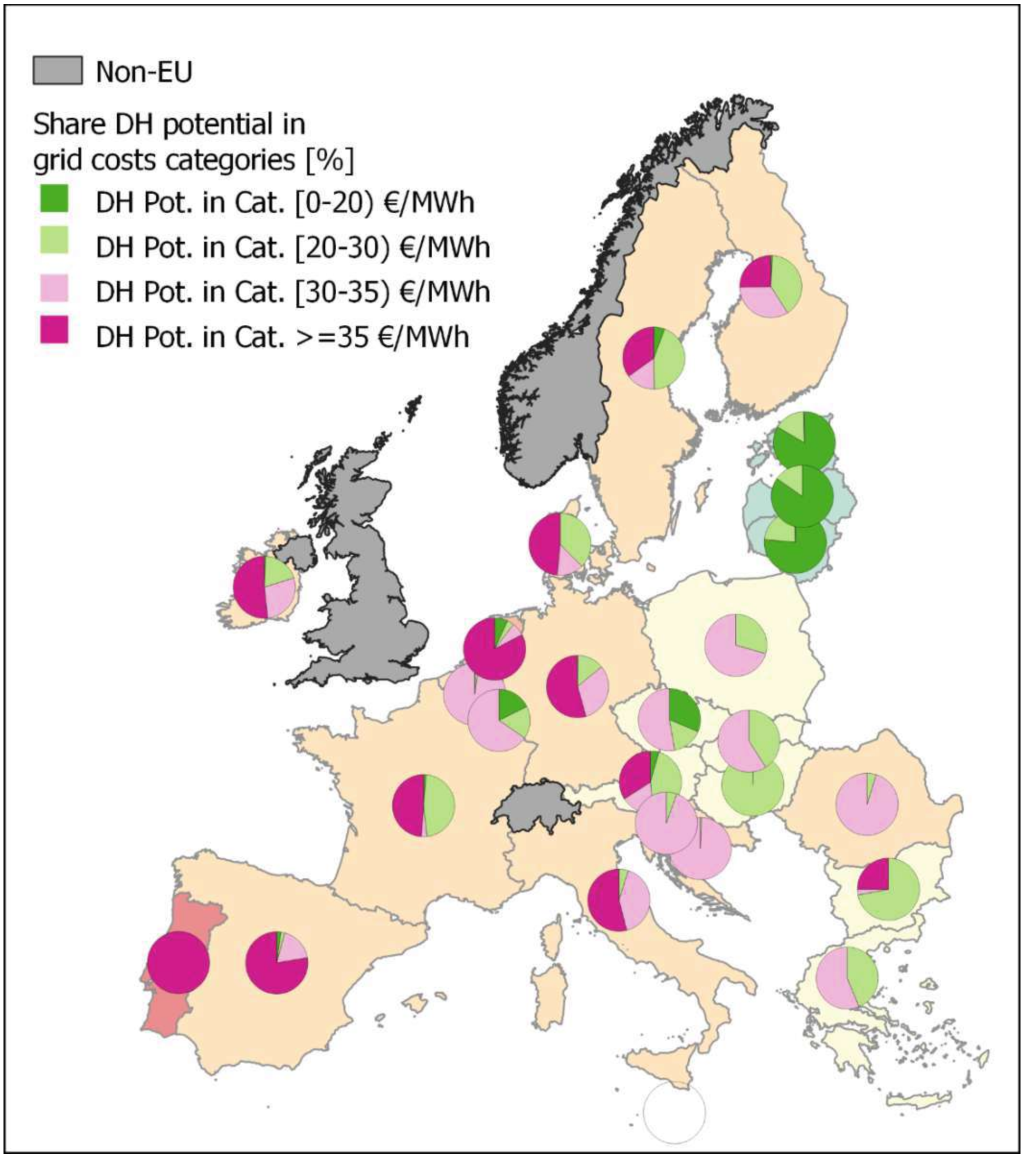


Figure 4-15 Share of DH potentials corresponding to average specific DH grid cost categories in EU member states

4.5.5 Impact of higher heat demand in 2050 on district heating potentials

This chapter examines the impact of the demand reductions till 2050 on DH potential. For this purpose, the baseline scenario (BL2050) from the sEEnergies project is used [67], [68]. Based on this scenario, the heat demand in EU-27 countries should reduce to 2088.7 TWh in 2050, which is 379.6 TWh higher than the estimated demand in 2050 by the best-case scenario. However, the additional 379.6 TWh heat demand is not uniformly dispersed across all regions. Under the BL2050 scenario, even slightly lower heat demand is expected for a few countries (e.g., Sweden) compared to the best-case scenario.

For the calculation, all other input data and parameters were kept unchanged. It should be emphasized that the goal of this chapter is solely to study the impact of heat demand levels and heat densities in 2050 on DH potential. A comparison of the scenarios is not the focus of this chapter.

A summary of the obtained results for the BL2050 scenario is provided in Table A-3 in the appendix of this thesis. The estimated DH potential, considering BL2050's heat demands, is 704.2 TWh. In absolute terms, the estimated DH potential is 173.6 TWh higher than the previous calculations. The estimated DH potential is equivalent to 34% of the total heat demand in EU-27 countries, which is three percentage points higher than the previous analysis. The average specific DH grid costs have changed at a country level, though with a mixed picture due to different distribution heat demands. On the EU-27 level, however, no changes in average specific DH grid costs were observed.

4.5.6 Discussion of results and limitations

The proposed method in this chapter facilitates the study of the DH potential under various future heat demand scenarios and DH market shares. However, this entails a few assumptions:

- The heat demand and covered heat demand by DH in years between 2020 and 2050 were interpolated based on Eq. 4-12 and Eq. 4-14,
- The DH market share evolution was considered uniformly for all hectare cells of each in a country.
- For the adjustment factor:
    - Heat supply of buildings in low plot ratio areas is conducted either with or without DH (having two or more heating systems in a building was excluded),
    - Using an adjustment factor curve for ten buildings per hectare.
- A minimum annual DH demand of 5GWh/year was set as a criterion for identifying DH areas.

The assumptions were applied uniformly in all regions. Where possible, conservative assumptions were made to avoid overestimating the DH potential. The assumptions impose limitations in applying the results in the implementation phases but are accurate enough for the pre-feasibility and feasibility studies.

This chapter also seeks to provide a realistic picture of DH potential and grid costs in low plot ratio areas by introducing an adjustment factor and using it inside the formula of the effective width (Eq. 4-22 and Eq. 4-23). The adjustment factor allows the modelling of the impact of DH market shares. It is clear that low plot ratio areas should not be overlooked for DH planning even though their DH potential is low and their specific DH grid cost is higher. The specific cost of distribution pipes in low plot ratio areas is sensitive to the DH market share, as shown in Figure 4-7; however, the specific distribution costs are close to each other at a given plot ratio. On the other hand, Figure 4-10 reveals that service pipes are more sensitive to DH market shares both at low and high plot ratio areas. The specific cost of service pipes can considerably increase if high market shares are not achieved.

Various data sets are used to break down the heat demand from energy balances to hectare level. As concluded in [66], these data sets are suitable for strategic purposes on aggregated levels of larger areas and might overestimate demand in sparse areas. The 5 GWh criterion as the minimum annual DH demand in DH areas, which was used in this chapter, ensures that no overestimation of DH potential is made. At the same time, this assumption neglects the areas with low DH potential.

The combination of a minimum annual DH demand of 5 GWh and a heat distribution cost ceiling guarantees that only suitable areas are identified as DH areas. For setting the heat distribution cost ceiling, as illustrated in Table A-2, the construction cost constant (*C1*) and construction cost coefficient (*C2*) in each country were considered. Looking at the columns for "Average specific DH grid cost in all DH areas over the lifetime" in Table A-2 shows that the cost ceilings are sufficiently relaxed for most countries. Exceptions are countries with a relatively low DH potential, like Portugal or Greece. In these cases, only a few DH areas were identified and extended up to the limit defined by the heat distribution cost ceiling.

Both best-case and BL2050 scenarios demonstrate ambitious heat demand reductions till 2050. The results show that the overall DH potential depends on the heat demand in 2050. The expansion of DH grids and achieving high DH market shares in 2050 is vital for the economic feasibility of DH, especially if ambitious demand reduction goals for 2050 are achieved. Otherwise, the existing grids might be over-dimensioned for future heat demands, and the levelized cost of heat generation and distribution will be high.

For an ultimate assessment of DH potential, it is also necessary to study the supply side and availability of heat sources. However, heat generation was beyond the scope of this chapter. Nevertheless, the results reported here can be used for a more detailed analysis of DH potential. A similar approach was followed by Fallahnejad et al. in their study of DH potential under climate neutrality in the case of Austria [6].

4.6 Conclusions

DH networks are not built all at once. The expansion of DH networks is a gradual process. This chapter used the existing theoretical framework of modelling heat distribution costs of DH systems and introduced an approach for modelling the gradual heat demand reduction and evolving DH grid expansion. This approach provides a more realistic picture of the heat distribution costs and DH potential since it does not assume 100% connection rates in DH areas.

Furthermore, this chapter suggests using an adjustment factor for the plot ratio for DH areas with DH market shares below 100%. The adjustment factor affects the costs of distribution pipes at low plot ratio areas ($pr \leq 0.1353$) and service pipes under all plot ratio ranges and provides a conservative estimation of costs. The impact of the adjustment factor on distribution and service pipes was elaborated in two examples. It was shown that at a given plot ratio, the cost of the service pipes is affected more heavily by DH market shares than distribution pipes.

An updated assessment of the DH potential across the EU member states, considering the future development of both heat demand and DH market share within DH areas, was presented. The calculations were performed for two different scenarios: The best-case scenario from a report on "renewable space heating under the revised Renewable Energy Directive" published by the European Commission [4] and the baseline scenario (BL2050) from sEEnergies project [67], [68]. The result of the latter scenario was used to check the impact of higher heat demands in 2050 on DH potential.

In the decarbonization scenario (best-case scenario), heat demand in EU-27 countries will decrease by 45% by 2050. Under this condition, maintaining the existing grid infrastructure while covering lower heat demand with DH will increase specific grid prices. To avoid high grid costs, DH grids should be expanded in economically favourable areas, and supply levels should be maintained or increased. In this chapter, the expected DH market shares defined for each member state for 2050 were considerably higher than their 2020 levels. Despite high DH market shares in 2050, DH potential can increase by only 11% by 2050 compared to 2020. A yearly investment of 4 billion Euros at the EU level is required to expand the DH grid under this scenario.

The result of the calculations for the BL2050 scenario showed three percentage points higher potential (34%) compared to the best-case scenario. The levelized costs of heat distribution were slightly different from the best-case scenario; however, on the EU-27 level, they remained unchanged. This result highlights the importance of expanding DH networks and achieving sufficiently high DH market shares within DH areas. This is achievable under favourable financial and political support schemes, such as DH zoning.

5 Economic assessment of the district heating potential in Austria

This chapter is mainly based on the peer-reviewed article: The Economic Potential of District Heating Under Climate Neutrality: The Case of Austria [6].

This chapter focuses on the requirement of the Energy Efficiency Directive for assessing the potential of efficient heating and cooling. The chapter describes the method for calculating the economic potential of efficient DH in Austria under different scenarios, assuming the full decarbonisation of the heating sector by 2050. A spatially explicit approach is used to derive heat demand density maps, heat distribution costs and potential DH areas. The obtained areas are clustered, and depending on their potential spreads, up to four supply portfolios on the installed generation capacities are assessed in each cluster. While this method maintains the level of detail, it significantly reduces the number of required sensitivity analyses. Finally, the least cost portfolios of DH supply in each cluster are identified and compared with the costs of individual heat supply. The economic potential of DH by 2050 is calculated accordingly. The analyses revealed that the DH market share within DH areas is the main driver of DH competitiveness. Depending on the scenario, the economic DH potential varies between 13% and 50% of space and water heating demand in Austria. The extensive application of renewable gases in this sector was not economically feasible under any scenario.

Datasets related to this chapter can be found in [72], hosted by Zenodo. In addition, the map material and other background data for the study are provided as part of the Austrian Heatmap [73].

5.1 State of the art

Article 14 of the Energy Efficiency Directive, adopted in 2012 (Directive (EU) 2012/27, hereon EED I), asks member states (MS) of the European Union (EU) to carry out a so-called "comprehensive assessment of the potential for the application of high-efficiency cogeneration and efficient district heating and cooling" in line with Annex VIII of the Directive by the end of 2015 [74]. The resulting national comprehensive assessment reports are accessible via the website of the European Commission (EC) [75]. Cornelis and Vingerhoets [2] analysed the national reports and concluded that the reports follow various methods, levels of detail and interpretations of the term "economic potential". A similar conclusion was drawn in 2018 by the

Joint Research Centre (JRC) of the European Commission (EC) in a synthesis report on the evaluation of national notifications related to Article 14 of the EED [3]. The synthesis report elaborates a list of recommendations, including an update of Annexes VIII and IX of the EED and the use of a reporting template to harmonise the outputs of comprehensive assessments by MS.

With the revised Energy Efficiency Directive from 2018 (Directive (EU) 2018/2002, hereon EED II), the requirements of Article 14 and Annex VIII were rephrased, asking to provide "comprehensive assessments of the potential for efficient heating and cooling" [76]. This was followed by a corresponding delegated regulation from the EU Commission [77] and recommendations [78].

Timewise, the EED I was adopted before the Paris Agreement [4] and the related adoptions of climate neutrality targets in Europe [5]. Therefore, the expected results and methodological aspects of the cost-benefit analysis (CBA) foreseen in the comprehensive assessment reports under Article 14 of the EED I were sharpened in EED II. However, the fundamental idea of the CBA remained still the same as under the EED I.

In Austria, the assessment of the potential for efficient DH in the scope of the EED I was performed in 2015 for the target year of 2025 [79], [80]. The DH potentials were calculated based on the heat demand densities and plot ratios. The heat distribution costs were assigned to the areas based on the heat demand density ranges. Furthermore, the CBAs were relatively limited as they were based only on the merit order of the existing technology mixes in the regions and their capacities compared to the DH potential. In other words, hourly coverage of heat demand by heat sources was not considered. The study concluded that 28% of the total demand could be covered by DH.

This chapter presents selected cost-benefit analyses done for the second round of the comprehensive assessments for the case of Austria, with a focus on the role and potential of district heating[2]. The analyses in this chapter comply with the 2040's full decarbonisation target announced in the Austrian government programme adopted in 2020 [82]. Accordingly, this was considered as a boundary condition in the calculations for the year 2050 as required according to the EED II. The economic analysis of DH on a national level, considering the spatiotemporal aspect of heat supply and demand under different scenarios, requires a significant amount of sensitivity analyses and, therefore, CPU time, which has not been done in other studies before. This chapter tackles this challenge and introduces a generic approach, which can be used as guidelines for similar studies in other countries.

[2] While part of the results were already presented in [81], a clear presentation of the full workflow and methodology as a potential guidance for similar future studies, as well as a discussion of limitations, was still missing. Moreover, some methodological extensions and updates are included (see Chapter 5.3 and, in particular, Chapter 5.3.5.2).

More than 20% of the space and water heating demand in Austria is supplied by DH (2018), of which about half is covered by biomass boilers and biomass CHP and the remaining part is covered mainly through gas-fired CHP and boilers. Also, for decentral heat supply, biomass holds the largest share covering 30% of the decentral space and water heating demand, followed by natural gas boilers (29%) and heating oil (19%). 12% of decentral space and water heating is covered by electricity, of which the larger part is direct resistance heating, and partly heat pumps, delivering an additional 6% of the heat demand through ambient heat. Solar thermal supplies about 3% of decentral heat demand (see also Figure 4-13, based on [83], [84], [85]).

5.2 Core objectives

The research question of this chapter is: What is the economic potential of efficient DH under different scenarios for the case of Austria, considering the decarbonisation targets? The scenarios are derived from combining two heat demand scenarios, two target years, economic and financial perspectives, and low and high energy prices.

This chapter is in line with the definition of efficient DH according to Jimenez Navarro et al. [28]. Accordingly, efficient DH and cooling by 2030 should follow "equal or more renewable energy technologies than fossil-fuelled individual generation energy technologies". By 2050, an efficient district heating and cooling should follow "exclusively a combination of renewable fuelled (either individual or combined generation) heat, including ambient heat, and waste heat sources".

The analyses were partially done with the help of open-source tools developed in the Horizon 2020 project Hotmaps [86]. These tools are not only used for the comprehensive assessments of the potential for efficient heating and cooling in Austria [79] but also are used by other MS such as Bulgaria [87], Estonia [88], Germany [89], Portugal [90] and Slovenia [91].

5.3 Methodology

For the analysis of the economic potential of efficient heat supply, 16 different scenarios from combining two heat demand scenarios, two target years, economic and financial perspectives, and low and high energy prices for the case of Austria are calculated. Besides the scenarios, several sensitivity analyses on influential parameters are performed. The focus of the chapter is on the supply of space and water heating to the residential and service sectors. The industry sector is considered a potential supplier of waste heat. However, the decarbonisation of process heat is not part of this chapter. Any heat supply option for the residential and service sectors which does not correspond to DH is referred to as an "individual heat supply".

The steps taken in the analyses are depicted as a workflow in Figure 5-1:

- Simulation of investment decisions in building shell efficiency measures in 2030 and 2050 for Austria presented in Krutzler et al. [92] and obtaining useful energy demand on the NUTS 0 level;
- Breaking down the useful energy demand on the NUTS 0 level to the hectare level by regionalisation;
- Identification of potential DH areas;
- Clustering of potential DH areas according to their characteristics in terms of DH suitability, resource potential and existing infrastructures;
- Calculation of the costs for:
    - the heat supply by DH for different heat generation portfolios, and
    - individual heat supply in different building types;
- Cost comparison of heat supply by DH with decentral heat supply

Detailed input parameters are provided in the Appendix B of this thesis.

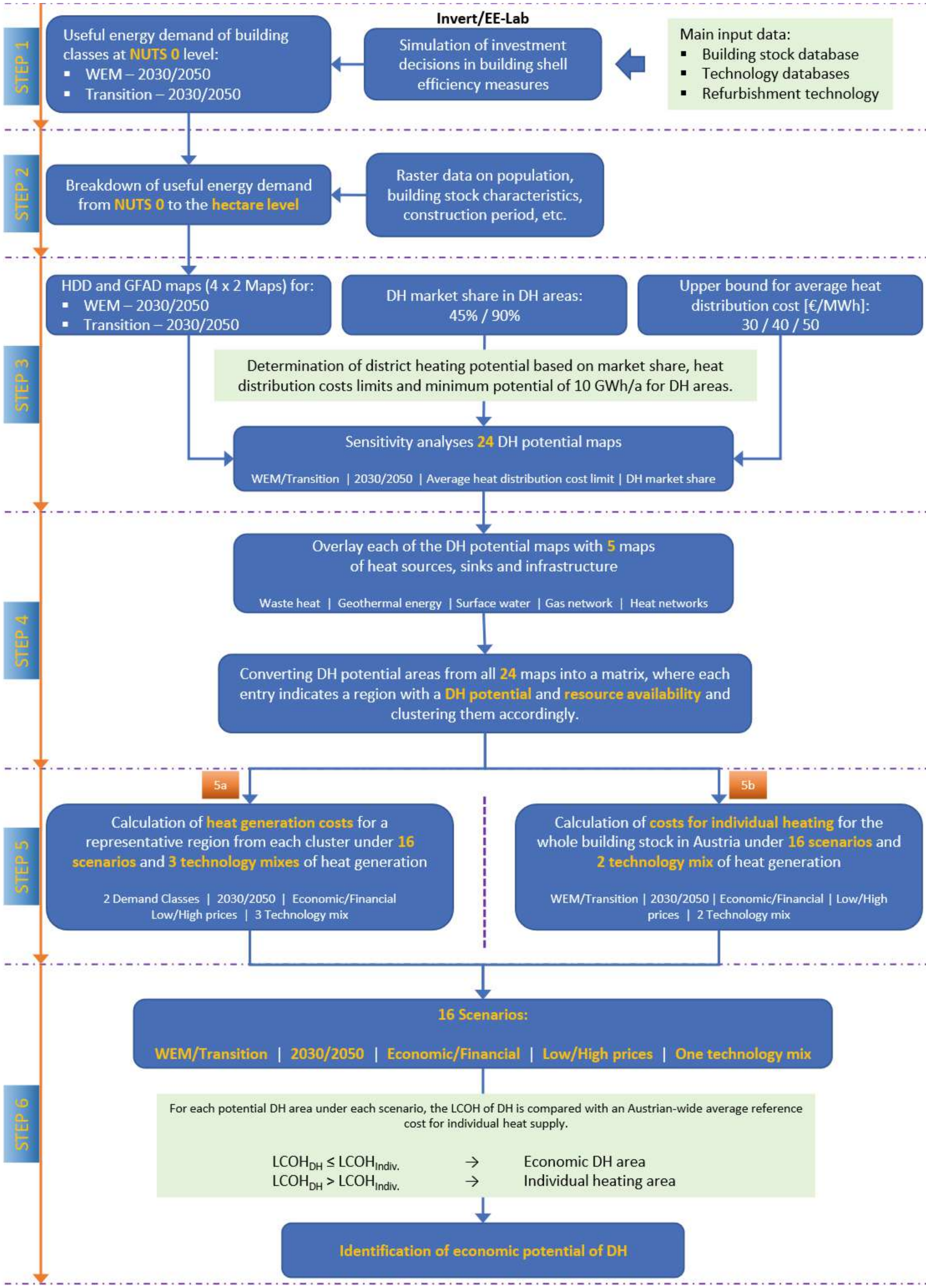


Figure 5-1 Method's workflow

5.3.1 Step 1: Simulation of investment decisions on building envelope efficiency measures

Krutzler et al. developed two climate target scenarios for the greenhouse gas emissions in Austria till 2050, namely "WEM" and "Transition" [92]. In the "WEM" scenario (with existing measures), it is assumed that the measures already implemented (Status 2016) remain in force with no changes until 2050. The "Transition" scenario depicts a pathway in which an 80% reduction in CO2 emissions compared to 1990 will be achieved by 2050 across all economic sectors.

The framework of these two scenarios is the basis for the simulation of investment decisions on efficiency improvement in the building envelope. The simulation was done with the Invert/EE-Lab model [93] to obtain the useful energy demand at the NUTS 0 level for 2030 and 2050. The inputs to the model are data on building stock characteristics, heating technologies and refurbishment measures. The model output is relevant for the space heating and hot water demand in the residential and service sectors. To demonstrate compliance with the reference climate target scenarios, resulting energy demands are referred to as "WEM" and "Transition" throughout this chapter.

While it is possible to reduce the useful energy demand for space heating and hot water by approximately 50% in the Transition scenario, the reduction in the WEM scenario is only about one-third of the base year. It is emphasised that neither the WEM nor the Transition scenario is in line with the current political requirements from the Austrian Government [74], the European Union [5], [94] and the Paris Agreement [4]. Further information on the scenario setting, the policy assumptions, the assumed economic framework conditions, and implied renovation and boiler replacement activities in the scenarios can be found in [92].

5.3.2 Step 2: Regionalisation of the useful energy demand from the NUTS 0 to the hectare level

In Step 2, the useful energy demand is broken down to the hectare level for the whole territory of Austria. This procedure is done based on the method developed by Müller et al. [95]. First, the useful energy demand is broken down to the NUTS 3 level. This step is done fully using the statistical data and heating degree days in each NUTS 3 area. Subsequently, the heat demand on the NUTS 3 level is broken to hectare level by using several datasets like population density, land use, human settlement and Open Street Map. The calculation for both WEM and Transition scenarios for 2030 and 2050 gives four heat demand density (HDD) maps on hectare resolution. A similar procedure for the heated gross floor area is followed, giving four heated gross floor area density (GFAD) maps.

Figure 5-2 shows how the heat demand densities differ between WEM and Transition scenarios and target years.

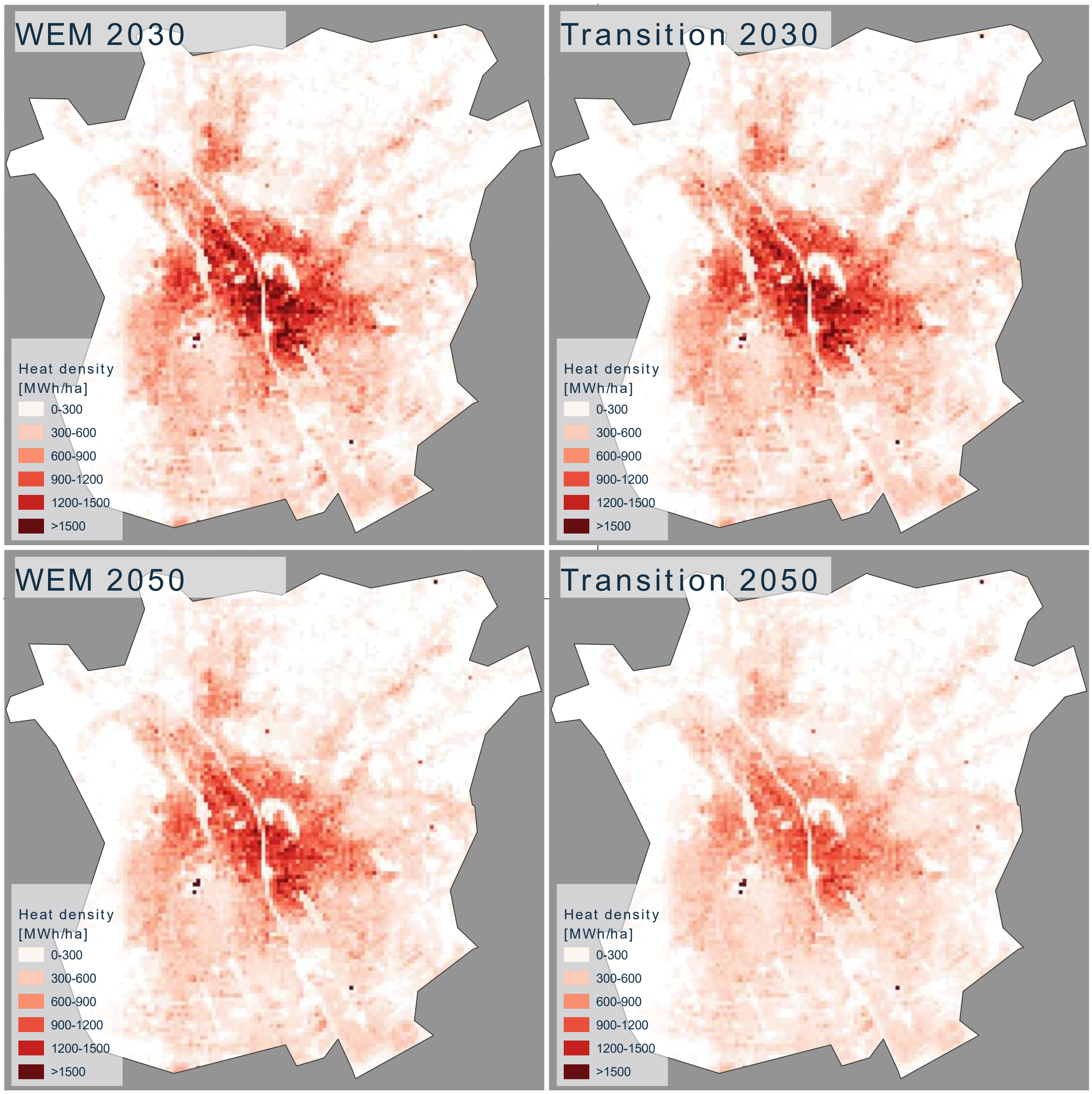


Figure 5-2: Distribution of heat demand densities for the exemplary case of Graz in the two heat demand development scenarios (WEM & Transition) for the years 2030 and 2050

5.3.3 Step 3: Identification of potential district heating areas

The effective width concept introduced by Persson et al. is used to estimate the heat distribution costs [29], [96]. The heat demand density and gross floor area density maps for both WEM and Transition scenarios from the previous step are used to calculate the annualised heat distribution costs in each hectare. Here, a constant heat supply of 30 years is considered for the analysis. The calculation is done both for 2030 and 2050 maps. Equations 5-1 to 5-4 show the calculation formulas.

$$Q_T = MS \cdot D_T \quad \text{(Eq. 5-1)}$$

$$C_d = \frac{C_1 + C_2 \cdot d_a}{n \cdot \frac{Q_T}{L} \cdot \sum_{t=0}^{n} (1+r)^{-t}} \quad \text{(Eq. 5-2)}$$

$$d_a = 0.0486 \cdot \ln(Q_T/L) + 0.0007 \quad \text{(Eq. 5-3)}$$

$$w = A_L/L = \begin{cases} 137.5e + 5 & [m] \quad 0 < e \leq 0.4 \\ 60 & [m] \quad e > 0.4 \end{cases} \quad \text{(Eq. 5-4)}$$

T	Calculation base year, here 2030 or 2050
D_T	Useful energy demand in year T [GJ]
Q_T	Useful energy demand covered by district heating in year T [GJ]
C_d	Levelized cost of heat distribution [€/GJ]
L	Trench length [m]
C_1	Construction costs constant [€/m], here 212 €/m
C_2	Construction costs factor [€/m²], here 4464 €/m²
d_a	Average pipe diameter [m]
e	Plot ratio [-]
n	Depreciation time, here 30 years
Q_T/L	Linear heat density [GJ/m]
r	Discount rate
w	Effective width [m]
A_L	Land area

Fallahnejad et al. proposed an approach for identifying potential DH areas [97]. This approach was updated and further elaborated in a more recent paper [98]. Two constraints are named for the identification of the potential DH areas:

- The annual heat demand within a potential DH area should be above a given threshold (lower bound for the heat demand in DH areas).
- The average heat distribution costs within a potential DH area may not exceed a given cost threshold (upper bound for the average heat distribution costs).

A lower bound of 10 GWh is set to identify the potential DH areas to assure the suitability of obtained areas for DH. Furthermore, sensitivity analyses on the DH market share within DH areas and the upper bound for the average heat distribution costs are run. Sensitivity analyses are distinguished by two cases of 45% and 90% for the DH market share and three cases of 30, 40 and 50 €/MWh for the upper bound for the average heat distribution costs. For each potential DH area, an average specific heat distribution cost ($\overline{C_{d,T}}$) is calculated, representing all hectare elements in that area. The calculation of $\overline{C_{d,T}}$ in a potential DH area is done by dividing the sum of grid costs (in €) by the discounted heat demand covered by DH (in MWh) in that area.

5.3.4 Step 4: Clustering district heating areas into region types

There are similarities between potential DH areas regarding heat demand, availability of heat sources and sinks, and availability of grid infrastructure. Calculating DH supply costs for similar potential DH areas will lead to similar results. As a result, potential DH areas are clustered into regions with similar characteristics to reduce the computation time.

Before the clustering, the potential DH areas for all scenarios and sensitivity analyses are overlayed with GIS layers on the availability of heat sources and grid infrastructure on the LAU 2 level (see Figure 5-3). The resulting information determines the characteristics of each potential DH area. The characteristics include:

- Availability of industrial waste heat with temperature > 100°C, suitable for direct feed into a DH using heat exchangers [81];
- Availability of industrial waste heat with temperature < 100°C, suitable for integration combined with a heat pump [81];
- Available potential for deep geothermal energy Klicken oder tippen Sie hier, um Text einzugeben.[99];
- Availability and size of surface water as a potential heat sink for heat pumps [100];
- Availability of gas network infrastructure [101], [102], [103];
- Availability of DH network in the vicinity of potential DH area [102].

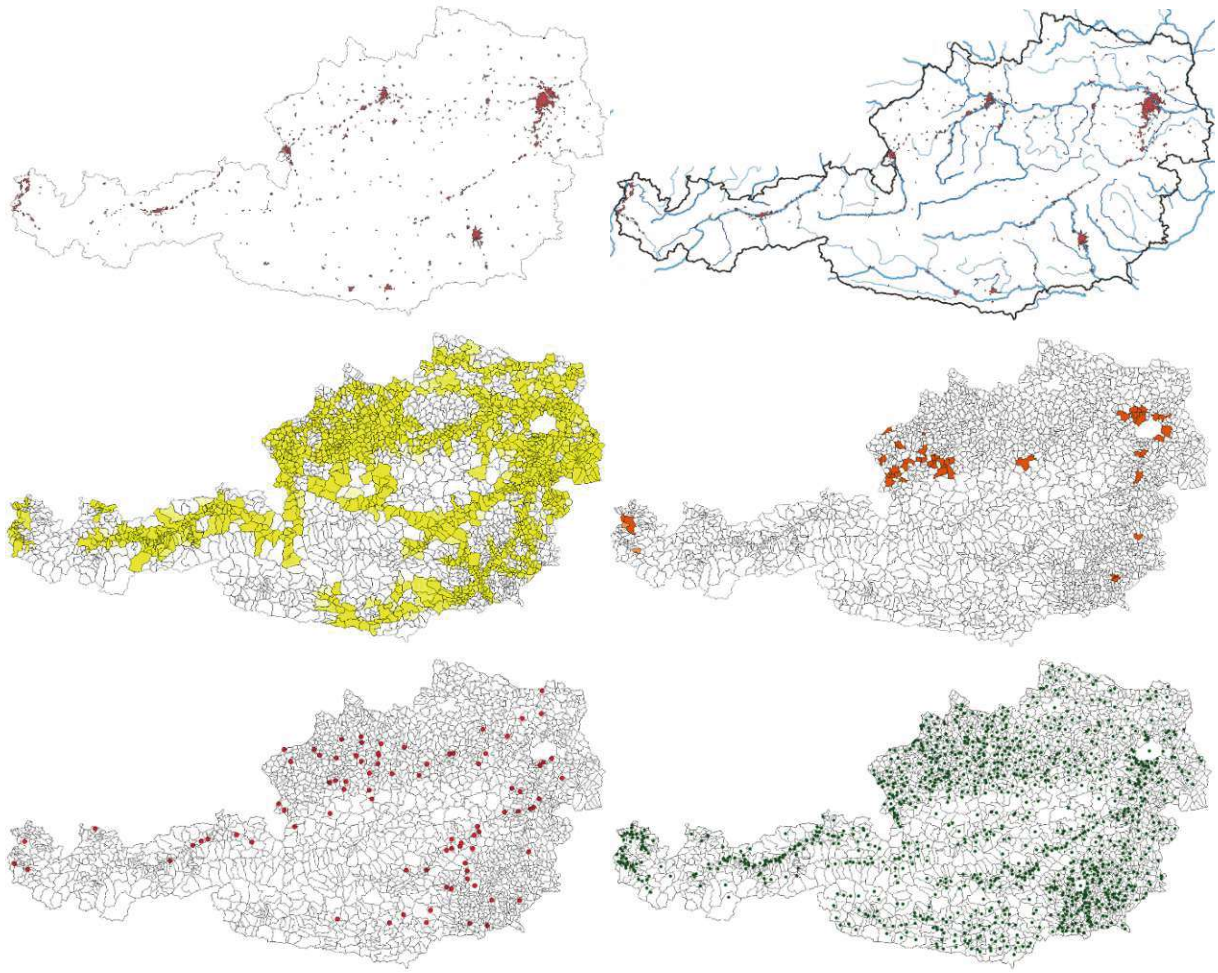


Figure 5-3: Potential district heating areas (top left), surface water (top right), availability of gas grid infrastructure (middle left), availability of geothermal potential (middle right), the potential for industrial waste heat (bottom left), existing district heating grids (bottom right) across Austria

Subsequently, a matrix of potential DH areas from all scenarios and sensitivity analyses with their characteristics is built. In total, ten typical regions are identified. The four DH regions with the highest heat demand are put in separate groups due to their significant size. These are the cities of Vienna, Graz, Linz and Salzburg. The remaining potential DH areas are grouped into six typical regions using the minimum "mathematical distance" clustering approach. The selected clustering approach is an agglomerative cluster performed with "Scipy" python library [104]. The selected linkage method is the Ward variance minimisation algorithm.

5.3.5 Step 5: Calculation of heat supply cost

In this step, the costs for DH supply and individual heat supply are calculated. Here, a standard calculation of the levelized costs of heat generation is applied, including CAPEX, O&M costs, energy carrier expenses, and CO2-emission costs. For the heat supply cost of the DH, the heat distribution costs are added up to the enumerated costs.

5.3.5.1 Step 5a: Calculation of the Heat Supply Cost in District Heating

For a given year (T), the heat generated by the DH supply units ($G_{th,T}$) should be greater than the sum of useful heat demand covered by DH (Q_T) and heat losses in grid and heat exchangers ($Q_{Loss,T}$) as shown in Eq. 5-5. Heat losses are modelled in a simplified manner and are assumed to be 10% of district heat generation. For a potential DH area, the sum of the specific heat generation costs ($C_{Gen,T}$) and the average specific heat distribution costs ($\overline{C_{d,T}}$) compose DH specific heat supply cost.

$$G_{th,T} \geq Q_T + Q_{loss,T} \qquad \text{(Eq. 5-5)}$$

$$C_{DH,T} = C_{Gen,T} + \overline{C_{d,T}} \qquad \text{(Eq. 5-6)}$$

The DH generation costs are calculated using an open-source dispatch model [105] developed by the Hotmaps project [30]. The model is a linear program with an hourly resolution. The objective function minimises the total costs for heat generation minus the revenues made from electricity generation, as shown in Eq. 5-7.

$$min(\ C_{DH,T} - \ Rev_{total,T}) \qquad \text{(Eq. 5-7)}$$

The objective function is subject to the constraint that the sum of heat generation of all units (j) and the sum of loadings (x_{load}) and unloadings (x_{unload}) of the heat storages in all hours (t) has to be greater or equal to the heat demand in each hour. More details on the mathematical formulation of the Hotmaps dispatch model are provided in [106].

$$\boldsymbol{s.t.} \quad \sum_{j,t} G_{th_{j,t}} + \sum_{hs,t}(x_{unload_{hs,t}} - x_{load_{hs,t}}) \geq \ Q_t + Q_{loss,t} \qquad \text{(Eq. 5-8)}$$

The heat demand, electricity prices, solar irradiation, and outdoor temperature are provided to the model in hourly profiles. Further model inputs are heat generation capacities with respective thermal and electrical efficiencies and fuel costs. The model outputs are among all the levelized heat generation, operation and fuel costs as well as the hourly operation of the supply units.

For each identified cluster in Chapter 5.3.4, the heat generation costs by DH are calculated separately. Based on the availability of resources and infrastructure, three technology mix portfolios are considered for each cluster:

- Business as Usual (BAU) with a predominant share of gas;
- Alternative 1: a composition of gas, renewables and waste heat, depending on resource availability in the region;
- Alternative 2: a composition of a predominant share of renewables and waste heat with no or limited gas, depending on resource availability in the region.

Depending on the DH potential spread, up to four sensitivity analyses on the installed generation capacities are performed for each cluster. Additional input parameters such as temperatures (air, water, heat sources) for the heat pumps, solar radiation, load profiles and resource availability were defined separately for each cluster.

The calculated heat supply costs from dispatch runs are allocated to the potential DH areas based on their potential. The most economic technology mix represents the optimal portfolio for the cluster.

Further assumptions and scenario specifications related to the heat generation costs of DH are elaborated in Chapter 5.3.7.

5.3.5.2 Step 5b: Calculation of the Heat Supply Cost of Individual Heating Systems

The renovation status of the buildings and the composition of the building stock are obtained from WEM and Transition scenarios [92]. Here, 20 different building categories for the buildings in the residential and service sectors are considered. In terms of building age classes, buildings in residential and service were allocated to 13 and 11 different classes, respectively. Additionally, the renovation state of each building category and age class are considered (renovated or not renovated).

The installed capacity for the individual heat supply is calculated based on the annual heat demand. The decentral heat supply module developed in the Hotmaps project [107], [108] is used to calculate the individual heat supply costs. Two different technology mixes of the individual heat supply for each building sub-category (based on building category, age class and renovation status) are considered, according to [21].

The specific cost and energy source requirements are calculated for each building sub-category. Obtained values are weighted according to the composition of the building stock and the technology mix. The most economic technology mix is used to calculate an Austrian-wide average reference cost for individual heat supply (€/MWh) for 2030 and 2050. A distinction of the individual supply cost for different regions in Austria was not possible, as the composition of the building stock in different potential DH areas is unknown. This reference cost is compared with the DH supply costs. Further assumptions and scenario specifications are elaborated in Chapter 5.3.7.

5.3.6 Step 6: Identification of the economic potential for efficient district heating

Efficient district heating implies:

- **equal or more** renewable energy technologies than fossil-fuelled individual generation energy technologies by 2030, and
- **exclusively** a combination of renewable fuelled heat, including ambient heat, and waste heat sources by 2050 [28].

In this respect, the results of the previous steps are used to identify the economic potential of efficient DH. Overall, 16 different scenarios from combining two heat demand scenarios, two target years, economic and financial perspectives, and low and high energy prices are calculated. Under each scenario, the heat supply costs of DH (heat generation and distribution costs) in each potential DH area are compared with an Austrian-wide average reference cost for individual heat supply. Accordingly, it is determined if a potential DH area is also an economic DH area:

- $LCOH_{DH} \leq LCOH_{Indiv.}$ → Economic district heating area
- $LCOH_{DH} > LCOH_{Indiv.}$ → Individual heating area

Under each scenario, the sum of potentials in economic DH areas determines the economic potential for efficient DH.

5.3.7 Overview of scenario assumptions and key input data

As stated in the Austrian government programme, it is assumed that renewable gas will account for 6% of the total gas supply in 2030 [82]. For the year 2050, it is assumed that the energy demand reduction due to forced building renovation and efficient new construction in WEM and Transition scenarios is sufficient to achieve full decarbonisation of the heating and cooling sector. This assumption implies that gas-based technologies will be supplied only with renewable gases in 2050.

Further assumptions on energy prices and CO2 emissions are summarised in Table 5-1. The corresponding implications on gas prices are shown in Table 5-2. Technology data, in particular cost data, are based on [109], [110], and [111]. For individual heat supply, retail prices are considered; for the DH supply, corresponding secondary energy prices are considered. Further information on energy carriers is summarised in the Appendix (Table B-1 and Table B-2).

Table 5-1: Assumptions and sources on prices and CO2 emissions

Energy Carrier	Assumptions	Data sources
Electricity	Hourly wholesale prices for Austria in two scenarios following an EU decarbonisation pathway obtained from SET-NAV project: Selected scenarios: Common EU-wide vision Vs. localised solutions. According to the policy target, there will be no net emissions from electricity generation in Austria in 2030.	Calculations with the Enertile model [112] in the H2020 project SET-NAV [113], [114]. Policy target from [82]
Gas	Share of green gas in the gas grid: in 2030: 6%, in 2050: 100%. For prices and further assumptions, see Table 5-2.	Gas share for 2030 is based on [10]. [47]–[52] result in a range of gas generation costs of 9-34 c€/kWh and were used to derive the assumptions in Table 5-2. Feedback from experts and stakeholders
Oil	Declining demand for oil leads to stable, low prices; no oil for heat supply in 2050	[113] and [121]
Biomass	Price stabilisation in the low-price scenario; a moderate price increase in the high-price scenario	Own analyses based on [122] and [123]; Feedback from experts and stakeholders
Waste	Costs: 0-5 €/MWh Reduction in specific emissions by 20% by 2050	Own assumptions; Feedback from experts and stakeholders
Industrial waste heat	Costs: 5-20 €/MWh depending on the temperature and price scenario	Own assumptions; Feedback from experts and stakeholders
CO_2 prices and costs	2030: 81-120 €/t 2050: 183-296 €/t External costs (Relevant ONLY for the economic perspective): 300 €/t	[112], [113], [121]; Feedback from experts and stakeholders

Table 5-2: Assumptions on the composition and supply costs of renewable gas in 2030 and 2050

	Low price				High price			
	2030		2050		2030		2050	
	Share [%]	Cost [€/MWh]	Share [%]	Cost [€/MWh]	Share [%]	Cost [€/MWh]	Share [%]	Cost [€/MWh]
P2G	5%	150.0	40%	110.0	5%	210.0	40%	170.0
H2	15%	80.0	40%	70.0	15%	120.0	40%	100.0
Biomethane	80%	60.0	20%	80.0	80%	80.0	20%	100.0
Total		**67.5**		**88.0**		**92.5**		**128.0**

Key input parameters for the CBA are energy and CO2 prices, emission factors, external costs, depreciation periods and interest rates. Two approaches are distinguished in all calculations according to [77]:

- **"Economic perspective"**: no taxes are taken into account, but external costs of CO_2 emissions are considered; the interest rate is 2%, reflecting low real interest rates in recent years in the EU; and the depreciation period corresponds to the technical lifetime of the infrastructures.
- **"Financial perspective"**: taxes and CO_2 prices are taken into account, but no external costs; the interest rate used is 4%, reflecting low real interest rates in recent years in the EU, but still considering a higher expected rate of return for the investors than under the "economic perspective"; and the depreciation period reflects the technical lifetime of the infrastructures.

While CO2 prices reflect the costs that DH operators should pay (financial perspective), external costs are the societal costs, independent of whether the GHG emitter needs to pay for it. Thus, societal costs (external costs) are considered in the economic perspective; whereas only the internalised costs that the GHG emitter needs to pay are taken into account in the financial perspective.

5.4 Results

5.4.1 Identification and clustering of potential district heating areas

For the WEM and Transition scenarios in 2030 and 2050, sensitivity analyses on the DH market share within DH areas and the upper bound for the average heat distribution costs were performed, resulting in 24 calculations to identify the potential DH areas. Figure 5-4 shows the extension and location of potential DH areas for an exemplary case.

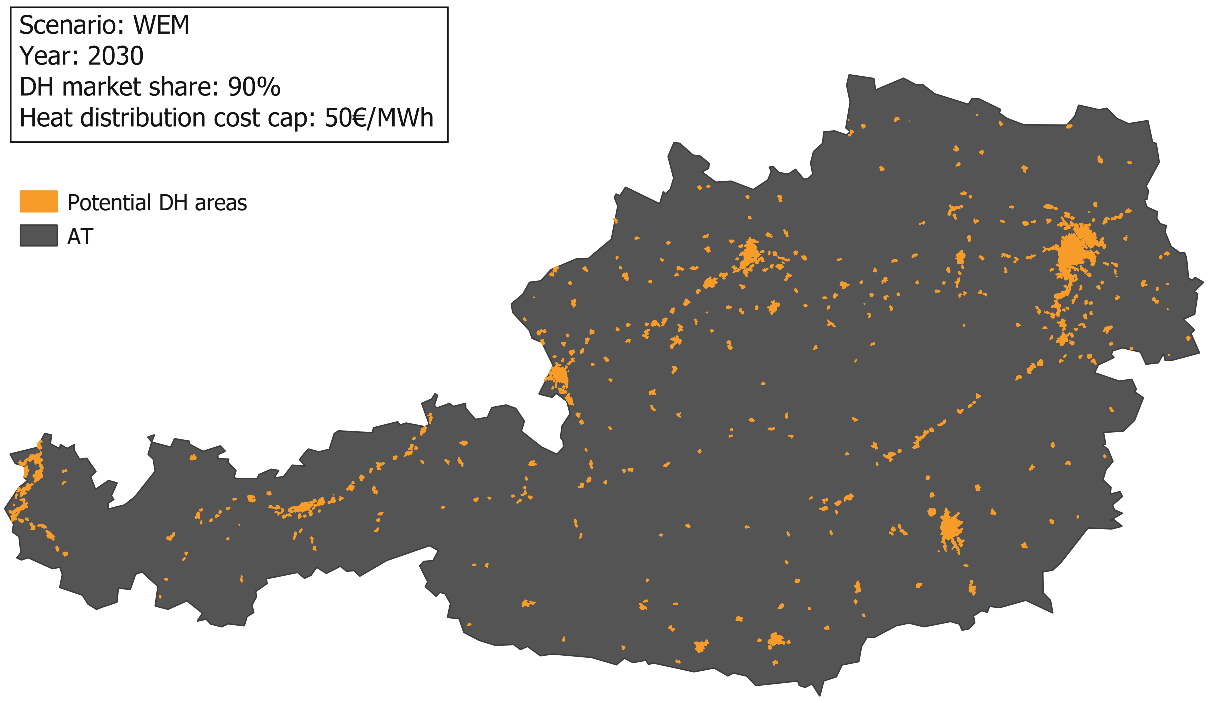


Figure 5-4: Regions potentially suitable for the use of district heating – a scenario with favourable assumptions for district heating in 2030

Depending on the parameter combination, the extension of the potential DH areas and the total DH potential vary. The DH potential in each sensitivity analysis is sorted ascendingly. Subsequently, the cumulative district potential is calculated, as depicted in Figure 5-5, for the exemplary case of the WEM scenario and the year 2050. As it can be seen in the figure, the market share has a significant impact on the total DH potential. Although the upper bound for the average heat distribution costs in DH areas positively relates to the total DH potential, its impact is considerably less than the market share.

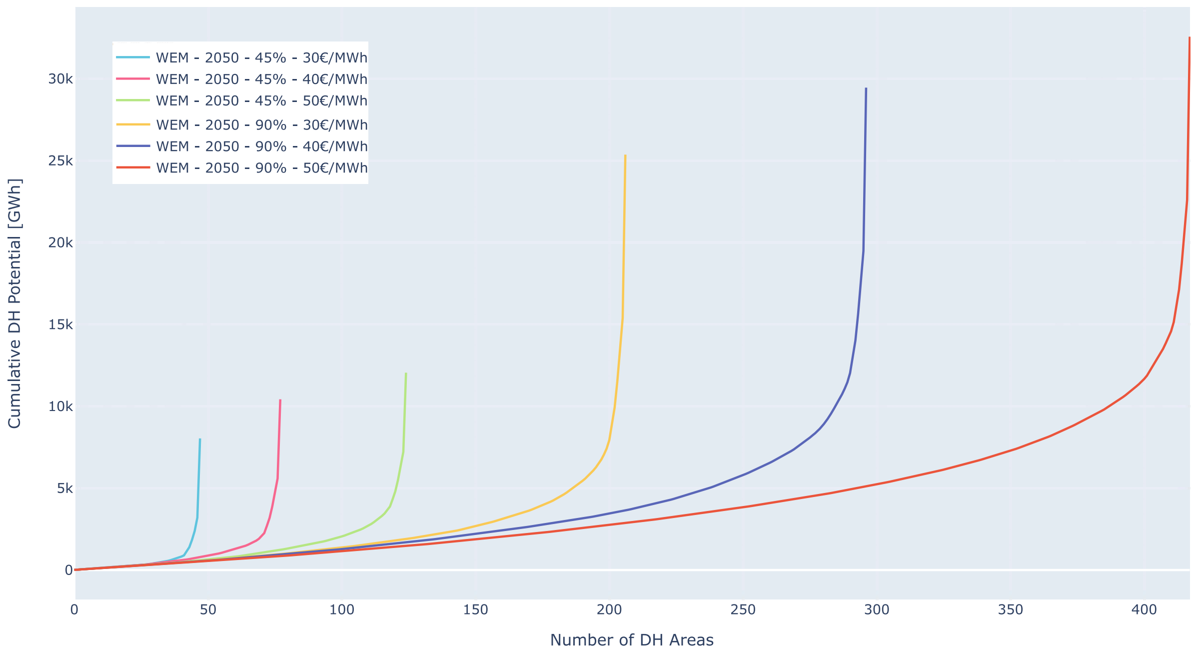


Figure 5-5: Cumulative district heating potential and number of areas identified under different scenario settings, WEM-scenario, 2050

All combinations of potential DH areas are displayed in the Austrian Heatmap [73] and are provided as supplementary data for this chapter [124].

As stated in Chapter 5.3.4, the clustering algorithm was applied to all identified potential DH areas from all scenarios, excluding four cities: Vienna, Graz, Linz and Salzburg. The result of the clustering approach is illustrated in Figure 5-6, showing the resource availability in six identified clusters (region types). It can be seen that DH and gas networks are already available in most of the identified potential DH areas. It also shows the regions with deep geothermal potential have limited surface water availability and industrial waste heat. Furthermore, there is a limited potential for industrial waste heat and deep geothermal energy in regions with large rivers.

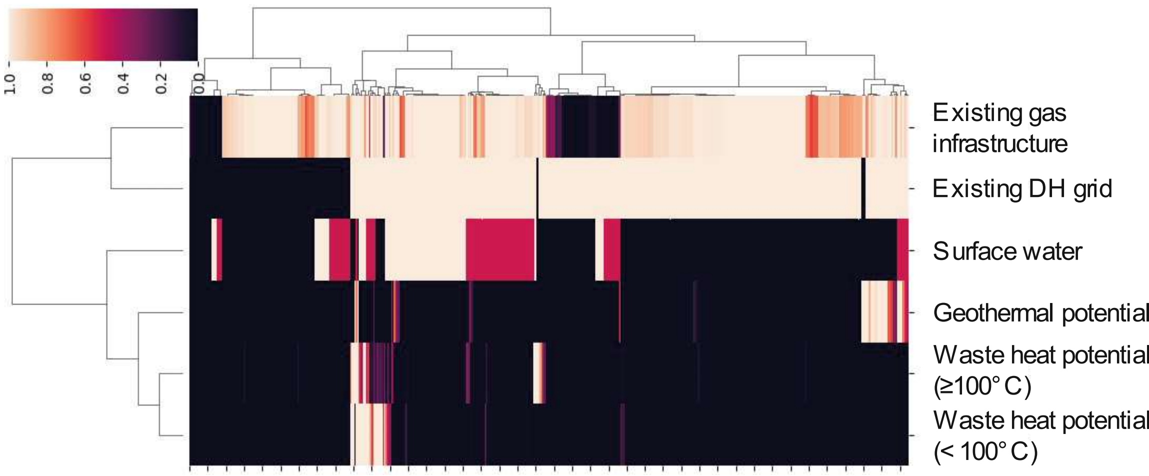


Figure 5-6: Visualisation of resource availability in the regions potentially suitable for district heating – "0" corresponds to "Not available", and "1" corresponds to "100% availability"

A qualitative presentation of the six region types and their characteristics is summarised in Table 5-3. It shows the number of potential DH areas. The last column in the table demonstrates how a scenario is favourable for DH. Region types 6 and 7 have a higher potential for DH. These are regions with existing DH grid infrastructure, with or without gas grid and good availability of surface water.

Table 5-3: Qualitative presentation of the six region types, their characteristics in terms of resource availability, number of regions and their size (colours are for the identification of similar entries)

	Existing DH grid	Gas grid availability	High-temperature waste heat availability	Low-temperature waste heat availability	Geothermal potential	Surface water potential	Number of regions per scenario (min-max) [-]	Heat demand of regions for each scenario (min-max) [GWh]	Sum of the heat demand of potential DH areas for each scenario (min-max) [GWh]
Type 5: Region without a grid, with an existing gas network	No	Yes	No	No	No	Low	2-90	10-136	54-1,670
Type 6: Region with the existing grid, without gas infrastructure	Yes	No	No	No	No	Low	5-195	10-675	290-9,200
Type 7: Region with existing grid, gas infrastructure and high potential for water heat pumps	Yes	Yes	No	No	No	High	2-66	10-1,100	48-5,200
Type 8: Region with existing grid, gas infrastructure and geothermal potential	Yes	Yes	No	No	Yes	No	1-43	10-50	13-750
Type 9: Region with existing grid, gas infrastructure and waste heat potential	Yes	Yes	Yes	Yes	No	Low	1-23	10-150	40-990
Type 10: Region with existing grid and gas infrastructure	Yes	Yes	No	No	No	No	0-24	0-320	0-1,400

5.4.2 The economic potential of district heating

As explained in Chapter 5.3.6, the economic potential of DH supply in a potential DH area is obtained by comparing the LCOH of DH supply costs with individual heat supply costs. Figure 5-7 and Figure 5-8 compare the LCOH of DH supply in different potential DH areas with the LCOH of individual heat supply in 2030 and 2050 from financial and economic perspectives, respectively. The x-axis shows the energy price scenario and sensitivity analyses on the upper bound of the average heat distribution costs and DH market share in DH areas. Each dot in the box-plot diagrams represents the LCOH for DH in a potential DH area. The red lines represent the average reference LCOH for individual heat supply. Thus, all potential DH areas whose corresponding dot (i.e., LCOH for DH) in the diagram fall below the red line are considered economic DH areas.

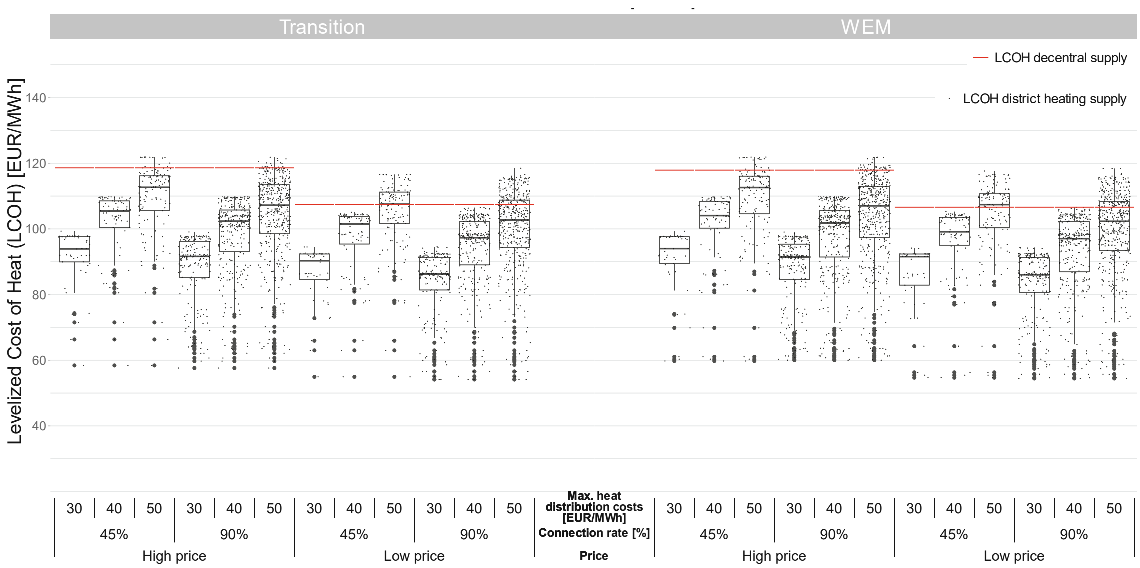


Figure 5-7: Comparison of LCOH of individual heat supply (red line) with those of district heating supply for different scenario variants in 2030, financial perspective

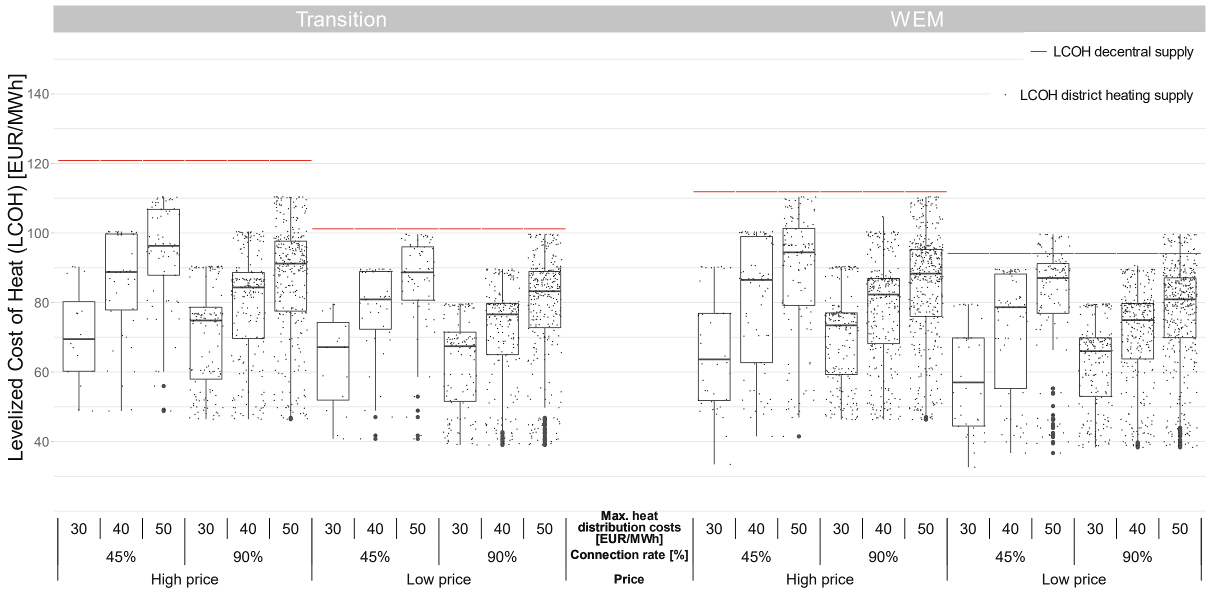


Figure 5-8: Comparison of LCOH of individual heat supply (red line) with those of district heating supply for different scenario variants in 2050, economic perspective

Under the selected scenarios, DH has high economic potential in most areas for 2050, especially under the assumption of high energy prices. For the year 2030, in the financial perspective, there is an economic DH potential in most areas. District heating is not economically feasible in a considerable number of areas if the maximum heat distribution cost of 50€/MWh is considered. There are a considerable number of areas in which decentralised technology proves to be more favourable than heat supply via heat grids. In the economic perspective for the year 2030, the opposite is true because the external costs of CO2 emissions lead to a strong decarbonisation effort for DH, whereas this is not so much the case for decentral heating. This leads to high costs for decentral supply options but to a lower extent for DH, which makes DH a viable option in all considered cases.

Figure 5-9 and Figure 5-10 illustrate the share and potential of DH areas where DH is not economically viable (where the LCOH of DH is higher than the LCOH of decentral heat supply mix):

- The higher the upper bound for the average heat distribution costs (used to identify potential DH areas) is, the higher the share of potential DH areas where DH is not economically viable is.
- Since the relative influence of energy prices on the individual heat supply is higher than on the DH supply, more areas cannot be supplied economically with DH under low energy prices compared to high prices. Also, the average size of areas where DH is not economical is higher in low energy prices cases than in high energy prices.

- It can be seen that the average potential of regions in which DH is not economically viable is well below 50 GWh/a in almost all cases in 2050. In 2030, due to the significant share of natural gas in the decentral supply mix, the consideration of external costs of CO2 emissions in the economic perspective leads to high costs of decentral heat supply and, thus, high economic potential of DH. For 2030, only in the financial perspective and under maximum heat distribution costs of 50 €/MWh, a significant number of potential DH areas are not economically feasible, with a mean size of below 25 GWh/a.

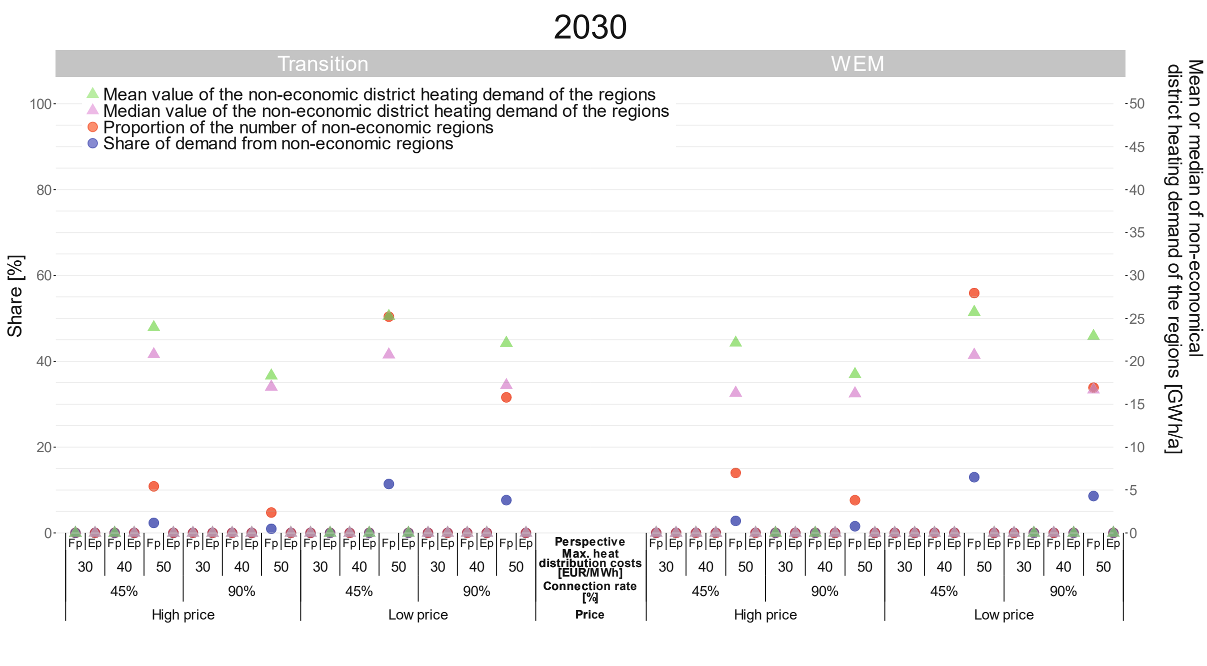


Figure 5-9: Share of potential district heating areas for which district heating is not economic (number and demand) and the average potential of these regions (median, mean), 2030, (FP: financial perspective, EP: economic perspective)

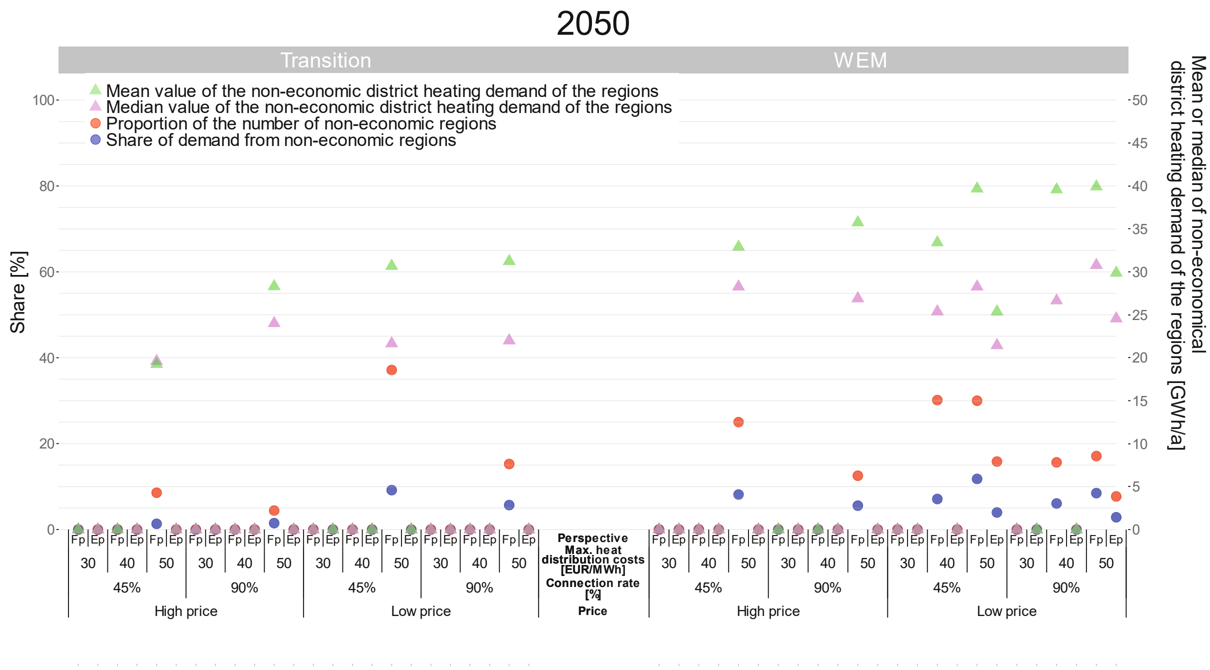


Figure 5-10: Share of potential district heating areas for which district heating is not economic (number and demand) and the average potential of these regions (median, mean), 2050, (FP: financial perspective, EP: economic perspective)

Figure 5-11 and Figure 5-12 show the resulting coverage of useful energy demand by DH (red dots) compared to Austria's total useful energy demand (blue dots). It can be observed that there is a strong dependence on the economic potential of the assumed DH market shares (45% Vs 90%). Also relevant is the dependence on the upper bound for the average heat distribution costs (30, 40, or 50 €/MWh). The differences between the assumptions on energy prices are minimal in terms of the impact on the economic potential of DH. As stated in Chapter 5.4.1, the upper bound for the average heat distribution costs in DH areas positively relates to the total DH potential. However, as shown in Figure 5-7 and Figure 5-8, this increases the overall heat supply costs of DH and in certain cases, negatively impacts the competitiveness of the DH system. This effect can also be traced in Figure 5-11. Under 90% DH market share in low price scenario, for both WEM and Transition cases, the increase of upper bound of the average grid costs from 40 to 50 €/MWh has no or limited impact on the increase of the economic potential of the DH. Therefore, it should be noted that investment in areas with high specific heat distribution does not always and everywhere lead to a better positioning of DH than the individual heat supply systems.

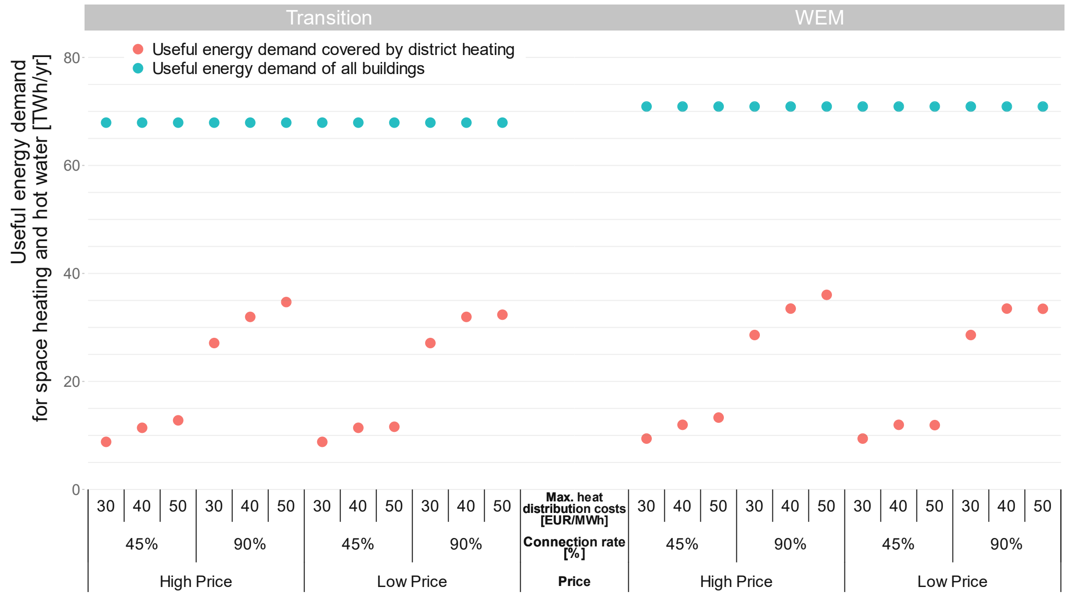


Figure 5-11: Economic potentials of district heating in the different scenarios calculated, financial perspective, 2030

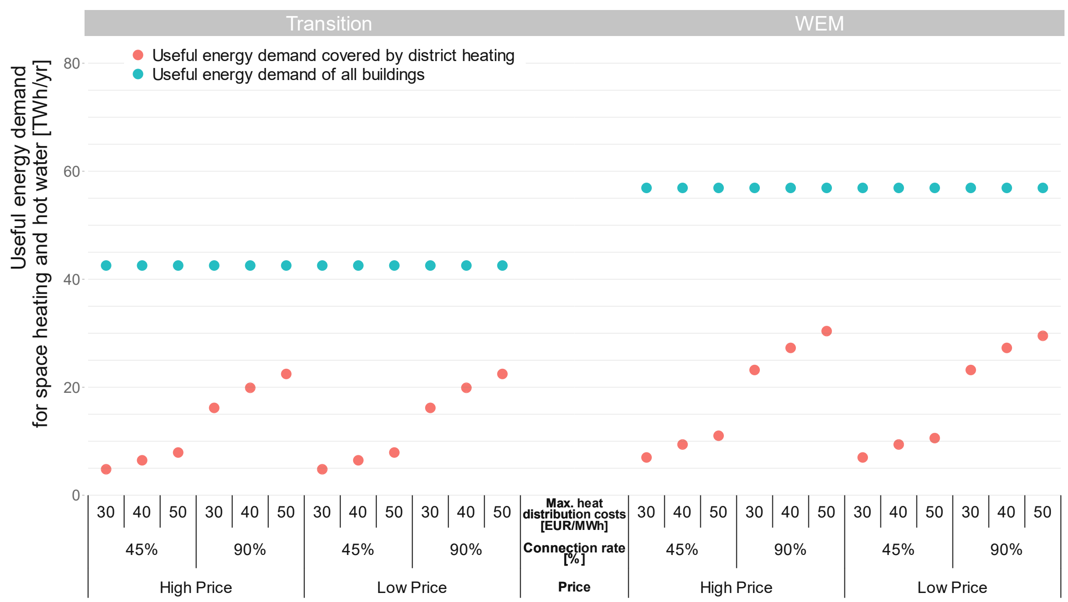


Figure 5-12: Economic potentials of district heating in the different scenarios calculated, economic perspective, 2050

Figure 5-13 and Figure 5-14 show the energy carrier mix for the supply of space heating and hot water (both DH and individual systems) in the different scenario options for 2030 and 2050 compared to the base year 2018. The background data of the both figures is provided in appendix in Table B-3, Table B-4, Table B-5, and Table B-6. In the figures 5-13 and 5-14, hatched lines distinguish the individual heat supply from DH.

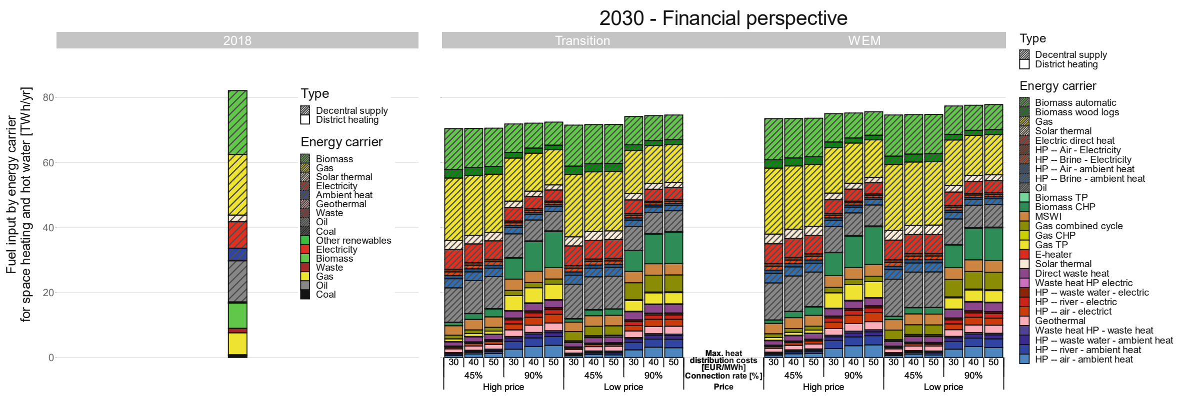


Figure 5-13: Energy mix for the provision of space heating and hot water in the different scenarios in 2030 for the financial perspective. (Sources for the base year 2018: [125], [126]; Source for the scenario runs: own calculations)

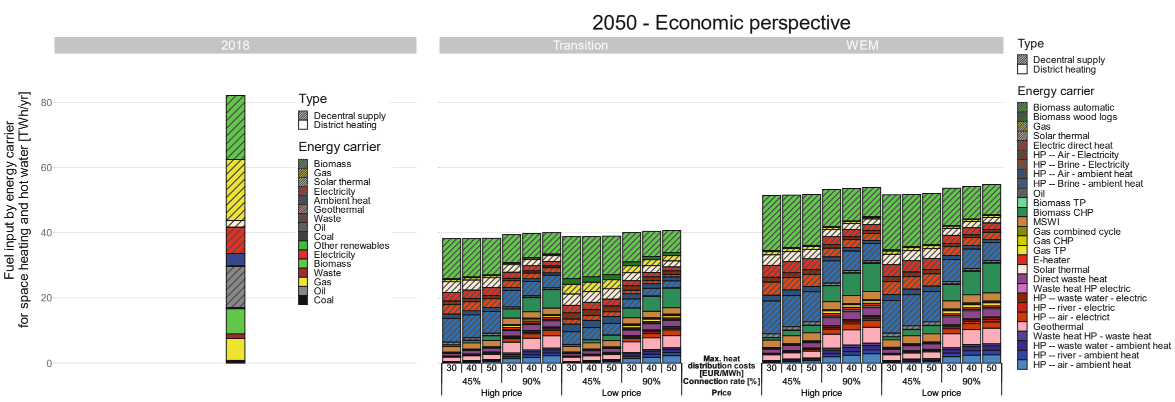


Figure 5-14: Energy mix for the provision of space heating and hot water in the different scenarios in 2050 for the economic perspective (Sources for the base year 2018: [125], [126]; Source for the scenario runs: own calculations)

There is a difference in the total fuel input between the WEM and Transition scenarios originating from the different demand levels. More relevant, however, is the distinction between variants of the DH market share (45% and 90%). If a higher DH market share can be achieved (e.g., through a stringent energy planning policy), a significantly higher share of the heat demand can be covered with DH. The synthesis of the results revealed that a higher market share also leads to the annexation of new areas to the previously identified potential DH areas under lower market shares. Consequently, a higher share of geothermal or waste heat utilisation is also possible, and large-scale heat pumps become more relevant for the coverage of the heat demand.

Regarding the decentral technology mix, it turns out that by 2030 it will be very difficult to strongly reduce the gas demand, which is why all scenarios still show a similar share of gas on the decentral heat supply. By 2050, a complete phase-out of gas in the individual heat supply mix is almost always the most economical option, except for the case of low prices under the transition scenario.

While the share of DH and decentral heat supply is distinct between the scenarios, the energy mix of district heat supply remains relatively robust under different sensitivity analyses and scenarios. This suggests that these parameters do not fundamentally change the selection of economic DH supply portfolios and technologies across Austria, and thus, the basic statements exhibit certain robustness.

5.4.3 Limitations

The LCOH for the individual heat supply within potential DH areas depends on the exact composition of building stock and heating technologies. However, in this chapter, an Austrian-wide average reference cost for individual heat supply was used. A distinction of the individual supply cost for different regions in Austria was not possible, as the composition of the building stock in different potential DH areas is unknown. Furthermore, a solid database with a high spatial resolution of buildings and heating systems distribution is still missing [127]. There are increasing activities and efforts to elaborate such datasets on the building level to support heat planning on the local, regional and national levels (see, e.g. the project "spatial energy planning" [128]).

There are uncertainties concerning the possible development of investment costs of technologies and their site requirements. In this regard, land costs for large-scale thermal storage systems and solar thermal energy or associated risks of an investment in deep geothermal energy can be enumerated as sources of cost uncertainties. On the other hand, there are also uncertainties with regard to the technological developments improving efficiencies and characteristics of a system, which can be expected in the future. Furthermore, the interplay of the different renewable DH technologies in the portfolio, even with heat storage systems, is complex and strongly dependent on the expected DH demand. The expected heat demand is, in turn, strongly dependent on the measures in the field of building renovation, as well as on the achievable market share. Since these factors cannot be predicted long-term, a continuously adapting planning process is required, both on heat network operators' and policy makers' sides.

Calculated heat supply costs of the DH include heat generation and distribution costs. Heat losses in the DH system are modelled in a simplified manner. Furthermore, the pumping costs were not included in the distribution costs.

A detailed analysis of renewable gas potentials is not the focus of this chapter. Baumann et al. [120] conclude that the demand for renewable gases by 2040 will exceed the Austrian potential of biomethane, which is around 20 TWh. The potential generation of H2 and e-gases could be higher; however, it depends strongly on the total electricity generation by renewable energy sources and the international context, both of which are not the focus of this study.

In the scenarios with a small efficiency increase, the pressure on biomass resource utilisation would strongly increase. Therefore, the decarbonisation in these scenarios is more difficult than in those with high renovation efforts. However, a detailed consideration of biomass potential, its allocation in different energy system sectors and the overall bio-economy is not in the scope of this chapter.

The role of thermal power plants and CHPs in a future renewable electricity system was not the focus of this study. Nevertheless, the analyses indicate that gas-fired thermal power plants will only be used with relatively low full-load hours by 2050 – under the premise that only renewable gas will be used.

According to the calculation results, in a few cases (e.g., 2050, financial perspective, low energy prices), the scenario with some share of gas on decentral heat supply might be more economic than the one with a complete gas phase-out. Such a scenario would lead to higher gas distribution costs if not carefully planned. Again, this would lead to higher gas prices for the end-user, which was not considered explicitly here.

Existing heat networks were not explicitly considered. This can be seen as a conservative assumption regarding the existing DH potential. The use of large thermal storage systems contributes significantly to the economic operation of the heating networks and is expected to play a key role in the evolution of smart energy systems (see, e.g. [129]). However, there are significant uncertainties regarding costs and other barriers in the context of this chapter, which were not analysed here in more detail. The possible future temperature reductions in heating networks were not considered. However, such a lowering is aspired and propagated and analysed in relevant studies (e.g. in [130], [131]). In particular, the thermal renovation of buildings supports a reduction of supply temperatures, which in turn facilitates the feed-in of low-temperature waste heat or solar thermal energy. Lowering temperature levels would also positively affect DH potentials, but these could not be quantified in detail within the scope of this study. The exogenous configuration of the different DH generation portfolios further limits the methodological approach, as it restricts the variety of solutions. However, by varying assumptions and consulting with DH companies, a high degree of realism could be achieved. Finally, there are natural limitations but also benefits of a detailed sectoral analysis compared to a full energy system model. Main links to other parts of the energy system are given, e.g., via electricity prices, prices of synthetic fuels or biomass potentials available for the heating and cooling sector. These links would be worth considering in further analyses.

The proposed methodology and workflow can be used as guidelines for similar studies in other countries. This holds in particular for the key steps outlined in Chapter 5.3. However, there might be good reasons to deviate in terms of mentioned limitations due to data availability, policy priorities, upcoming debates or uncertainties. Also, the parameterisation, e.g., in terms of energy price scenarios, needs to be adapted to recent or expected upcoming trends. The availability of highly granular data sets from new sources in spatial and temporal terms can improve the level of detail in the proposed method. For example, it would be relevant to include the split of heating systems and applied energy carriers in calculating the LCOH of individual heat supply options.

5.5 Conclusions

This work aimed to assess the economic potential of DH in Austria in 2030 and 2050. This was achieved by performing six separate steps. It was demonstrated that clustering potential DH areas and assigning a few supply portfolios to each cluster is a good approach to keep, on the one hand, the number of model-runs and CPU time limited and, on the other hand, maintain the level of detail in the analyses. Considering the enumerated limitations, the approach can be used as a guideline for similar studies in other countries.

The basic underlying assumption in this chapter was that the goal of (net) climate neutrality in Austria would be achieved between 2030 and 2050. This assumption means that fossil energy sources still play a role in determining the economic potential for 2030, but no longer for 2050. For 2050, it was therefore assumed, among other things, that the final demand for gas would need to be met by renewable gases. Thus, CO2 prices or external costs of CO2 emissions are no longer relevant anymore in the evaluation of the year 2050. Under these conditions, the following key conclusions can be derived from the obtained results:

Decarbonisation of the heating and cooling supply in Austria is possible, but only under some key assumptions and framework conditions:

- Extensive efforts are needed to refurbish buildings: These are the basic prerequisite, e.g., for efficient use of heat pumps, as well as for a moderate demand for resources to cover the remaining heat demand (even if this aspect could not be explicitly addressed in the context of this paper).
- The electricity supply should also be decarbonised for the decarbonisation of space and water heating. Heat pumps are a relevant technology in covering the heat demand.

An economic DH potential in a range of 13% to over 50% was calculated, depending on the different assumptions. The sensitivity analyses revealed that the economic potential of DH depends, above all, on the market share achieved in DH areas. The results showed that by doubling the market share from 45% to 90%, the DH potential is more than doubled. The upper bound for the average heat distribution costs in DH areas positively relates to the total DH potential. However, it should be noted that investment in areas with high specific heat distribution costs does not always and everywhere lead to better positioning of DH than the individual heat supply systems.

Regarding the technology mix for DH, the following conclusions can be derived from the cost-benefit analysis:

- Renewable gas, in general, is not a cost-effective option for decarbonising the space and water heating sector. For DH generation, the heat supply portfolios, including a higher share of renewable gas, turned out to be more expensive than the solutions with a low share of renewable gas. For this reason, they did not appear in the results. In the decentral heat supply, the cost comparison between the two alternative mixes, in most cases, leads to a decision for the scenario with an almost complete phase-out of gas.
- According to the cost-benefit analysis, biomass holds a significant share of the economic renewable heat potential. In the scenarios with a small efficiency increase, the pressure on biomass resource utilisation would increase very strongly. Therefore, the decarbonisation in these scenarios is more difficult than in those with high renovation efforts.
- Heat pumps play an essential role in the economic potential for decentral heat supply and DH. This is the case, although seasonal fluctuations in heat source temperatures, such as rivers, explicitly were considered in the modelling of the large-scale heat pumps. This results in cases with a significantly reduced use of heat pumps in the coldest periods of the year, whereby the heat storage systems then play a significant role.
- Large-scale solar thermal plants can be an economically viable option; however, they are highly dependent on the overall structure of the generation portfolio and on the achievable cost reductions – which in turn scale strongly with the size of the plants.
- The role of thermal storage for a fully decarbonised DH supply was considered in the modelling. It was, however, not explicitly discussed. A more thorough analysis of the role of different dimensions and types of thermal storage, particularly in the context of decreasing heat supply temperature and 4^{th} generation of the DH (see, e.g. [131]), would be important to be addressed in further research.

6 Conclusions and outlook

6.1 Findings referring to the research questions

The core objective of this thesis is to develop and apply methodologies to estimate the DH potential on the EU, national and local levels, and to elaborate the technical, economic and policy implications of results at each level. Four main articles provide insights into the estimation of the DH grid costs and DH potential and answer the underlying research questions raised in Chapter 1.2. The current chapter outlines the key findings.

For **Research Question 1**: "What are the main advantages and disadvantages of using a generic DH grid modelling approach based on a regression model for determination of the DH potentials, and to what extent do its results align with those obtained from an optimization-based model? What are the challenges of using each model in the context of DH grid modelling and DH potential?" Chapter 3 suggested an approach for determining DH potential based on the effective width concept with the aim of decreasing the data intensity and computational complexity so that it can be applied to different spatial resolutions. The suggested approach encompasses various techno-economic aspects such as estimation of pipe dimensions, trench length or grid costs; however, it simplifies some other aspects related to the heat supply or hydraulic of the heat transfer. Therefore, the approach is well-suited for the pre-feasibility studies and strategic analyses. It was shown that the proposed method for estimating heat distribution costs serves as a reliable proxy for costs and potentials when compared to an optimization-based approach, offering a faster and less data-intensive process.

In existing literature, the estimation of DH grid costs and DH potential often assumes a 100% connection rate in DH areas. However, in reality, DH networks are not developed all at once; their expansion is a gradual process. The approach used in Chapter 3 and in its mature form in Chapter 4 provides a more accurate assessment of heat distribution costs and DH potential through modelling the gradual heat demand reduction and evolving DH grid expansion.

For **Research Question 2**: "What is the impact of connection rates in sparse urban and suburban areas on the DH potentials?" the impact of DH market shares of less than 100% was investigated by introducing an adjustment factor for plot ratio in sparse areas. This adjustment factor influences the costs of distribution pipes in low plot ratio areas ($pr < 0.14$) and service pipes across all plot ratio ranges, providing a conservative cost estimate. It was shown that, at a given plot ratio, the cost of the service pipes is more influenced by DH market shares than distribution pipes.

Within the identified DH areas under the Best-Case scenario for EU-27 countries, only 34.1 TWh out of 687 TWh in 2050's heat demand exists in the low plot ratio areas ($pr < 0.14$). In terms of DH potential, it accounts for 28 TWh out of 531 TWh. Without achieving high DH market shares, connecting sparse areas to the DH system would not be possible economically.

For **Research Question 3**: "What is the impact of gradual heat demand reduction and DH market share increase in DH areas on the economic viability and potential of the DH systems on the EU level?" two scenarios of heat demand reduction were considered. It has been shown that DH can fulfil one-third of the total heat demand of EU-27 in 2050, even with high DH connections. Importantly, it has been revealed that even with significantly higher DH connection rates in 2050, a substantial decrease in heat demand (Best-Case scenario) will not result in a significant increase in DH potential (only an 11% potential increase was observed). A more moderate reduction in heat demand, as in scenario Base Line 2050, with high DH connection rates in 2050, will lead to a 47% increase in demand coverage by DH from 2020 to 2050. These findings indicate that it is possible to maintain current DH heat supply levels even in a scenario with greater demand reductions by a more extensive expansion of DH networks.

In the Best-Case scenario, it was demonstrated that over 40% of the DH potential in 2050 is associated with higher heat distribution costs of above 35 EUR/MWh at the EU-27 level. However, this situation varies among different member states and is heavily influenced by current DH market shares, distribution of heat demand, construction cost levels, and the extent of demand reduction. DH areas with low annual heat demands, i.e., below a few GWh, and low average heat demand densities often necessitate greater specific grid investments.

For **Research Question 4**: "How to identify the economic potential of DH on a national level while considering the spatiotemporal aspect of heat supply and demand under different scenarios, and how can it be used as a guideline for similar studies in other countries?" a six-step approach was introduced. By using this method, we can avoid the need for separate calculations for each municipality or commune. Instead, DH areas that share similarities in size, grid infrastructure availability, and heat sources are grouped together as clusters, and their economic potential are calculated. This simplified approach helps to address the complex task of assessing the national economic potential of DH. To account for the simplification, numerous sensitivity analyses were conducted. Despite the extensive sensitivity analyses, this approach saves time by reducing the effort required for model and data preparation, as well as result synthesis. The transparency of the approach and the availability of calculation modules with an open-source license make it applicable to any region. It is, however, important to take into account the limitations of the model when interpreting the results.

6.2 Strengths and limitations of the applied methodology

The main strengths of the proposed methodologies are transparency, replicability, and computational efficiency, which have been detailed in each chapter. These approaches are well-suited for analysing DH potentials at the local, regional, and national levels. The computational efficiency allows for running a large number of calculations within a short period, enabling easy investigation of the impact of different parameters. For estimating the DH potential, only two data sets are required: a heat demand density map and a gross floor area density map, both of which are available in open-source data sources. For estimating the efficient DH potential additional input data is required; however, the proposed approach still provides significant computational advantages through clustering and generalizing the solution.

The approach for the identification of the potential DH areas involves using GIS to represent results and provide performance indicators for each potential DH area. This allows for the visualization of the location, extent, heat demand distribution, average heat demand density, approximate trench length, and average DH grid costs in absolute and specific terms for each identified DH area. Additionally, the approach tracks the development of heat demand and DH market share, making it possible to monitor their gradual evolution. The results can be used to prioritize areas for developing or expanding DH. Furthermore, it is also feasible to create an expansion pathway for identified areas, outlining development phases to maximize revenues or minimize costs, although this was not explored in this thesis.

The thesis also investigated the DH potential and grid costs in low plot ratio areas by introducing an adjustment factor and using it inside the formula of the effective width (Eq. 4-22 and Eq. 4-23) to study the impact of DH market shares. It is clear that low plot ratio areas should not be overlooked for DH planning even though their DH potential is considered generally moderate and their specific DH grid cost is higher.

Besides the enumerated strengths, there are limitations that should be considered while using proposed methodologies. These limitations are summarized in the following paragraphs.

The formula of the effective width has been obtained through an interpolation of the empirical data of the existing DH grids [29]. The fact that 3rd generation of DH systems was dominant in the empirical dataset may lead to a worse modelling of DH grid costs for other DH generations. This limitation is also valid for the supply and return temperature levels and may lead to better or worse modelling of DH grid costs depending on their working temperature levels. Accordingly, the approach lacks the capability to account for the influence of temperature levels on both DH grid costs and operating costs.

The assumptions made for the determination of the potential DH areas have an impact on the results. These assumptions are:

- The heat demand and covered heat demand by DH in years between base year and target year are interpolated based on Eq. 4-12 and Eq. 4-14,
- The DH market share evolution is considered uniformly for all hectare cells within each study area.
- For the adjustment factor:
    - Heat supply of buildings in low plot ratio areas is conducted either with or without DH (having two or more heating systems in a building was excluded),
    - Using an adjustment factor curve for ten buildings per hectare.
- A minimum annual DH demand of 5GWh/year was set as a criterion for identifying DH areas.

The above assumptions impose limitations in applying the results in the implementation phases but are accurate enough for the pre-feasibility and feasibility studies.

Obtained DH potentials are sensitive to the input data and parameters, as shown in Chapter 4. The 5 GWh criterion as the minimum annual DH demand in DH areas, which was used in this chapter, ensures that no overestimation of DH potential is made. At the same time, this assumption may exclude favourable areas with low demand from DH potential analyses.

The method assumes that the plot ratios remain constant over the lifespan of the pipelines. However, this assumption hinders the modelling of development areas in cities where new neighbourhoods or districts are expected to emerge in the future. Therefore, it is important for future studies to also consider the evolution of gross floor areas and their impact on DH potentials.

With regard to the cost of the grid infrastructure, it is assumed that the investment decision is made at the beginning of the study horizon. No delay between the investment decision, construction phase and commissioning of the DH grids is modelled. Furthermore, the cost of substations was not included in the overall grid infrastructure costs.

Existing heat networks were not considered for the determination of potential DH areas and their corresponding grid costs. This can be seen as a conservative assumption regarding the existing DH potential. The distance of the potential DH areas from heat sources has also not been considered in the analyses. This can slightly influence the overall heat distribution costs and accordingly, can lead to a slight decrease or increase of the specific costs.

In addition to the enumerated limitations for the determination of the potential DH areas, there are limitations for estimating the economic DH potential, which are listed in the following paragraphs.

The LCOH for the individual heat supply within potential DH areas depends on the exact composition of building stock and heating technologies. In Chapter 5, however, an Austrian-wide average reference cost for individual heat supply was used as the composition of the building stock in different potential DH areas is unknown due to the lack of a solid database.

There are uncertainties and risks regarding the potential investment costs of technologies and their site requirements, which were not considered in this thesis. Additionally, there are uncertainties related to technological developments that may improve the efficiencies and characteristics of a system in the future. Furthermore, the interaction of different renewable DH technologies in the portfolio, including heat storage systems, is complex and heavily reliant on the expected DH demand. Anticipated heat demand is closely linked to building renovation efforts and achievable market share, both of which are unpredictable in the long term. This necessitates a continuously adaptive planning process for both heat network operators and policymakers.

The calculated costs for supplying heat through the DH system encompass the expenses associated with heat generation and distribution. The model for heat losses in the DH system is quite simplified. Additionally, the costs related to pumping and substations were not factored into the distribution costs. Similarly, expenses related to planning or administration were excluded from the analyses because they are location-dependent and vary between different areas.

According to the calculation results, in a few cases (e.g., 2050, financial perspective, low energy prices), the scenario with some share of gas on decentral heat supply might be more economic than the one with a complete gas phase-out. Such a scenario would lead to higher gas distribution costs if not carefully planned. Again, this would lead to higher gas prices for the end-user, which was not considered explicitly in this thesis.

In particular, the thermal renovation of buildings facilitates a reduction in supply temperatures, thereby enabling the integration of low-temperature waste heat or solar thermal energy. While the potential impact on DH capabilities was not extensively quantified within the scope of this thesis due to the exogenous configuration of various DH generation portfolios, efforts were made to enhance realism by adjusting assumptions. It is also important to note that the full energy system was not modelled in the analyses of the economic DH potential.

6.3 Highlight

The following highlights express the main takeaways of this thesis:

- The proposed DH grid modelling approach based on a regression model for the determination of the DH potentials provides reliable estimations that fulfil the needs for DH potential analyses at the pre-feasibility stages, especially considering components related to the gradual development of heat demand and DH market shares.

- Grid expansion and connection of additional buildings to the DH network in economically favourable DH areas are crucial to maintaining the specific costs of the DH grid infrastructure.
- Decarbonisation targets strongly affect the parameterization of the approach, and accordingly on the DH potentials.
- Clustering of DH areas based on the availability of the infrastructure and renewable potentials and generalising the results to all regions with similar characteristics allows the analysis of economic DH potential on a national level.
- DH can cover more than 30% of the total heat demand (excluding process heat demand) in EU-27 up to 2050
- In Austria the economic district heating potential can exceed 50% of heat demand.

6.4 Conclusions

DH networks are not built all at once, and their expansion is a gradual process. This thesis demonstrated an endeavour to use the existing theoretical framework of modelling heat distribution costs of DH systems and introduced an approach for modelling the gradual heat demand reduction and evolving DH grid expansion to provide a realistic picture of the heat distribution costs and DH potential. In addition, aspects related to the economic potential of the DH systems on a national level were presented.

The suggested approaches in this thesis aimed to decrease the data intensity and computational complexity so that they can be applied to different spatial levels. The assumptions impose limitations in applying the results in the implementation phases but are accurate enough for the pre-feasibility and feasibility studies and strategic analyses.

The novel algorithm for the identification of potential DH areas, not only allows finding suitable DH areas with the highest DH potential based on provided inputs but also allows tuning the obtained results for the identification of focus regions. The parameters for minimum heat demand at the hectare level, targeted future DH market share, minimum heat demand at DH areas after achieving targeted market share, heat distribution cost ceiling and discount rate provide degrees of freedom, supporting maximizing coverage or profit in DH areas. Thanks to the low computational effort, performing sensitivity analyses on each of the input parameters, regardless of the size of the case study, can be done with limited effort. Besides returning GIS layers that demonstrate the extent of the potential DH areas, the approach returns valuable indicators at the level of a single DH area, or collectively on a regional level. The indicators can be easily compared with each other when performing sensitivity analyses.

Also, an updated assessment of the DH potential across the EU member states, considering the future development of both heat demand and DH market share within DH areas, was presented. In the decarbonization scenario (best-case scenario), heat demand in EU-27 countries will decrease by 45% by 2050. Under this condition, maintaining the existing grid infrastructure while covering lower heat demand with DH will increase specific grid prices. To avoid high grid costs, DH grids should be expanded in economically favourable areas. In such a way, DH supply levels can be maintained or even increased. Although the expected DH market shares for 2050 were set considerably higher than their 2020 levels, DH potential could increase by only 11% by 2050 compared to 2020. Given the yearly investment of 4 billion Euros at the EU level to expand the DH grid under this scenario, achieving a high DH market share calls for favourable financial and political support schemes.

For modelling the impact of DH connection rates below 100% in sparse areas, the use of an adjustment factor for the low plot ratio areas ($pr < 0.14$) was introduced. The impact of the adjustment factor on distribution and service pipes was elaborated in two examples. It was shown that at a given plot ratio, the cost of the service pipes is more sensitive to DH market shares than distribution pipes. The analyses of DH potential at the EU-27 level showed that DH in low plot ratio areas compose approximately 5% of overall DH potential under given conditions.

This thesis also dealt with the assessment of the economic potential of DH in Austria in 2030 and 2050. An economic DH potential in a range of 13% to over 50% was calculated, depending on the different assumptions. The sensitivity analyses revealed that the economic potential of DH depends, above all, on the market share achieved in DH areas. The results showed that by doubling the market share from 45% to 90%, the DH potential is more than doubled. The upper bound for the average heat distribution costs in DH areas positively relates to the total DH potential. However, it should be noted that investment in areas with high specific heat distribution costs does not always and everywhere lead to better positioning of DH than the individual heat supply systems. It was demonstrated that clustering potential DH areas and assigning a few supply portfolios to each cluster is a good approach, on the one hand, to keep the number of model-runs and CPU time limited and, on the other hand, to maintain the level of detail in the analyses. Considering the enumerated limitations, the approach can be used as a guideline for similar studies in other countries.

6.5 Outlook

Despite the limitations, the methods and approaches presented in this thesis for identifying the potential for DH can be used for comprehensive assessments, cost-benefit analyses, and heat planning. The availability of DH potential on local, regional and national levels does not guarantee its utilization, as there are challenges and barriers to implementing DH-related plans. While DH can play a vital role in renewable-based heat supply, its utilization can be hindered by various factors grouped into, but not limited to, five main categories: technical, regulatory, economic, municipal capacity, and stakeholder support.

- **Technical Barriers**: During the planning stage, technical challenges can hinder the implementation of heating plans if not properly dealt with. For example, uncertainties surrounding geothermal energy, such as environmental concerns and lengthy permitting processes, require thorough consideration. Additionally, limitations in infrastructure, such as insufficient electricity grid capacity for heat pumps, as well as obstacles in the distribution of technologies like hydrogen and biomass, also present substantial risks.
- **Regulatory Barriers**: The effective adoption and use of district heating (DH) relies significantly on supportive policies and legislation. Without mandatory regulations, such as those mandating the substitution of natural gas boilers with more sustainable options, the progress of the heat transition could be hindered. The lack of policies backing DH zones can hinder even well-designed heat plans and the implementation of DH systems.
- **Economic Barriers**: Economic considerations are pivotal in determining the viability of DH systems. While DH can be cost-effective in areas with high demand, the substantial initial investment can discourage building owners. Furthermore, municipalities may face challenges in evaluating the cost-effectiveness of DH systems due to limited transparency from DH companies. The shift from natural gas also brings financial risks, such as higher network fees for remaining consumers and reduced revenue for municipalities.
- **Municipal Capacity and Resources**: Small municipalities may face challenges in effectively preparing and implementing heat plans due to limited technical, financial, and legal expertise. As a result, they may need to seek assistance from external experts, potentially impacting the quality of the plans. Additionally, access to current and comprehensive data is essential for successful heat planning but can be a significant obstacle for these municipalities. These aspects may limit the utilization of DH systems in small municipalities.
- **Stakeholder Support**: Engagement with stakeholders, such as energy companies and building owners, is essential for the successful implementation of heat plans. Without their participation, stakeholders may feel their interests are not represented, leading to resistance. Involving stakeholders early in the process can help address their concerns and improve the overall success of the heat plans.

For an effective implementation of DH, significant barriers must be overcome. Sharing experiences between municipalities, enhancing transparency, and building stakeholder support are essential strategies to facilitate the transition to a renewable-based heat supply with the DH system. Ultimately, the successful implementation of DH systems depends on a combination of enforceable policies, financial incentives, and strong collaboration among all parties involved.

7 List of papers

Below you find the list of papers used for writing this dissertation. The level of contribution of Mostafa Fallahnejad, as the author of this dissertation, in each of the following papers has been provided in Table 7-1.

- Fallahnejad M, Hartner M, Kranzl L, Fritz S. Impact of distribution and transmission investment costs of district heating systems on district heating potential. Energy Procedia 2018;149:141–50. https://doi.org/10.1016/j.egypro.2018.08.178.
- Fallahnejad M, Kranzl L, Hummel M. District heating distribution grid costs: a comparison of two approaches. IJSEPM 2022;34:79–90. https://doi.org/10.54337/ijsepm.7013.
- Fallahnejad M, Büchele R, Habiger J, Hasani J, Hummel M, Kranzl L, et al. The economic potential of district heating under climate neutrality: The case of Austria. Energy 2022;259:124920. https://doi.org/10.1016/j.energy.2022.124920.
- Fallahnejad M, Kranzl L, Haas R, Hummel M, Müller A, García LS, et al. District heating potential in the EU-27: Evaluating the impacts of heat demand reduction and market share growth. Applied Energy 2024;353:122154. https://doi.org/10.1016/j.apenergy.2023.122154.

Additional support or foundation for the contents of this thesis can be found in the following co-authored papers:

- Billerbeck A, Breitschopf B, Winkler J, Bürger V, Köhler B, Bacquet A, Popovski E, Fallahnejad M, Kranzl M, Ragwitz M. Policy frameworks for district heating: A comprehensive overview and analysis of regulations and support measures across Europe. Energy Policy 2023;173:113377. https://doi.org/10.1016/j.enpol.2022.113377.
- Manz P, Billerbeck A, Kök A, Fallahnejad M, Fleiter T, Kranzl L, et al. Spatial analysis of renewable and excess heat potentials for climate-neutral district heating in Europe. Renewable Energy 2024;224:120111. https://doi.org/10.1016/j.renene.2024.120111.

7 List of papers

Table 7-1 Level of contribution by the first author (H: High; M: Medium; L: Low; N/A: Not Applicable)

Title of Publication:	Impact of distribution and transmission investment costs of district heating systems on district heating potential	District heating distribution grid costs: a comparison of two approaches	The economic potential of district heating under climate neutrality: The case of Austria	District heating potential in the EU-27: Evaluating the impacts of heat demand reduction and market share growth
Journal/Conference/Book:	Energy Procedia	International Journal of Sustainable Energy Planning and Management	Energy - The International Journal	Applied Energy
DOI:	https://doi.org/10.1016/j.egypro.2018.08.178	http://doi.org/10.54337/ijsepm.7013	https://doi.org/10.1016/j.energy.2022.124920	https://doi.org/10.1016/j.apenergy.2023.122154
Term	Level of contribution by the first author			
Conceptualization	H	H	H	H
Methodology	H	H	M	H
Software	H	H	M	H
Validation	M	H	M	H
Formal analysis	N/A	N/A	N/A	N/A
Investigation	N/A	N/A	N/A	N/A
Resources	H	H	M	H
Data Curation	H	H	M	H
Writing: Original Draft	H	H	H	H
Writing: Review & Editing	H	H	H	H
Visualization	H	H	H	H
Supervision	L	H	L	H
Project administration	N/A	N/A	N/A	N/A
Funding acquisition	N/A	N/A	N/A	N/A

8 Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author used Grammarly in order to improve the readability and language of the manuscript. After using this tool, the author reviewed and edited the content as needed. The Author takes full responsibility for the content of the published thesis.

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Appendices

Appendix A

This appendix belongs mainly to the Chapter 4 and provides input data used for the analyses and a summary of outputs.

Appendix A.1

shows the construction cost constants and coefficients in different EU-27 countries. These values are obtained from the sEEnergies project [12]. Where sEEnergies do not provide the data, coefficients from the most similar countries have been used. These countries are distinguished by an asterisk (*).

Table A-1 construction cost constants and coefficients in the EU-27 member states

Country	C1 [EUR/m]	C2 [EUR/m2]	Country	C1 [EUR/m]	C2 [EUR/m2]
DE	349	4213	IE*	549	2236
AT*	349	4213	IT	349	4213
BE*	549	3370	LT	71	3262
BG*	349	4213	LU*	549	3370
CY*	540	2087	LV*	71	3262
CZ*	349	4213	MT*	540	2087
DK*	439	4073	NL	549	3370
EE*	71	3262	PL*	349	4213
EL*	540	2087	PT*	354	4314
ES	354	4314	RO*	349	4213
FI*	439	4073	SE	439	4073
FR*	349	4213	SI*	540	2087
HR*	349	4213	SK*	349	4213
HU*	349	4213			

Appendix A.2

Input parameters and obtained calculation results for the EU-27 countries for the best-case and BL2050 scenarios are summarized in Table A-2 and Table A-3, respectively.

Fill Colour	Description
	Input
	Output
	EU-27
	Not Relevant/Applicable

Table A-2 Summary of input and output parameters obtained for the **best-case scenario**

Country	Demand [TWh]		Changes in demand [%]	DH market share in DH areas		Heat distribution cost ceiling [EUR/MWh]	Average specific DH grid cost in all DH areas over the lifetime [EUR/MWh]	Demand in identified DH areas [TWh]		Share of demand in DH areas from total demand in the country [%]		DH potential [TWh]		Share of DH potential from total demand in the country [%]	
	2020	2050		2020	2050			2020	2050	2020	2050	2020	2050	2020	2050
AT	84.2	43.1	-49%	55%	80%	36.0	28.4	36.8	16.9	44%	39%	20.3	13.6	24%	31%
BE	115.2	47.4	-59%	15%	70%	33.6	32.7	24.0	8.7	21%	18%	3.6	6.1	3%	13%
BG	24.3	14.3	-41%	64%	75%	38.4	30.0	9.6	6.4	40%	45%	6.2	4.8	25%	33%
CY	2.7	2.6	-3%												
CZ	92.3	51.9	-44%	44%	80%	34.8	28.0	50.2	27.0	54%	52%	22.1	21.6	24%	42%

Country	Demand [TWh]		Changes in demand [%]	DH market share in DH areas		Heat distribution cost ceiling [EUR/MWh]	Average specific DH grid cost in all DH areas over the lifetime [EUR/MWh]	Demand in identified DH areas [TWh]		Share of demand in DH areas from total demand in the country [%]		DH potential [TWh]		Share of DH potential from total demand in the country [%]	
	2020	2050		2020	2050			2020	2050	2020	2050	2020	2050	2020	2050
DE	805.8	356.4	-56%	32%	75%	36.0	33.6	342.6	140.2	43%	39%	109.6	105.1	14%	29%
DK	58.8	35.2	-40%	88%	90%	39.6	32.6	32.9	17.0	56%	48%	29.0	15.3	49%	43%
EE	12.5	5.9	-53%	58%	80%	36.0	15.1	9.1	3.8	72%	65%	5.3	3.1	42%	52%
EL	38.5	29.4	-23%	29%	70%	31.2	29.4	12.2	8.9	32%	30%	3.5	6.2	9%	21%
ES	145.7	111.0	-24%	3%	70%	36.0	34.7	61.0	45.3	42%	41%	1.8	31.7	1%	29%
FI	76.6	43.0	-44%	63%	90%	37.2	31.0	56.8	29.4	74%	68%	35.8	26.5	47%	62%
FR	487.5	303.4	-38%	15%	75%	40.8	33.7	192.7	105.5	40%	35%	28.9	79.1	6%	26%
HR	25.2	10.1	-60%	37%	80%	32.4	31.3	7.0	3.0	28%	29%	2.6	2.4	10%	23%
HU	80.0	40.4	-49%	33%	80%	30.0	28.7	31.3	16.0	39%	39%	10.3	12.8	13%	32%
IE	34.0	21.7	-36%	0%	70%	36.0	32.9	1.3	1.2	4%	5%	0.0	0.8	0%	4%
IT	383.4	223.2	-42%	17%	70%	36.0	34.5	159.9	88.4	42%	40%	27.2	61.9	7%	28%
LT	17.4	9.1	-48%	78%	90%	32.4	16.5	10.9	5.9	63%	65%	8.5	5.3	49%	59%
LU	7.8	4.3	-45%	29%	80%	32.4	28.8	5.1	2.6	65%	61%	1.5	2.1	19%	49%
LV	15.4	6.3	-59%	57%	80%	32.4	16.1	11.1	4.7	72%	74%	6.3	3.7	41%	59%
MT	0.8	0.9	11%												
NL	135.6	72.2	-47%	26%	75%	38.4	36.5	41.8	23.0	31%	32%	10.9	17.3	8%	24%
PL	244.2	121.1	-50%	51%	80%	31.2	29.8	124.0	54.7	51%	45%	63.2	43.8	26%	36%
PT	27.9	20.0	-29%	33%	70%	40.8	40.6	4.8	3.5	17%	17%	1.6	2.4	6%	12%
RO	83.8	37.1	-56%	43%	75%	32.4	31.1	27.8	12.3	33%	33%	12.0	9.2	14%	25%

Country	Demand [TWh]		Changes in demand [%]	DH market share in DH areas		Heat distribution cost ceiling [EUR/MWh]	Average specific DH grid cost in all DH areas over the lifetime [EUR/MWh]	Demand in identified DH areas [TWh]		Share of demand in DH areas from total demand in the country [%]		DH potential [TWh]		Share of DH potential from total demand in the country [%]	
	2020	2050		2020	2050			2020	2050	2020	2050	2020	2050	2020	2050
SE	86.2	77.8	-10%	86%	90%	42.0	31.3	64.9	55.1	75%	71%	55.8	49.6	65%	64%
SI	12.2	6.8	-44%	52%	80%	31.2	30.8	2.9	1.5	24%	22%	1.5	1.2	12%	17%
SK	30.8	14.5	-53%	74%	90%	32.4	29.6	13.0	5.7	42%	39%	9.6	5.1	31%	35%
EU-27	**3,128.8**	**1,709.1**	**-45%**				**31.8**	**1,333.6**	**686.6**	**43%**	**40%**	**476.9**	**530.6**	**15%**	**31%**

Table A-3 Summary of input and output parameters using 2050's heat demands from the sEEnergies project (**BL2050**)

Country	Demand [TWh]		Changes in demand [%]	DH market share in DH areas		Heat distribution cost ceiling [EUR/MWh]	Average specific DH grid cost in all DH areas over the lifetime [EUR/MWh]	Demand in identified DH areas [TWh]		Share of demand in DH areas from total demand in the country [%]		DH potential [TWh]		Share of DH potential from total demand in the country [%]	
	2020	2050		2020	2050			2020	2050	2020	2050	2020	2050	2020	2050
AT	84.2	49.1	-42%	55%	80%	36.0	27.4	38.4	24.8	46%	50%	21.1	19.8	25%	40%
BE	115.2	72.1	-37%	15%	70%	33.6	33.0	32.1	21.1	28%	29%	4.8	14.8	4%	20%
BG	24.3	26.2	7%	64%	75%	38.4	32.2	11.7	13.1	48%	50%	7.5	9.8	31%	38%
CY	2.7	1.5	-45%												
CZ	92.3	52.6	-43%	44%	80%	34.8	30.5	49.3	26.6	53%	51%	21.7	21.3	24%	40%
DE	805.8	451.8	-44%	32%	75%	36.0	33.1	400.7	242.3	50%	54%	128.2	181.7	16%	40%
DK	58.8	51.9	-12%	88%	90%	39.6	30.4	35.7	29.8	61%	57%	31.4	26.8	53%	52%
EE	12.5	9.8	-22%	58%	80%	36.0	13.6	9.2	6.5	73%	66%	5.3	5.2	43%	53%
EL	38.5	24.5	-36%	29%	70%	31.2	31.1	9.9	6.8	26%	28%	2.9	4.8	7%	20%
ES	145.7	213.1	46%	3%	70%	36.0	33.6	76.3	105.8	52%	50%	2.3	74.0	2%	35%
FI	76.6	49.3	-36%	63%	90%	37.2	28.7	48.3	31.8	63%	64%	30.4	28.6	40%	58%
FR	487.5	309.1	-37%	15%	75%	40.8	35.9	193.7	105.0	40%	34%	29.1	78.8	6%	25%
HR	25.2	10.5	-58%	37%	80%	32.4	32.0	4.0	1.1	16%	10%	1.5	0.9	6%	8%
HU	80.0	44.3	-45%	33%	80%	30.0	29.2	27.1	12.7	34%	29%	8.9	10.2	11%	23%
IE	34.0	15.5	-54%	0%	70%	36.0	35.5	0.1	0.0	0%	0%	0.0	0.0	0%	0%
IT	383.4	308.7	-19%	17%	70%	36.0	33.4	182.9	147.7	48%	48%	31.1	103.4	8%	33%
LT	17.4	12.7	-27%	78%	90%	32.4	16.8	10.9	7.0	62%	55%	8.5	6.3	49%	49%
LU	7.8	5.4	-31%	29%	80%	32.4	31.9	4.1	2.4	52%	44%	1.2	1.9	15%	35%

Country	Demand [TWh]		Changes in demand [%]	DH market share in DH areas		Heat distribution cost ceiling [EUR/MWh]	Average specific DH grid cost in all DH areas over the lifetime [EUR/MWh]	Demand in identified DH areas [TWh]		Share of demand in DH areas from total demand in the country [%]		DH potential [TWh]		Share of DH potential from total demand in the country [%]	
	2020	2050		2020	2050			2020	2050	2020	2050	2020	2050	2020	2050
LV	15.4	15.6	1%	57%	80%	32.4	12.9	11.5	10.5	75%	67%	6.6	8.4	43%	54%
MT	0.8	1.0	17%												
NL	135.6	93.2	-31%	26%	75%	38.4	37.8	32.2	16.0	24%	17%	8.4	12.0	6%	13%
PL	244.2	123.4	-49%	51%	80%	31.2	29.5	115.9	59.4	47%	48%	59.1	47.5	24%	39%
PT	27.9	17.3	-38%	33%	70%	40.8	39.6	2.4	1.3	8%	7%	0.8	0.9	3%	5%
RO	83.8	39.8	-52%	43%	75%	32.4	31.6	21.9	8.8	26%	22%	9.4	6.6	11%	17%
SE	86.2	66.2	-23%	86%	90%	42.0	32.0	53.5	37.6	62%	57%	46.0	33.9	53%	51%
SI	12.2	8.2	-33%	52%	80%	31.2	30.3	2.8	2.0	23%	24%	1.4	1.6	12%	19%
SK	30.8	15.9	-48%	74%	90%	32.4	30.7	12.8	5.7	42%	36%	9.5	5.2	31%	32%
EU-27	**3,128.8**	**2,088.7**	**-33%**				**31.8**	**1,387.2**	**925.7**	**44%**	**44%**	**477.0**	**704.2**	**15%**	**34%**

Appendix B

This appendix belongs mainly to the Chapter 5 and provides input data used for the analyses.

Table B-1: Prices, CO2 factors and external costs in 2030

	Low Price					**High price**				
Energy carrier	Taxes and charges		Emission factor	CO_2 price	External costs	Taxes and charges		Emission factor	CO_2 price	External costs
	Without	With				Without	With			
	€/MWh	€/MWh	tCO_2/MWh	€/tCO_2	€/tCO_2	€/MWh	€/MWh	tCO_2/MWh	€/tCO_2	€/tCO_2
Use in district heating										
Electricity	56	73	0.008	81	300	67.1	84.1	0.012	121.1	300
Natural Gas	29.6	33.6	0.2	81	300	38.2	42.2	0.2	121.1	300
Biogas/ Syngas	68.2	82.2	0.002	81	300	93.2	97.2	0.003	121.1	300
Heating oil	48.4	53.4	0.266	81	300	62.9	68	0.266	121.1	300
Wood chips	18.6	18.6	-	81	300	21.7	21.7	-	121.1	300
waste	-	-	0.13	81	300	5	5	0.13	121.1	300
Waste heat <100°C	5	5	-	81	300	10	10	-	121.1	300
Waste heat >100°C	15	15	-	81	300	20	20	-	121.1	300
Use in the residential sector										
Electricity	136.5	199.7	0.008	-	300	147.6	213.1	0.012	-	300
Natural Gas	59.6	80.5	0.2	-	300	68.2	90.9	0.2	-	300
Biogas/ Syngas	98.2	126.8	0.002	-	300	123.2	156.8	0.003	-	300
Heating oil	55.7	72.8	0.266	-	300	70.2	90.2	0.266	-	300
Wood logs	31.7	38	-	-	300	39.2	47	-	-	300
Pellets	53.3	63.9	-	-	300	62.2	74.7		-	300
Use in the service sector										
Electricity	136.5	166.5	0.008	-	300	147.6	177.6	0.012	-	300
Natural Gas	59.6	67	0.2	-	300	68.2	75.7	0.2	-	300
Biogas/ Syngas	98.2	105.6	0.002	-	300	123.2	130.6	0.003	-	300
Heating oil	55.7	60.7	0.266	-	300	70.2	75.2	0.266	-	300
Wood chips	25.2	25.2	-	-	300	31.2	31.2	-	-	300
Pellets	53.3	53.3	-	-	300	62.2	62.2	-	-	300

Table B-2: Prices, CO2 factors and external costs in 2050.

	Low Price					High price				
Energy carrier	Taxes and charges		Emission factor	CO_2 price	External costs	Taxes and charges		Emission factor	CO_2 price	External costs
	Without	With				Without	With			
	€/MWh	€/MWh	tCO_2/MWh	€/tCO_2	€/tCO_2	€/MWh	€/MWh	tCO_2/MWh	€/tCO_2	€/tCO_2
Use in district heating										
Electricity	88.7	105.7	0.002	183	300	127.5	144.5	0.009	296	300
Natural Gas	31.9	35.9	0.2	183	300	41.2	45.2	0.2	296	300
Biogas / Syngas	88.7	92.7	0.003	183	300	128.7	132.7	0.011	296	300
Heating oil	42.5	47.5	0.266	183	300	55.3	60.3	0.266	296	300
Wood chips	17.9	17.9	-	183	300	28.4	28.4	-	296	300
waste	-	-	0.104	183	300	5	5	0.104	296	300
Waste heat <100°C	5	5	-	183	300	10	10	-	296	300
Waste heat >100°C	15	15	-	183	300	20	20	-	296	300
Use in the residential sector										
Electricity	169.2	239.1	0.002	-	300	207.9	285.5	0.009	-	300
Natural Gas	61.9	83.2	0.2	-	300	71.2	94.5	0.2	-	300
Biogas / Syngas	118.7	151.4	0.003	-	300	158.7	199.4	0.011	-	300
Heating oil	49.8	65.7	0.266	-	300	62.5	81	0.266	-	300
Wood logs	32.3	38.7	-	-	300	51.2	61.4	-	-	300
Pellets	51.2	61.5	-	-	300	81.3	97.6		-	300
Use in the service sector										
Electricity	169.2	199.2	0.002	-	300	207.9	237.9	0.009	-	300
Natural Gas	61.9	69.3	0.2	-	300	71.2	78.7	0.2	-	300
Biogas / Syngas	118.7	126.1	0.003	-	300	158.7	166.1	0.011	-	300
Heating oil	49.8	54.8	0.266	-	300	62.5	67.5	0.266	-	300
Wood chips	25.6	25.6	-	-	300	40.7	40.7	-	-	300
Pellets	51.2	51.2	-	-	300	81.3	81.3	-	-	300

Table B-3: Energy mix for the provision of space heating and hot water in the different scenarios in 2030 for the economic perspective. (Source: own calculations)

	Energy demand scenario:	Transition scenario				WEM scenario			
	Energy price:	high price		low price		high price		low price	
	Market share:	45%	90%	45%	90%	45%	90%	45%	90%
Energy carrier for individual heat supply [TWh/a]	Biomass	14.17	8.54	14.48	9.14	14.24	8.62	14.59	9.26
	Solar thermal	2.61	1.57	2.67	1.69	2.80	1.70	2.87	1.82
	Ambient energy	3.54	2.13	3.61	2.28	3.69	2.24	3.78	2.40
	Electricity	7.47	4.50	7.63	4.82	7.58	4.59	7.76	4.93
	Gas	17.89	10.78	18.28	11.54	19.01	11.51	19.47	12.36
	Oil	9.87	5.95	10.08	6.37	10.66	6.46	10.92	6.93
Energy carrier for district heating [TWh/a]	Biomass	2.50	11.31	1.97	9.87	2.66	11.85	2.03	10.29
	MSW	3.23	3.49	3.23	3.49	3.34	3.60	3.34	3.61
	Solar thermal	0.09	0.14	0.08	0.14	0.09	0.15	0.08	0.15
	Waste heat	1.96	2.88	1.98	3.09	2.05	2.94	2.08	3.19
	Ambient heat	2.18	7.61	1.70	6.76	2.26	7.89	1.71	6.94
	Geothermal	1.47	2.42	1.47	2.41	1.53	2.51	1.53	2.51
	Electricity	1.46	4.73	1.09	4.08	1.51	4.91	1.09	4.20
	Gas	2.10	6.36	3.41	8.90	2.17	6.59	3.52	9.21

Table B-4: Energy mix for the provision of space heating and hot water in the different scenarios in 2030 for the financial perspective. (Source: own calculations)

	Energy demand scenario	Transition scenario				WEM scenario			
	Energy price	high price		low price		high price		low price	
	Market share	45%	90%	45%	90%	45%	90%	45%	90%
Energy carrier for individual heat supply [TWh/a]	Biomass	14.09	8.45	14.09	8.45	14.15	8.48	14.15	8.48
	Solar thermal	2.60	1.56	2.60	1.56	2.78	1.67	2.78	1.67
	Ambient energy	3.52	2.11	3.52	2.11	3.67	2.20	3.67	2.20
	Electricity	7.43	4.45	7.43	4.45	7.53	4.51	7.53	4.51
	Gas	17.79	10.67	17.79	10.67	18.88	11.32	18.88	11.32
	Oil	9.82	5.89	9.82	5.89	10.59	6.35	10.59	6.35
Energy carrier for district heating [TWh/a]	Biomass	1.84	7.04	1.42	5.51	1.94	7.54	1.47	5.94
	MSW	2.99	3.04	3.00	3.04	3.09	3.14	3.10	3.14
	Solar thermal	0.08	0.27	0.08	0.27	0.09	0.28	0.09	0.28
	Waste heat	1.73	2.24	1.78	2.33	1.81	2.28	1.86	2.37
	Ambient heat	2.76	9.76	2.94	10.38	2.90	10.18	3.10	10.83
	Geothermal	1.46	2.38	1.46	2.37	1.52	2.48	1.51	2.46
	Electricity	2.14	7.45	2.29	7.93	2.24	7.77	2.40	8.27
	Gas	0.91	2.97	0.96	3.09	0.94	3.07	1.00	3.20

Table B-5: Energy mix for the provision of space heating and hot water in the different scenarios in 2050 for the economic perspective. (Source: own calculations)

	Energy demand scenario:	Transition scenario				WEM scenario			
	Energy price:	high price		low price		high price		low price	
	Market share:	45%	90%	45%	90%	45%	90%	45%	90%
Energy carrier for individual heat supply [TWh/a]	Biomass	11.54	6.78	13.69	8.27	16.15	9.74	20.99	12.94
	Solar thermal	2.97	1.75	3.23	1.95	2.99	1.80	3.55	2.19
	Ambient energy	7.92	4.66	5.81	3.51	11.10	6.69	6.96	4.29
	Electricity	6.14	3.61	5.42	3.27	8.60	5.19	6.98	4.30
	Gas	0.66	0.39	2.82	1.70	0.92	0.55	4.70	2.90
	Oil	0.75	0.44	0.00	0.00	1.04	0.63	0.00	0.00
Energy carrier for district heating [TWh/a]	Biomass	1.59	5.98	1.75	6.51	2.56	9.10	2.72	9.87
	MSW	1.95	2.02	2.10	2.06	2.47	2.56	2.67	2.60
	Solar thermal	0.06	0.33	0.05	0.32	0.09	0.44	0.07	0.43
	Waste heat	1.32	2.47	1.31	2.38	1.76	3.19	1.74	3.07
	Ambient heat	0.95	3.87	0.49	3.51	1.01	4.62	0.63	4.31
	Geothermal	1.56	3.76	1.59	3.74	2.07	4.86	2.10	4.79
	Electricity	0.73	3.05	0.31	2.37	0.80	3.64	0.40	2.86
	Gas	0.30	1.10	0.86	1.66	0.38	1.39	1.09	2.10

Table B-6: Energy mix for the provision of space heating and hot water in the different scenarios in 2050 for the financial perspective. (Source: own calculations)

	Energy demand scenario:	Transition scenario				WEM scenario			
	Energy price:	high price		low price		high price		low price	
	Market share:	45%	90%	45%	90%	45%	90%	45%	90%
Energy carrier for individual heat supply [TWh/a]	Biomass	11.51	6.67	13.41	7.78	15.84	9.15	15.99	9.45
	Solar thermal	2.96	1.72	3.17	1.84	2.93	1.69	2.96	1.75
	Ambient energy	7.90	4.58	5.69	3.30	10.89	6.29	10.99	6.50
	Electricity	6.12	3.55	5.31	3.08	8.44	4.88	8.52	5.04
	Gas	0.65	0.38	2.76	1.60	0.90	0.52	0.91	0.54
	Oil	0.74	0.43	0.00	0.00	1.02	0.59	1.03	0.61
Energy carrier for district heating [TWh/a]	Biomass	1.47	5.78	1.69	6.14	2.34	8.77	2.64	9.33
	MSW	1.93	1.98	1.93	1.97	2.45	2.50	2.45	2.49
	Solar thermal	0.07	0.36	0.06	0.32	0.10	0.49	0.09	0.43
	Waste heat	1.36	2.46	1.31	2.40	1.85	3.22	1.78	3.14
	Ambient heat	1.01	4.03	1.02	4.25	1.43	5.37	1.26	5.29
	Geothermal	1.57	3.78	1.55	3.71	2.07	4.88	2.04	4.77
	Electricity	0.82	3.37	0.75	3.19	1.15	4.42	0.93	3.93
	Gas	0.20	0.90	0.33	1.17	0.26	1.14	0.42	1.47